Good Painting Practice

SSPC Painting Manual Volume 1

Fourth Edition



SSPC Painting Manual

Volume 1
Good Painting Practice
Fourth Edition

Executive Editor
Dr. Richard W. Drisko

Production Editor
Pamela Groff

Technical Illustrator
Renee Zmuda

SSPC: The Society for Protective Coatings
40 24th Street, 6th Floor
Pittsburgh, PA 15222

Foreword

The fourth edition of SSPC's **Painting Manual Volume 1: Good Painting Practice** represents the first comprehensive update of this key title in many years. More than 30 industry leaders have contributed over 40 chapters that cover every aspect of industrial painting—from the fundamentals of surface preparation for steel, concrete, and other surfaces to the complexities of painting particular facilities and structures. Over 20 new chapters have been added to address the coating industry's constantly evolving technologies and procedures.

It has been nearly 50 years since the release of the first edition this book. SSPC remains committed to assisting today's protective coating specialists as they strive for improved performance and economics, while conforming to government requirements concerning health, safety, and the environment. We thank our authors for sharing their knowledge with colleagues through this important work and look forward to a future of continued cooperation in developing quality standards and publications for the protective coatings industry.

William L. Shoup
Executive Director
Society for Protective Coatings
Pittsburgh, PA

Introduction

The information in this book is provided at a basic level to permit personnel with limited technical training to address current problems with the best available materials, equipment, and technologies. The scope of this book has been broadened to include information on the coating of concrete and the management of coating projects. These are areas that have not received needed attention in the past. The book's intended audience remains contractors, engineers, specifiers, formulators, suppliers, technicians, maintenance painters, users, and manufacturers who are looking for state-of-the-art technologies to meet specific requirements.

This book is intended to be a companion to *SSPC Painting Manual Volume 2: Systems and Specifications.* Volume 2 can be used effectively to implement the recommendations of this book and facilitate the incorporation of SSPC specifications into procurement documents.

Presentation of Chapters

This book is divided into sections in which related topics are grouped for the convenience of the reader.

Section 1. Corrosion

Control of metal corrosion is probably the chief reason for applying coatings. Thus, it is important that coatings personnel have a basic understanding of the impact of corrosion and the systems available for its control.

Chapter 1.1. **Corrosion of Metals** describes the causes and mechanisms of metal corrosion. It also describes the most commonly found types of industrial corrosion.

Chapter 1.2. **Designing Structures for Good Painting Performance** describes how corrosion on metal structures can be minimized by avoiding those features that promote both corrosion and deterioration.

Chapter 1.3. **Mechanisms of Corrosion Control by Coatings** describes the basic mechanisms by which coatings may be used to control metal corrosion. It also describes the requirements for each mechanism.

Chapter 1.4. **Properties of Coating Generic Types** describes the general chemical and physical properties of different generic coatings and how these properties contribute to the total corrosion control process.

Chapter 1.5. **Organic Coatings: Composition and Film Formation** discusses the components of organic coatings and their functions in providing the protective film that guards against corrosion.

Chapter 1.6. **Cathodic Protection of Coated Structures** describes the basic mechanisms and applications of cathodic protection to coated metal structures. It describes the environments in which cathodic protection can be effective and emphasizes the synergistic effects of using cathodic protection in conjunction with protective coatings in a total corrosion control program.

Chapter 1.7. **Coating Galvanized Steel** describes hot dipping of galvanized steel for industrial service and surface treatment and coating to provide additional years of protection to the steel.

Section 2. Surface Preparation

Surface preparation is perhaps the most critical part of coating operations and typically also the most expensive.

Chapter 2.1.**Overview of Steel Surface Preparation** describes the practical and economic effects of obtaining the recommended levels of surface preparation of steel before application of coatings.

Chapter 2.2. **Hand and Power Tool Cleaning** describes both the oldest processes for preparing surfaces prior to painting and those power tools common in cleaning operations.

Chapter 2.3. **Nonmetallic Abrasives** describes when and how these abrasives can be used most effectively.

Chapter 2.4. **Metallic Abrasives** describes how to use these abrasives most efficiently (including recycling) to achieve desired levels of cleanliness and profile.

Chapter 2.5. **Abrasive Air Blast Cleaning** describes recommended techniques to achieve optimum cleaning rates and levels of cleanliness and profile.

Chapter 2.6. **Centrifugal Blast Cleaning** describes the techniques used and advantages and disadvantages of this process.

Chapter 2.7. **Wet Abrasive Blast and Pressurized Water Cleaning (Waterjetting)** describes the techniques used and advantages and disadvantages of this process.

Chapter 2.8. **The Effect of Soluble Salts on Protective Coatings** describes different techniques for removing soluble salts from contaminated surfaces and analyzing the problems inherent with the presence of such salts. It also describes possible adverse effects on coating performance, if removal is inadequate.

Chapter 2.9. **Other Methods of Surface Preparation** describes pickling, chemical stripping, baking soda blast cleaning, pliant media blasting, dry-ice blasting, and electrochemical stripping.

Chapter 2.10. **Solvent and Pre-Cleaning** describes removing any contaminants that cannot be removed by subsequent mechanical cleaning and surface profiling.

Chapter 2.11. **Dehumidification During Coating Operations** describes the technology of dehumidification and temperature control in enclosed spaces and the importance of such equipment during surface preparation and coating application and curing.

Section 3. Surface Preparation of Concrete and Other Surfaces for Coating

Surface preparation of concrete and other surfaces requires special techniques as described in these chapters.

Chapter 3.1. **Concrete Surface Preparation** describes recommended methods of preparing concrete surfaces to achieve the desired levels of cleanliness and surface profile.

Chapter 3.2. **Surface Preparation of Nonferrous Surfaces** describes techniques for preparing aluminum, copper, and nickel alloys, stainless steel, and wood and polymer resin-based composites for coating application and optimum performance.

Section 4. Coating Materials

An understanding of the basics of coating materials is essential for their proper utilization. Section 4 describes the different coatings available for a variety of purposes.

Chapter 4.1. **Coatings for Industrial Steel Structures** presents general information on the use of coating systems for the protection of steel surfaces.

Chapter 4.2. **Coatings for Concrete** describes how coating concrete surfaces differs from coating steel.

Chapter 4.3. **Powder Coatings** describes powder coating materials, application methods, substrates, and curing techniques.

Chapter 4.4. **Thermal-Spray (Metallized) Coatings for Steel** describes how metallizing is used to protect steel from corrosion. It also describes sealing and topcoating to provide optimum corrosion protection.

Section 5. Application Methods and Equipment

Section 5 describes different methods of coating application and the equipment used in

the shop and field.

Chapter 5.1. **Application of Industrial Coatings** describes all coating application methods and the advantages and limitations of each.

Chapter 5.2. **Contractor Equipment: An Overview** describes the types of equipment typically used for successful industrial maintenance painting.

Chapter 5.3. **Shop Painting of Steel** describes different types of industrial and light industrial/commercial paint shops, their methods of operation, and their advantages and limitations when compared to on-site field painting.

Section 6. Coating Specific Structures

Section 6 describes how to prepare surfaces and apply coatings to specific structures. It also describes the special problems associated with coating each of these structures.

Chapter 6.1. **Painting Highway Bridges and Structures** describes recommended materials and methods for coating steel bridges in the field.

Chapter 6.2. **Corrosion Protection of Water and Fuel Tanks** provides an overview of the industry guidance in this area and examples of practical experience in applying this guidance.

Chapter 6.3. **Linings for Vessels and Tanks** describes accepted practices for selecting and applying protective coatings to the interior surfaces of steel tanks.

Chapter 6.4. **Painting Chemical Plants** describes the recommended methods for coating equipment and structures located in these harsh environments.

Chapter 6.5. **Painting Waste Water Treatment Plants** describes the coating systems used for various areas of waste water treatment plants.

Chapter 6.6. **Painting Petroleum Refineries** describes the recommended coating methods for these facilities.

Chapter 6.7. **Painting Power Generating Facilities** describes the common methods for generating electrical power and the best coating systems for each type of power facility.

Chapter 6.9. **Painting Steel Surfaces in Pulp and Paper Mills** provides a framework for establishing and executing successful maintenance coating programs in pulp and paper mills with associated guidelines for ensuring quality coatings work.

Chapter 6.10. **Painting Hydraulic Structures** describes the coating materials and methods used to protect locks, dams, and other components of hydraulic structures.

Chapter 6.11. **Coatings for Buried and Immersed Metal Pipelines** describes the fundamentals of selection, application, inspection, and performance of coatings buried in soils or immersed in water.

Chapter 6.12. **Painting Ships** describes problems with ship corrosion and new construction and maintenance coating systems for various ship components.

Section 7. Inspection of Coating Operations

Section 7 describes standard industry inspection methods used in all coating operations to ensure that job specification requirements are fully met.

Chapter 7. **Inspection** describes all commonly used inspection practices and tools.

Section 8. Safety and Health

Section 8 describes the many health and safety concerns in the coatings industry and the actions that should be taken to protect workers and the environment.

Chapter 8. **Safety and Health in the Protective Coatings Industry** addresses OSHA safety regulations as well as directives from NIOSH and other organizations.

Section 9. Government Regulation Affecting the Coatings Industry

Section 9 reviews those government regulations impacting the coatings industry. A general knowledge of these regulations is necessary to conduct coating operations.

Chapter 9.1 **Air Quality Regulations** addresses the Clean Air Act, national ambient air quality standards, and hazardous air pollutants.

Chapter 9.2 **Waste Handling and Disposal** covers sources of waste in painting activities and relevant federal and state regulations.

Chapter 9.3 **Other Regulations Affecting Protective Coatings** describes the impact of water quality standards, CERCLA (Superfund), and lead abatement programs.

Section 10. Programmed Painting

Section 10 describes various aspects of designing programmed painting systems to provide for structural protection at minimal expense.

Chapter 10.1 **Total Protective Coatings Programs** describes how to prepare and manage a total protective coatings program for an industrial or government activity.

Chapter 10.2. **Comparative Painting Costs** presents guidance in cost estimating coating operations in various regions of the U.S.

Chapter 10.3. **Using Plant Surveys to Maintain Coating Protection of Structures** describes how minimum, mid-level, and detailed field surveys can be used to resolve various maintenance painting challenges.

Chapter 10.4. **Preparing a Specification for a Coating Project** summarizes the Construction Specifications Institute (CSI) format for preparing job specifications.

Chapter 10.5. **Maintenance Painting Programs** describes the elements of a maintenance painting program—when to start and how to accomplish the steps.

Sections 11 and 12. Coating Performance and Failures

Sections 11 and 12 describe quality control methods for good coating performance and those coating failures that may occur when quality control is lacking.

Chapter 11. **Quality Control for Protective Coatings Projects** provides an overview of quality control inspection procedures and roles.

Chapter 12. **Coating Failures** addresses the common causes of coating defects on industrial structures and the associated preventative or corrective actions.

Dr. Richard W. Drisko
Executive Editor

Table of Contents

To use this Table of Contents: scroll down or use the bookmarks in the navigation pane at left to move to a different location in this index. Click on a **blue document title** to view that document. To return to this index after viewing a document, click the "Previous Menu" bookmark in the navigation pane.

Foreword
William H. Shoup

Introduction
Richard W. Drisko

Chapter 1.1 **Corrosion of Metals**
James F. Jenkins and Richard W. Drisko 1

Chapter 1.2 **Designing Steel Structures for Good Painting Performance**
James F. Jenkins and Richard W. Drisko 13

Chapter 1.3 **Mechanisms of Corrosion Control by Coatings**
Richard W. Drisko and James F. Jenkins 21

Chapter 1.4 **Properties of Generic Coating Types**
Richard W. Drisko and James F. Jenkins 29

Chapter 1.5 **Organic Coatings: Composition and Film Formation**
Richard W. Drisko and James F. Jenkins 41

Chapter 1.6 **Cathodic Protection of Coated Structures**
James F. Jenkins and Richard W. Drisko 49

Chapter 1.7 **Coating Galvanized Steel**
Richard W. Drisko 57

Chapter 2.1 **Overview of Steel Surface Preparation**
H. William Hitzrot 63

Chapter 2.2 **Hand and Power Tool Cleaning**
Preston S. Hollister, R. Stanford Short, Florence Mallet, and Brian Harkins 69

Chapter 2.3 **Nonmetallic Abrasives**
H. William Hitzrot and James Hansink 77

Chapter 2.4 **Metallic Abrasives**
H. William Hitzrot 83

Chapter 2.5 **Abrasive Air Blast Cleaning**
Scott Blackburn 91

Chapter 2.6 **Centrifugal Blast Cleaning**
Hugh Roper and Allen Slater 105

Chapter 2.7 **Wet Abrasive Blast and Pressurized Water Cleaning (Waterjetting)**
Lydia M. Frenzel 111

Chapter 2.8 **The Effect of Soluble Salts on Protective Coatings**
Bernard R. Appleman 119

Chapter 2.9 **Other Methods of Surface Preparation**

2.9.1 **Pickling**
Thomas J. Langill and John W. Krzywicki 139

2.9.2 **Chemical Stripping**
John Steinhauser 145

2.9.3 **Sodium Bicarbonate (Baking Soda) Blast Cleaning**
Mike Doty and Delia L. Downes 149

Chapter 2.9 **Other Methods of Surface Preparation, cont.**

2.9.4 **Pliant Media Blasting**
Tony Anni 155

2.9.5 **Carbon Dioxide (Dry-Ice) Blasting**
Robert W. Foster 161

2.9.6 **Electrochemical Stripping**
Rudolf Keller and Brian J. Barca 169

Chapter 2.10 **Solvent and Chemical Pre-Cleaning**
Melvin H. Sandler, Samuel Spring, and Charles S. Bull 175

Chapter 2.11 **Dehumidification During Coating Operations**
Art Pedroza, Jr., James D. Graham, and Richard W. Drisko 183

Chapter 3.1 **Concrete Surface Preparation**
Benjamin S. Fultz 189

Chapter 3.2 **Surface Preparation of Nonferrous Surfaces**
Norm Clayton 201

Chapter 4.1 **Coatings for Industrial Steel Structures**
Richard W. Drisko 211

Chapter 4.2 **Coatings for Concrete**
Richard W. Drisko 219

Chapter 4.3 **Powder Coating**
Albert G. Holder 227

Chapter 4.4 **Thermal-Spray (Metallized) Coatings for Steel**
Robert A. Sulit 235

Chapter 5.1 **Application of Industrial Coatings**
Frank W. G. Palmer 251

Chapter 5.2 **Contractor Equipment: An Overview**
Michael Damiano 267

Chapter 5.3 **Shop Painting of Steel**
Richard W. Drisko and Raymond E.F. Weaver 281

Chapter 6.1 **Painting Highway Bridges and Structures**
Robert Kogler 289

Chapter 6.2 **Corrosion Protection of Water and Fuel Tanks**
Joseph H. Brandon 299

Chapter 6.3 **Linings for Vessels and Tanks**
Wallace P. Cathcart, Albert L. Hendricks, and Joseph H. Brandon 309

Chapter 6.4 **Painting Chemical Plants**
J. Roy Allen, David M. Metzger, and J. Bruce Henley 317

Chapter 6.5 **Painting Waste Treatment Plants**
James D. Graham 327

Chapter 6.6 **Painting Petroleum Refineries**
W.E. Stanford and SSPC Staff 337

Chapter 6.7 **Painting Power Generation Facilities**
Ronald R. Skabo and Bryant (Web) Chandler 343

Chapter 6.8 **Painting Steel Structures in Pulp and Paper Mills**
Randy Nixon and David C. Bennett 349

Chapter 6.9 **Painting Hydraulic Structures**
Alfred D. Beitelman 359

Chapter 6.10 **Coatings for Buried and Immersed Metal Pipelines**
Richard W. Drisko 371

Chapter 6.11 **Painting Ships**
Earl Bowry 377

Chapter 7 **Inspection**
Kenneth A. Trimber and William D. Corbett 393

Chapter 8 **Safety and Health in the Protective Coatings Industry**
Daniel P. Adley and Stanford T. Liang 419

Chapter 9.1 **Air Quality Regulations**
Bernard R. Appleman 441

Chapter 9.2 **Waste Handling and Disposal**
Bernard R. Appleman 455

Chapter 9.3 **Other Regulations Affecting Protective Coatings**
Bernard R. Appleman 467

Chapter 10.1 **Total Protective Coatings Programs**
Richard W. Drisko and James F. Jenkins 489

Chapter 10.2 **Comparative Painting Costs**
L. Brian Castler, Jayson L. Helsel, Michael F. MeLampy, and Eric Kline 495

Chapter 10.3 **Using Plant Surveys to Maintain Coating Protection of Structures**
Richard W. Drisko 517

Chapter 10.4 **Preparing a Specification for a Coating Project**
Richard W. Drisko 521

Chapter 10.5 **Maintenance Painting Programs**
Richard W. Drisko and Joseph H. Brandon 531

Chapter 11 **Quality Control for Protective Coatings Projects**
Thomas A. Jones 541

Chapter 12 **Coating Failures**
Richard W. Drisko 553

Index (View only) 571

Chapter 1.1
Corrosion of Metals

James F. Jenkins and Richard W. Drisko

Introduction

This chapter describes in basic terms the causes and mechanisms of corrosion. Corrosion is defined as "the chemical or electrochemical reaction between a metal and its environment resulting in the loss of the material and its properties."[1] Various types of corrosion are discussed and the basic principles behind the use of protective coatings and cathodic protection for corrosion control are also covered. The strategies used in corrosion control by design are briefly discussed as well. This basic knowledge helps in understanding how protective coatings, cathodic protection, and other corrosion control methods can best be used as part of a total corrosion control program. Further information on these corrosion control methods can be found in subsequent chapters.

Why Metals Corrode

With few exceptions, metallic elements are found in nature in chemical combination with other elements. For example, iron is usually found in nature in the form of an ore, such as iron oxide. This combined form has a low chemical energy content and is very stable. Iron can be produced from iron ore by a high temperature smelting process. The heat that is added during smelting breaks the chemical bond between the iron and the oxygen. As a result, the iron and other metals used in structural applications have a higher energy content than they do in their original state, and are relatively unstable.

Corrosion is a natural process. Just like water flows to seek the lowest level, all natural processes tend towards the lowest possible energy states. Thus, iron and steel have a natural tendency to combine with other chemical elements to return to their lower energy states. In order to do this, iron and steel will frequently combine with oxygen, present in most natural environments, to form iron oxides, or "rust," similar chemically to the original iron ore. **Figure 1** illustrates this cycle of refining and corrosion of iron and steel.

When rust forms on an iron or steel structure, metal is lost from the surface, reducing cross section and strength. Rust is also unsightly and can cause contamination of the environment and industrial products. It is further detrimental in that it is not a stable base for coatings.

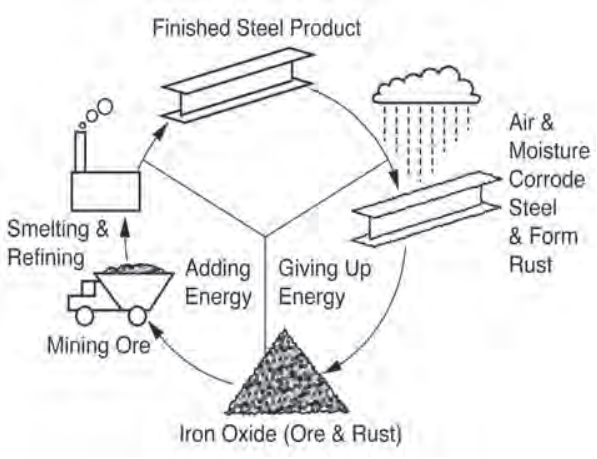


Figure 1. The corrosion cycle.

Immunity and Passivity

Some metals such as gold and platinum have lower energy levels in their metallic form than when combined with other chemical elements. These metals are often found in nature in the metallic form and do not tend to combine with other elements. They are thus highly resistant to corrosion in most natural environments. These materials are said to be immune to corrosion in those natural environments.

Other metals and alloys, while in a high energy state in their metallic forms, are resistant to corrosion due to formation of passive films (usually oxides) on their surfaces. These films form through a natural process similar to corrosion, and are usually invisible to the naked eye. They are, however, tightly adherent and continuous and serve as a barrier between the underlying metal and the environment. Stainless steels, aluminum alloys, and titanium are examples of metals that are in a high energy state in their metallic forms, but are relatively resistant to corrosion due to the formation of passive films on their surfaces. However, particularly in the case of stainless

steels and aluminum alloys, this film is not resistant to all natural environments and can break down in one or more particular environments. This breakdown of the passive film often results in rapid, localized corrosion, due to the electrochemical activity of the parts of the surface that remain passive. **Figure 2** shows an example of such rapid, localized corrosion. (Note: This type of rapid, localized corrosion does not occur when paint coatings break down. Although paints provide a similar type of protection to the underlying metal, they are usually not electrochemically active.)



Figure 2. Corroded low-alloy steel bridge where protective outside film has been lost.

The Mechanism of Corrosion

The combination of metals with other chemical elements in the environment—what is commonly called corrosion—occurs through the action of the electrochemical cell. The electrochemical cell consists of four components: an anode, a cathode, an electrolyte, and a metallic path for the flow of electrons. When all four of these components are present as shown in **Figure 3** "cyclic reaction" occurs that results in corrosion at the anode.

The key to understanding corrosion and corrosion control is that all of the components of this electrochemical cell must be present and active for corrosion to occur. If any one of the components is missing or inactive, corrosion will be arrested.

Anode

At the anode in an electrochemical cell, metal atoms at the surface lose one or more electrons and become positively charged ions. The generic chemical equation for this type of reaction is:

$$M^o \rightarrow M^+ + e^-$$

where M^o is a neutral metal atom, M^+ is a positively charged metal ion, and e^- is an electron. Corrosion occurs as the positively charged ions enter the electrolyte and are thus effectively removed from the metal anode surface. The electrons remain in the bulk metal and can move through the metal to complete other reactions. In the case of iron (Fe) two electrons are usually lost, and the equation is:

$$Fe^o \rightarrow Fe^{++} + 2\ e^-$$

where Fe^o is an iron atom and Fe^{++} is an iron (ferrous) ion. After the iron ions (Fe^{++}) enter the electrolyte, they usually combine with oxygen in a series of reactions that ultimately form rust.

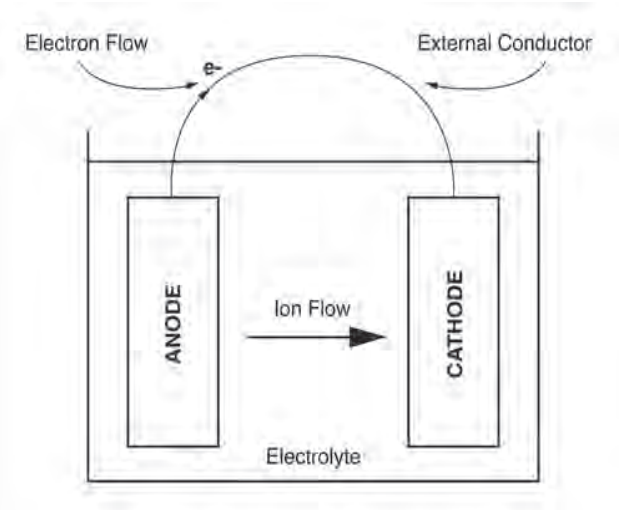


Figure 3. The basic components of the electrochemical cell.

Cathode

At the surface of the cathode in an electrochemical cell, the electrons produced by the reactions at the anode are "consumed," i.e., used up by chemical reactions. The generic chemical equation for this type of reaction is:

$$R^+ + e^- \rightarrow R^o$$

or

$$R^o + e^- \rightarrow R^-$$

In this equation, R stands for any of a number of possible compounds that can exist in an oxidized form (R^+) and in a reduced form (R^o).

Many cathodic reactions are possible in

natural environments. The cathodic reactions that actually occur are dependent on the chemical composition of the electrolyte. In many instances where the electrolyte is water, the cathodic reaction is:

$$2\ H_2O + O_2 + 4\ e^- \rightarrow 4\ OH^-$$

In this reaction, two water molecules (H_2O) combine with one oxygen molecule (O_2) and four electrons to form four hydroxide ions (OH^-). In this case, the water and oxygen are reduced as in the generic cathodic reaction above. These hydroxide ions tend to create an alkaline environment at active cathodic areas.

Metallic Path

A metallic path between the anode and the cathode allows electrons produced at the anode to flow to the cathode. A metallic path is required in the corrosion cell because the electrolyte cannot carry free electrons. In many cases, where the anode and cathode are on the same piece of metal, the metal itself is the “metallic path” that carries the electrons from the anode to the cathode.

Electrolyte

The electrolyte serves as an external conductive media and a source of chemicals for reactions at the cathode, and as a reservoir for the metal ions and other corrosion products formed at the anode. Within the electrolyte, a flow of charged ions balances the flow of electrons through the metallic path. Under atmospheric conditions, the electrolyte consists of just a thin film of moisture on the surface, and the electrochemical cells responsible for corrosion are localized within this thin film. Under immersion conditions, however, much more electrolyte is present, and the electrochemical cells responsible for corrosion can involve much larger areas.

Rate of Reaction

Many factors can affect corrosion, but the bottom line is that the rate at which corrosion occurs is limited by the rate of reaction at the least active component of the electrochemical cell. For example, if there is an incomplete metallic path, this may be the limiting factor in the overall corrosion reaction. In this case, the electrochemical cell responsible for corrosion is similar to that in a flashlight battery when the flashlight is switched off **(see Figure 4).** When a battery is installed in a circuit such as a flashlight, no current flows until the flashlight is switched on. The high effective resistance of the open switch prevents current flow and the electrochemical discharge of the battery. Similarly, an incomplete metallic path prevents corrosion. The nature of the electrolyte may also affect the overall corrosion reaction. If the available electrolyte is very pure water that has relatively few ions, the ion flow can be the limiting factor. In many cases of corrosion under immersion conditions, the amount of oxygen available for the cathodic reaction is the limiting factor. Many methods for controlling corrosion target only one component of the overall electrochemical cell. By controlling the rate of just one of the reactions involved in the overall electrochemical cell, the overall rate of corrosion can be controlled.

It should be noted that temperature has an effect on the rate of the corrosion reaction. However, this effect is very complex, and is beyond the scope of this text. In the case of dissimilar metal corrosion, the potential difference between the metals also has an effect on reaction rate. This is discussed in the galvanic corrosion section of this chapter.

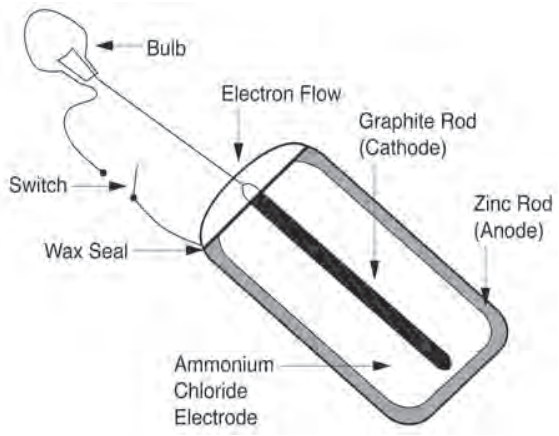


Figure 4. The dry cell battery.

Measuring Corrosion

There are many methods of measuring corrosion:

Weight Loss

Weight loss is one of the most widely used methods of measuring corrosion. A sample is first carefully cleaned to remove all surface contamination. After cleaning, it is weighed. It is then exposed to the

environment in question and then recleaned and reweighed after a given period of time. If no corrosion has occurred, there will be no weight loss.

Size Measurement

The dimensions of the sample are measured before and after exposure. No change in dimensions indicates that no corrosion has occurred.

Visual Observation

Even minor amounts of corrosion are readily visible due to roughening of the surface.

Chemical Analysis

Surface deposits and the environments are tested for corrosion products. If surface deposits and the environment test negative for corrosion products (i.e., none present), it can be assumed that no corrosion has occurred.

Forms of Corrosion

No Attack

As stated in section immunity and passivity, some metals and alloys are essentially unaffected by corrosion in certain environments. This may be either because they are more stable in their metallic forms than in a combined forms or because they form natural protective films on their surfaces that provide completely effective passivity. However, just because a given metal or alloy is essentially unaffected by corrosion in one or more environments does not mean that it is resistant to corrosion in all environments. That no corrosion has occurred can be verified by one of the methods described in the previous section.

Uniform Corrosion

Uniform corrosion is a form of corrosion in which a metal is attacked at about the same rate over the entire exposed surface. While considerable surface roughening can take place in uniform corrosion, when the depth of attack at any point exceeds twice the average depth of attack, the corrosion is no longer considered to be uniform.

When a metal is attacked by uniform corrosion, the location of anodic and cathodic areas shifts from time to time, i.e., every point on the surface acts as both an anode and a cathode at some time during the exposure. A schematic representation of uniform corrosion is shown in **Figure 5,** where anodic and cathodic sites periodically reverse. In this case, the metallic path is through the metal itself. The electrolyte may either be a thin film of moisture in atmospheric exposure, a liquid in which the surface is immersed, or water contained in moist earth.

The amount of uniform corrosion is usually measured by weight loss. If weight loss is determined over a given period of time, it can also be used to calculate an average rate of metal loss over the entire surface. This corrosion rate is usually expressed in mils (0.001 inch) per year (mpy) or millimeters per year (mm/yr).

This is a good way to measure the amount and rate of corrosion if the corrosion is truly uniform; however, these average rates can give misleading results if the corrosion is not uniform over the entire surface. (See the section on pitting for further information.) Direct measurement of metal loss through metal thickness is also sometimes performed and can be used to determine corrosion rate in mpy or mm/yr.

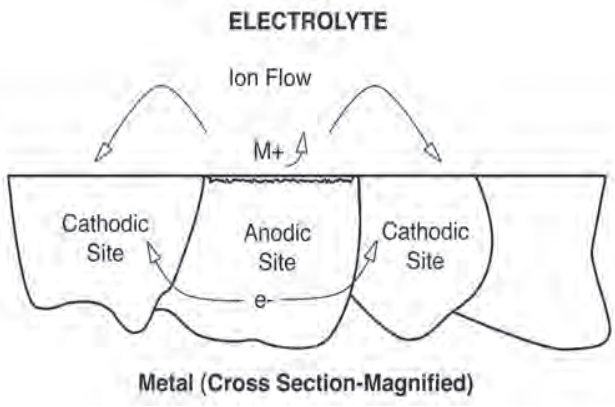


Figure 5. The corrosion cell on a metal surface.

Since corrosion rates commonly vary with time (e.g., slower as corrosion products form protective films), they are usually measured over several different intervals. Corrosion rates can also be measured continuously for extended periods, using electrochemical techniques to determine how the rates are affected by time.

A coating is a very effective tool in combating uniform corrosion because corrosion usually proceeds slowly at local sites where the coating breaks down or is damaged. These areas can therefore be repaired before significant damage occurs, assuming that

inspection identifies the defects at an early stage.

Galvanic Corrosion

When two or more dissimilar metals are connected by a metallic path and exposed to an electrolyte, galvanic corrosion can occur as shown in **Figure 6.** This dissimilar metal corrosion is driven by the difference in electrical potential between the metals. An electrochemical cell is formed in which the more active metal acts as an anode and the less active metal acts as a cathode. In galvanic corrosion, the more active metal corrodes more than if it were not electrically coupled, and the less active metal corrodes less than if it were not electrically coupled.

A "galvanic series" table that lists metals in order of their electrical potential in a given environment can be used to determine which metal in a given combination will act as an anode and which will act as a cathode. **Table 1** is a galvanic series derived from exposure of common metals to seawater. The galvanic activity of metals in other environments is similar to that in seawater, but significant differences may occur. It should be noted that in North America, galvanic series are listed with the most active metals at the top, but the opposite may be true in other parts of the world. To determine which convention has been used in a particular galvanic series table, look for active metals like zinc, magnesium or aluminum and see if they are listed at the top or at the bottom. It should also be noted that some metals, such as the 300 Series stainless steel, are listed twice.

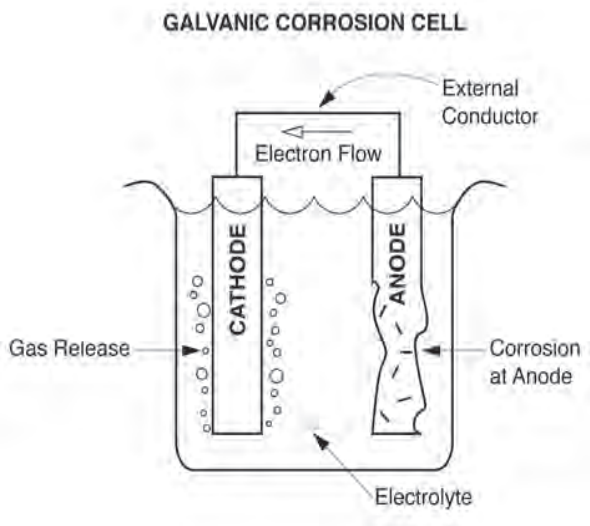


Figure 6. Galvanic corrosion cell.

In atmospheric exposures, the anodic area and cathodic area involved in galvanic corrosion are usually about equal in size. This is because the electrical resistance of the thin film of moisture acting as the electrolyte is very large over distances much more than 1/8 inch or so (1-2 mm). Under immersion conditions, however, the effective resistance of the electrolyte is much less and galvanic corrosion effects have a much greater range. The cathodic reaction is often the limiting factor in corrosion under immersion conditions due to the limited availability of dissolved oxygen.

As described in cathode section, in many instances where the electrolyte is water, the cathodic reaction is:

$$2\,H_2O + O_2 + 4\,e^- \rightarrow 4\,OH^-$$

Thus, the rate at which electrons can be consumed at the cathode limits the rate of galvanic attack in these situations.

Table 1. Galvanic Series Derived from Exposure of Common Metals to Seawater.

Magnesium – More Active
Zinc
Galvanized Steel (zinc coating intact)
Aluminum and Aluminum Alloys
Mild Steel
Cast Iron
Active 300 Series Stainless Steel
Lead-Tin Solder
Lead
Tin
Naval Brass
Yellow Brass
Red Brass
Copper
Titanium
Passive 300 Series Stainless Steel
Graphite
Gold
Platinum – Less Active

The amount of galvanic corrosion that occurs in a given situation can be measured indirectly by monitoring the current flow between the anodes and cathodes. It can also be measured directly by determining the weight loss of the anodic and cathodic materials, or by some other direct means of measurement such as pitting depths or thickness measurements as appropriate to the form of attack.

Relative rates of galvanic attack can be

assessed by looking at the distance between the metals in a galvanic series. For example, steel is farther from copper than it is from lead in the galvanic series, so the rate of galvanic attack on a piece of steel would be expected to be higher if coupled to a piece of copper than if coupled to a piece of lead, all other things being equal.

Actual rates of galvanic attack are difficult to predict. They depend on the potential difference between the metals involved and the relative areas of affected anodic and cathodic surface. However, the relative areas of affected anode and cathode surface can, and often do, have a greater effect on galvanic corrosion than the potential difference between the metals involved. If the anode is large and the cathode is small, the low rate at which electrons can be consumed at the cathode results in little acceleration of corrosion on the larger anodic surface. **(Figure 7)** On the other hand, if the anode is small and the cathode is large, a relatively large number of electrons can be consumed at the cathode and this effect is concentrated over a smaller anode, resulting in a substantial acceleration of corrosion at the small anodic area. In this case, there is a large acceleration of corrosion at the anode. The effect of area ratio on galvanic corrosion is shown more graphically in **Figure 8.**

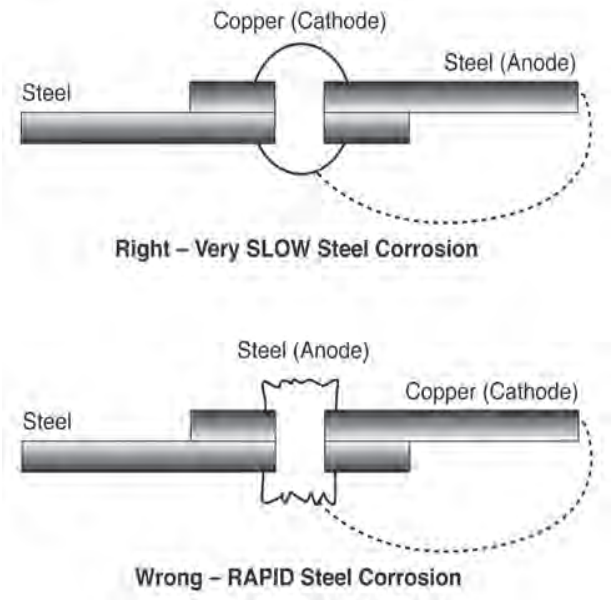


Figure 7. Rate of corrosion.

The area ratio effect is important when using coatings as a means of corrosion control. Coatings can effectively isolate most of the surface of a metal from the electrolyte and can therefore be used to control galvanic corrosion. If galvanic corrosion is active, coating of the anode alone can result in having a small anode and large cathode with catastrophic results. This is because a small break in the coating on the anode will create a small anode-large cathode situation.

Even though the cathodic material may be highly corrosion resistant, it is the galvanic corrosion of the anodic material that is important in such cases. When in doubt, the entire system should be coated; the mistake should not be made of coating only the anodic material and thereby creating an adverse area ratio. When only the cathode is coated, the effective anode/cathode area ratio is increased thus reducing corrosion at the anode.

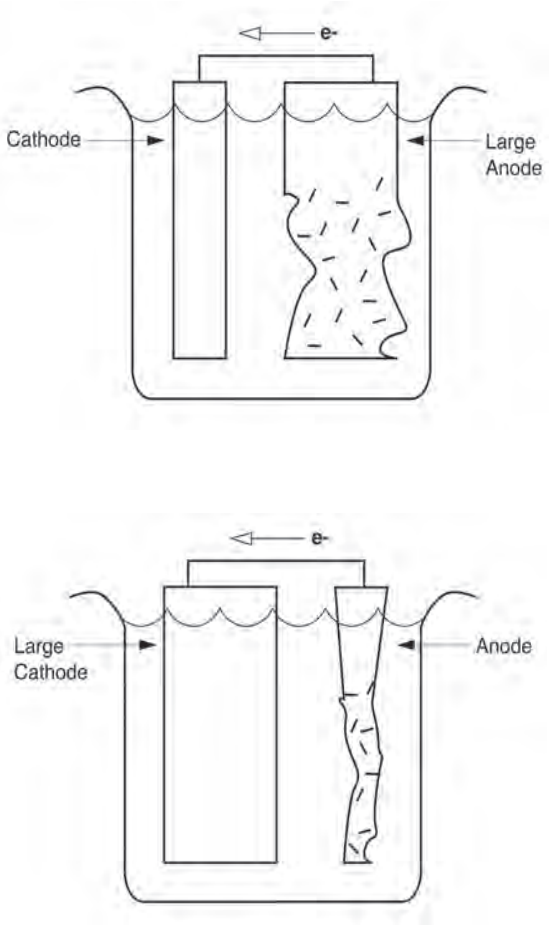


Figure 8. The area effect in galvanic corrosion. Top: "Benign" area ratio—small cathode has little effect on large anode. Bottom: "Adverse" area ratio—large cathode has great effect on small anode.

Pitting

Pitting corrosion (also called simply “pitting”) occurs when the amount of corrosion at one or more points on a metal is much greater than the average amount of corrosion. In some cases, the entire surface is corroded, but unevenly. In other cases, some areas are essentially unattacked. **Figure 9** shows an example of pitting corrosion being measured. Pitting can occur through several mechanisms. Metals are not chemically or physically homogeneous. Some areas may have more of a tendency to be anodic than others and the shifting of anodic and cathodic areas that is necessary for uniform corrosion does not occur. This lack of homogeneity may be due to inclusions within the metal or to the combination of metallurgical phases that are naturally present in many alloys.

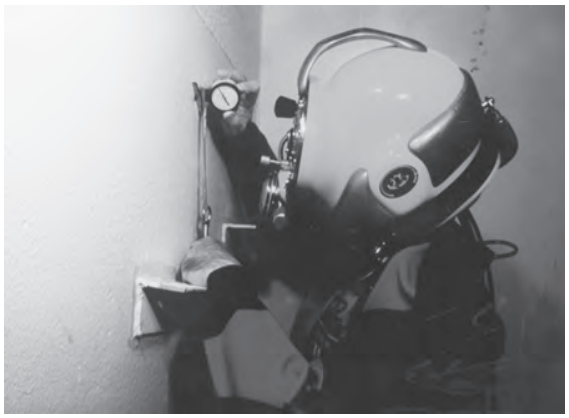


Figure 9. Diver using a depth gauge to measure pit depths. Courtesy Underwater Engineering Services, Inc.

Another mechanism of pitting occurs by local breakdown of passive films on a metal. In this case, the area with the passive film is cathodic to the area without the passive film and a type of galvanic (dissimilar metal) corrosion occurs. The potential difference between areas with the passive films and sites lacking the passive film allows active corrosion to occur. This can be seen in Table 1 for 300 Series stainless steel where the 300 Series stainless steels occupy two positions, one much more active than the other. The more active position is occupied by material that is not protected by a passive film and the less active position is occupied by material that is protected by a passive film.

Since pitting attack is, by definition, non-uniform, weight loss is not a suitable method for measurement of pitting corrosion rates. In some cases, uniform corrosion rates in mpy or mm/yr are given for metals that actually have corroded by localized attack such as pitting. Such corrosion rates often greatly understate the actual depth of penetration of corrosion into the metal. In some applications, such as a structural beam, scattered pitting may not cause too much trouble, but a single pit through a tank wall or pipe handling a hazardous liquid can be disastrous even though most of the surface may be relatively unaffected.

The amount of pitting is established by direct measurement of the depth of pits and the number of pits that occur in a given surface area. Pitting is essentially a random process; therefore, statistical sampling and analysis are often performed. Pit depths may be measured in several ways. One of the simplest ways is with a pit depth gauge that uses a dial micrometer and a pointed probe. For pitting corrosion, weight losses are only determined to establish that the deepest pit has more than twice the average metal loss based on weight loss, which is the point where uneven uniform corrosion becomes, by definition, pitting corrosion.

Where pitting occurs at a significant rate, localized corrosion can have disastrous effects (e.g., in the case of a tank). In such cases, coatings alone are seldom effective in controlling corrosion as coating defects and degradation are inevitable. However, when coatings are combined with other forms of corrosion control, particularly cathodic protection, effective control of pitting corrosion is possible.

Concentration Cell Corrosion

Concentration cell corrosion is often called crevice corrosion because the differences in environment that drive this type of corrosion are often located in and adjacent to crevices. These crevices commonly occur at joints and attachments. Crevices can be formed at metal-to-metal joints or metal to non-metal joints. Deposits of debris or corrosion products can also form crevices.

Concentration cell corrosion commonly occurs by one of two different mechanisms. **Figure 10** illustrates these two types of concentration cell corrosion. The most common is oxygen concentration cell corrosion. In this type of corrosion, the availability of oxygen is less inside the crevice than it is outside the crevice.

This affects the cathodic reaction:

$$2\ H_2O + O_2 + 4e^- \rightarrow 4\ OH^-$$

Low oxygen concentration inhibit this reaction by limiting the availability of one of the reactants. Any factor that inhibits the cathodic reactions on a surface will make the anodic reactions on that surface more prevalent. Thus, in oxygen concentration cell corrosion, the surfaces inside the crevice are exposed to a lower oxygen environment and become anodic with respect to the surfaces outside the crevice and corrosion occurs inside the crevice area. In some cases, the corrosion of the surface outside the crevice is reduced.

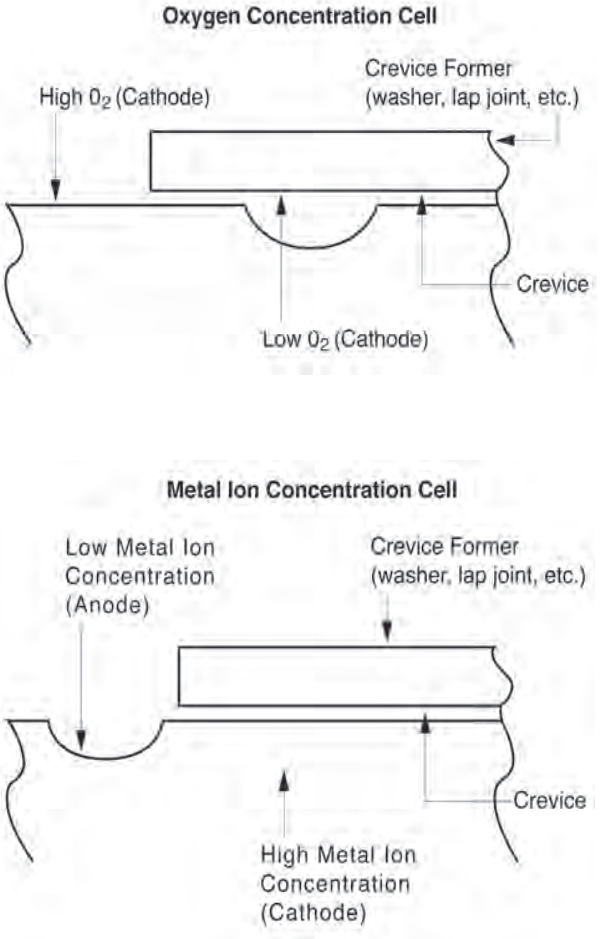


Figure 10. Concentration cell corrosion. Top: Oxygen concentration cell. Bottom: Metal ion concentration cell.

As in galvanic corrosion, oxygen concentration cell corrosion is accelerated by the adverse area ratio between the anode and the cathode. For example, the crevice area formed under a bolt head is usually small with respect to the area of the material being fastened together. Like galvanic corrosion, concentration cell corrosion is normally accelerated under immersion conditions.

Another possible mechanism of concentration cell corrosion is based on differences in metal ion concentration. In this case, the limited circulation inside the crevice causes a buildup of corrosion products. A buildup of metal ions (M^+) will inhibit the generic anodic reaction:

$$M^o \rightarrow M^+ + e^-$$

This is because a buildup of reaction products (M^+) inhibits the reaction. Any factor that inhibits the anodic reaction will cause the area to become more cathodic. In metal ion concentration cell corrosion, the area inside the crevice becomes the cathode and the area outside becomes the anode. This is opposite to the distribution of attack in oxygen concentration cell crevice attack. This form of crevice attack is usually less severe than oxygen concentration cell corrosion because the anode/cathode area ratio is not adverse in this case. There is a large anodic area outside the crevice and only a small cathodic area inside the crevice.

The type of crevice corrosion that occurs in a given situation depends on the metals involved and the environments to which they are exposed. Stainless steels are particularly sensitive to oxygen concentration cell attack and copper alloys are commonly susceptible to metal ion concentration cell attack. Iron and steel show relatively minor effects of crevice corrosion. For iron and most other steels, crevices corrode more than adjacent surfaces under atmospheric conditions primarily because they remain wet more of the time.

Sealants, which are intended to keep the environments out of crevice areas, are sometimes successful in preventing crevice corrosion under atmospheric conditions, but are relatively ineffective in preventing crevice corrosion under immersion conditions. Coating of the external surfaces (the area surrounding the crevice), however, can reduce the intensity of oxygen concentration cell attack by reducing the cathodic area.

Stray Current Corrosion

Stray current corrosion is most commonly encountered in underground environments but can

also occur under immersion conditions. In stray current corrosion, an electrical current flowing in the environment adjacent to a structure causes one area on the structure to act as an anode and another area to act as a cathode. Direct current (DC) is the more damaging type of stray current, but alternating current (AC) can also cause stray current attack. In underground soil environments, stray current corrosion can be caused by currents arising from direct current railway systems, mining operations using direct current, welding operations, and underground cathodic protection systems. Stray currents can also be induced naturally on long underground pipelines. This is due to the interaction between the electrically conductive pipeline and the earth's magnetic field. Stray currents can also be induced through improper grounding of electrical systems in buildings. **Figure 11** shows a typical stray current situation caused by an electric railway.

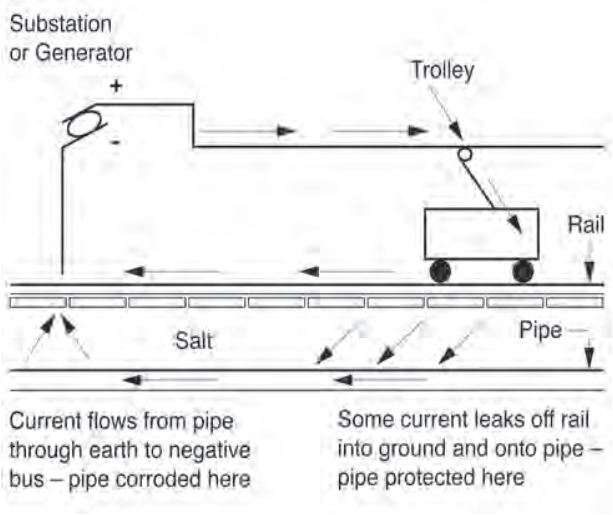


Figure 11. Stray current caused by electric railway.

In this example, the pipeline becomes a low resistance path for the current returning from the train to the power source. Wherever the pipeline is caused to be more positive by the stray current, corrosion occurs at a higher rate.

Stray currents can be detected by electrical measurements. If stray currents are found to be a problem, they can be reduced or eliminated by several techniques including: reducing the current flow in the ground by modifying the current source; electrical bonding to control the current flow; and application of cathodic protection to counterbalance the stray current flow. Coatings are very useful in controlling stray currents as they can effectively electrically isolate the buried structure from the environment so that it does not become a low resistance path. If the structure is coated only in the more positive (anodic) areas, corrosion may become concentrated at defects in these areas, as in the case of galvanic corrosion. This is because the effective cathodic area will be large and the effective anodic areas at coating defects will be small. Very rapid corrosion can occur if stray currents are present and only the anodic areas are coated.

Other Forms of Corrosion

There are many other forms of corrosion, such as:

- Dealloying
- Intergranular attack
- Stress corrosion cracking
- Hydrogen embrittlement
- Corrosion fatigue
- Erosion corrosion
- Cavitation corrosion
- Fretting Corrosion

However, these forms of corrosion are not commonly controlled or affected by the application of protective coatings. More information on these forms of corrosion can be found in References 1 through 3.

Methods for Corrosion Control

Many different methods can be used to control corrosion. By combining some of these methods, the cost of corrosion and its effect on the function of the structure can be minimized.

Protective Coatings

Protective coatings are widely used to control corrosion. In the broadest sense, any material that forms a continuous film on the surface of a substrate can be considered to be a protective coating. Protective coatings control corrosion primarily by providing a barrier between the metal and its environments. This barrier reduces the activity of the chemical reactions responsible for corrosion by slowing the movement of the reactants and reaction products involved.

Organic Coatings. Organic coatings are usually liquid applied coatings that are converted to a solid film after application. The barrier action responsible for the

primary protective action of organic coatings is often enhanced by the addition of chemicals that inhibit corrosion, or by loading with zinc to provide galvanic (cathodic) protection to the underlying metal.

Metallic Coatings. Metallic coatings are thin films of metal applied to a substrate. These coatings can be applied by dipping the metal to be coated in a molten metal bath (e.g., galvanizing), by electroplating, and by thermal spray. There are two generic types of metallic coatings, those that are anodic to the underlying metal (called here "anodic metallic coatings") and those that are cathodic to the underlying metal (called here "cathodic metallic coatings"). Both of these generic types provide barrier protection, but they differ in their ability to provide corrosion protection when they are damaged or defective.

Cathodic Protection

Cathodic protection can provide effective control of corrosion in underground and immersion conditions. In its simplest form, (a sacrificial anode system), cathodic protection is essentially an intentional galvanic corrosion cell designed so that the structure to be protected acts as a cathode. It therefore has a reduced corrosion rate. The anodic material that is intentionally added to the system corrodes at an accelerated rate. Impressed current systems are similar, but instead of using sacrificial anodes, they provide protection by inducing a current in the system from an external power supply.

Cathodic protection, combined with the use of appropriate protective coatings, can provide better control of corrosion than either method used alone. The barrier action provided by the coating reduces the surface area to be protected by cathodic protection. This in turn reduces the cost of the cathodic protection system by decreasing the amount of anodic material that is consumed in sacrificial anode systems, or the amount of current that must be supplied in an impressed current system. It should be noted that the effectiveness of the coating system is also improved because corrosion does not occur at coating defects or damaged areas.

Good Design

Many of the factors that affect how corrosion will attack a given system can be addressed at the design stage. For example, corrosion can be controlled to some degree by avoiding structural features that trap and hold moisture, by avoiding joints that cannot be effectively protected by coatings, and by avoiding sharp edges where coatings are to be used. Particularly in cases where protective coatings are used as a part of the total corrosion control system, another important design factor is to allow for easy coating maintenance. Good design also provides for easy access for coating inspection, surface preparation, and coating application.

Materials Selection. The compatibility of materials with their environments should be a basic consideration in any engineering design. However, it is not always practical or possible to use materials that are highly resistant to corrosion. Materials selection is only one aspect of the overall design process. Other design considerations besides materials selection include the ability of the various types of corrosion control measures to reduce the effects of corrosion and the effect of corrosion on overall system function. A good design balances all of these factors to obtain the desired system performance and lifetime at the least cost.



Figure 12. A Munters rental dehumidifier setup to protect the hotwell of the condenser in a power generation plant. Dry air circulates through the equipment, preventing corrosion from occuring. Courtesy Munters Moisture Control Services.

Corrosion Allowance. Except in cases where special

highly corrosion-resistant materials are used, some corrosion is always inevitable. Therefore, successful designs will consider the type and extent of corrosion anticipated and will make allowances for the metal loss that will occur. Particularly where uniform corrosion is anticipated, this corrosion allowance is often provided by making the components thicker. While this is often considered to be a "factor of safety," it actually provides extra metal to compensate for metal losses due to corrosion that is likely to occur when and where the corrosion control methods used are not completely effective. The overall system design must be based on the type and amount of corrosion that will occur. Periodic inspections must be performed to verify that the amount of corrosion is within safe limits. This is a frequent practice in chemical process industries.

Change of Environment. In some circumstances, corrosion is controlled by changing the environment. In liquid handling systems, this may be accomplished by removing oxygen from the system by deaeration, or by the addition of corrosion inhibitors. In other cases, the environment is changed by controlling atmospheric conditions, e.g., dehumidification may be used to control corrosion in interior spaces. An example of a dehumidification system is shown in **Figure 12.** Such corrosion control measures may be required during manufacture of critical equipment or may be used as a temporary means to control corrosion until other corrosion control methods can be applied. Dehumidification of the interior of tanks during and after blast cleaning and prior to the application of a protective coating is one example of this type of environmental control.

Summary

Corrosion is an electrochemical process that naturally occurs on most metals when they are exposed to aggressive environments. Rusting of steel in atmospheric or immersion conditions is a common example of corrosion. The electrochemical process responsible for corrosion involves four components: an anode, a cathode, a metallic path, and an electrolyte. The rate of the overall corrosion reaction can be controlled by limiting the activity of any one of these components. There are many forms of corrosion, which all depend on the activity of electrochemical cells, but differ in the location and distribution of attack.

There are many ways to control corrosion. One way is to select materials that are resistant to attack in the specific exposure environment. Another is to use cathodic protection and/or protective coatings. The application of protective coatings is one of the most important means of corrosion control. In most cases, the best way to control corrosion is to use a combination of two or more appropriate corrosion control methods.

References

1. ASTM G15-83. *Standard Terminology Related to Corrosion and Corrosion Testing;* ASTM: West Conshokoen, PA.
2. Van Delinder, L.S. *Corrosion Basics: An Introduction;* NACE: Houston, 1984.
2. Fontana, Mars G. *Corrosion Engineering*, *3rd Edition;* McGraw Hill: New York, 1986.
3. Atkinson, J.T.N; Van Droffelaar, H. *Corrosion and Its Control: An Introduction to the Subject, 2nd Edition;* NACE: Houston, 1994.
4. Uhlig, Herbert H. *Corrosion and Corrosion Control: An Introduction to Corrosion Science and Engineering, 3rd Edition;* John Wiley & Sons, Inc.: New York, 1985.
5. Munger, Charles G. *Corrosion Prevention by Protective Coatings;* NACE: Houston, 1984.

About the Authors

James F. Jenkins

James F. Jenkins retired in 1995 after 30 years of service to the U.S. Navy in corrosion control for shore and ocean-based facilities. Now a consultant, he is a registered corrosion engineer in the state of California. Mr. Jenkins received his BS degree in metallurgical engineering from the University of Arizona.

Dr. Richard W. Drisko

Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society for Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy's center of expertise on coatings for shore structures. He is a professional corrosion engineer in the state of California, an SSPC certified protective coatings specialist (PCS), and a NACE International certificated corrosion specialist. Dr. Drisko received his BS, MS, and PhD degrees from Stanford.

Chapter 1.2
Designing Structures for Good Coating Performance

James F. Jenkins and Richard W. Drisko

Introduction

This chapter describes how the corrosion performance of a structure can be affected by its design. It also describes how corrosion control methods, such as protective coatings, are affected by design. Corrosion and corrosion control should not be ignored during initial design and construction simply because corrosion will frequently not be a problem for several years of operation. Designing a structure so that it can be effectively protected by coatings and other corrosion control methods is often the key to successful corrosion control.[1-3]

Design as a Process

For many people, the word "design" brings to mind an actual product, such as a specification with its associated drawings. However, when corrosion control is the objective, it is useful to think of design as a process rather than an actual product. When thought of in this way, it becomes apparent that many people forming a "design team" should be involved. It is only through successful integration of the efforts of each specialized member of this team that a successful final design can be produced.

Participants in the Design Process

Many people participate in, or affect, the design process. The roles of the mechanical or civil engineer, materials specialist, corrosion engineer, and coating specialist are fairly well understood. There are, however, others such as accountants, planners, estimators, and drafting and contract specialists who can also affect the overall design. Operating and maintenance personnel, too, should often be included in the design team, but their valuable input is frequently not utilized. Whatever the composition of the design team, each member must be able to communicate continuously and effectively with the others. This requires that each member of the team understand the basics of the other members' jobs.

The corrosion engineers should be involved in the entire design process from beginning to end—since their role is to oversee all of the aspects of the design that can affect the corrosion performance of the system. If corrosion control is only considered late in the design process, or worse yet, after the design is completed, efficient corrosion control can seldom be achieved. In many cases, the corrosion engineer will need to consult with a coating specialist during the design process to determine which coatings to use for specific applications and the advantages and limitations of the various coating systems available. Again, the effective use of coatings must be considered during the design process and not after the design is essentially completed.

The Need for a Specific Specification

Because most methods of corrosion control require many steps and consideration of many details in order to provide effective protection of a structure, it is vital that specifications be "specific." This means that all of the steps and details required for corrosion control should be included in the specification (usually a narrative covering material and process requirements) and associated drawings. For example "sandblast and paint after fabrication," added as a note to a drawing of a complex steel fabrication, does not provide sufficient information as to what is to be done, what materials should be used, and what the desired product can be expected to do. It is only by outlining the entire process in a specification and including all of the requirements that the final objective can be reliably achieved.

Engineering standards, which are usually based on previous work or on typical applications, can provide a useful tool in preparing specifications; however, additional information is often pertinent and required. It is also often necessary to develop the design and specification for a specific environment. What works well in a temperate climate may not work well in a tropical or arctic climate.

Without proper specifications for all the materials and processes, the personnel fabricating the structure or maintaining the system will not know

precisely what the designer had in mind. Even if those personnel are attempting to do a good job, they may not understand that their actions could have an adverse effect on the overall system. For example, sacrificial anodes are frequently inadvertently coated during drydocking of ships. In such cases, the coating applicator is simply trying to coat all exposed metal, not realizing that this action results in loss of the cathodic protection required for system performance. Anodic surfaces are also frequently inadvertently coated, which results in adverse area ratios. In order to avoid problems like these, it is appropriate to include in the specification a section of "items not to coat."

Selecting Materials

Selecting Coatings

The selection of coatings is an important part of the design and specification process. Coatings are a very useful method for corrosion control that can be integrated into the overall design. A structure is considered to be well-designed for corrosion control when coatings can be effectively applied, and can effectively control the types and location of likely attack. However, coatings are not very effective at correcting "built-in" corrosion problems, i.e., they can seldom effectively control corrosion that is the result of design deficiencies. For example, coatings are very effective at controlling uniform corrosion but are not very effective at controlling localized attack such as pitting. The selection of coatings also involves selecting methods for surface preparation; surface inspection prior to coating; handling of coating materials; coating application; shipment to the job site; and coating inspection both during and after application.

Selecting Structural Materials

The selection of structural materials for a system is also a vital part of the design and specification process. The materials and the design must be considered together in order to make appropriate choices. Materials may be selected that are resistant to the types of corrosion that can result in system failure. Or, if the materials selected are not inherently resistant to corrosion, effective means of controlling corrosion of the materials must be included in the design. Like all other aspects of design, material selection must be a part of the design process and not an afterthought.

Problems that Can Occur as a Result of Improper Materials

Failure to consider the incompatibility of structural metals, or other types of improper materials selection can lead to corrosion problems. Following are some examples of the possible problems related to improper materials selection that are easy to avoid at the design stage but difficult to resolve after construction.

Galvanic Corrosion. Galvanic corrosion is possible whenever two or more dissimilar metals are used in a system. Although it is limited to the immediate area of contact between the metals in atmospheric exposures, galvanic corrosion can affect much greater areas over long distances when the exposure is underground or underwater. Also, inappropriate use of coatings (such that an adverse area ratio is created) can actually accelerate galvanic corrosion. Avoiding galvanic corrosion problems involves controlling the design so that adverse area ratios of dissimilar metals are not created. This approach is much easier than correcting the problems after the structure is built.

As shown in **Figure 1,** electrical isolation of dissimilar metals is a possible solution to galvanic corrosion problems. However, electrical isolation is often difficult to achieve and maintain under practical conditions. If electrical isolation is used to avoid galvanic corrosion, the design and specification must include testing to verify isolation both during construction and in an ongoing maintenance program.

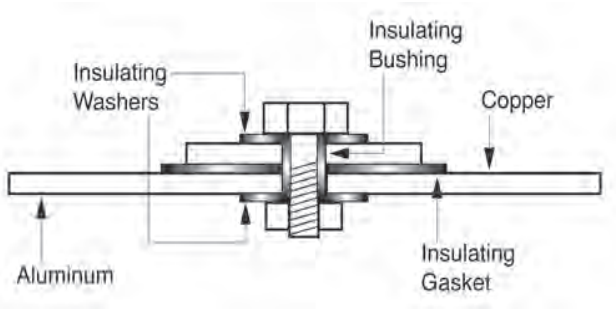


Figure 1. Method of avoiding galvanic corrosion between dissimliar metals.

Contact of corrosion susceptible metals with materials such as thermal insulation, wood, and fabrics that can trap and hold moisture against the metal surface should be avoided. These contact areas are

often difficult to seal or coat, and maintenance of the sealants and coatings under absorptive materials usually requires removal and replacement of the absorptive materials at a high cost.

In some cases, corrosion products from one metal can bleed onto another metal and cause rapid attack. Copper corrosion products are very aggressive toward aluminum, steel, and stainless steel, thus contamination of these metals with copper corrosion products must be considered and avoided at the design stage. Iron corrosion products can also accelerate the corrosion of aluminum and stainless steels.

Geometric Considerations

Many geometric features can affect corrosion performance. These can generally be classified as:

- Water traps (configurations that trap and hold water)
- Crevices
- Sharp edges
- Inaccessible areas

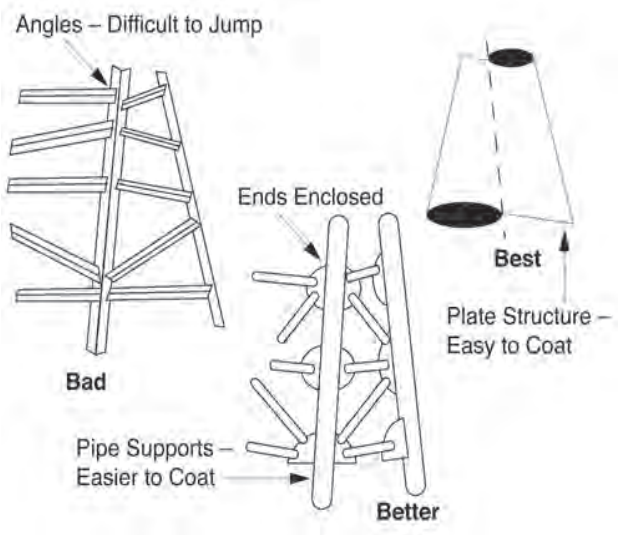


Figure 2. Evolution of design simplicity.

Water traps are intrinsically corrosion prone because moisture accelerates corrosion. Crevices are also intrinsically corrosion prone because they can retain moisture and present the opportunity for concentration cell corrosion; however, another reason is because they cannot be effectively protected using coatings. The same goes for sharp edges and inaccessible areas; they cannot be effectively protected using coatings. Complex shapes in general are usually more susceptible to corrosion than simple shapes and are certainly more difficult to coat effectively. **Figure 2** shows the evolution of a complex design with many members and crevices, through a structure with fewer crevices and features that are difficult to coat, to a final design that is very easy to coat effectively.

Reference 1 describes fabrication details, surface finish requirements and proper design for tanks and vessels to be coated internally. Many of these design principles are also applicable to other systems. References 2, 3, and 4 give many other examples of how good design can provide optimum resistance to corrosion.

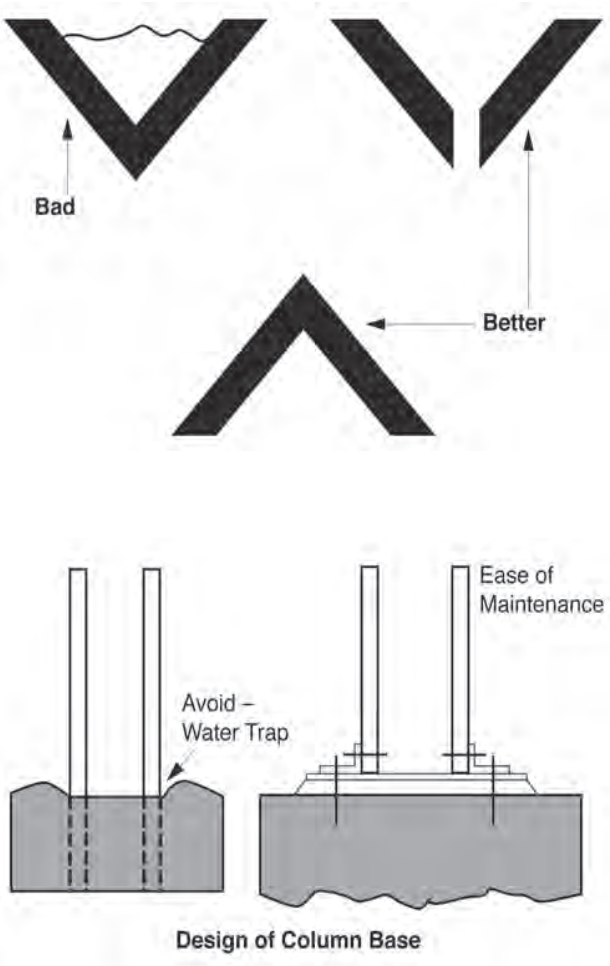


Figure 3. Features that trap and hold debris.

Water Traps

When designing a structure, an important consideration for corrosion control is the avoidance of geometric features that in atmospheric exposures can trap and hold water. This is because metals corrode much faster when there is a perceptible moisture film on their surfaces than when dry. So-called “water traps” are fairly easy to avoid at the design stage, but

may be difficult to remedy after construction. **Figure 3** shows several examples of surface orientations that can serve as water traps. This figure also shows some alternative designs, e.g., with drain holes, that can help avoid the accumulation of moisture. When the environment is contaminated by dirt and debris, the avoidance of water traps becomes even more important, since trapped dirt and debris tend to retain moisture and further increase the time of wetness on the surface. In addition, when there is contamination by dirt and debris, drain holes used to prevent accumulation of moisture may become clogged and become ineffective unless periodically cleaned. Proper orientation that avoids the problem altogether is usually a better solution than the use of drain holes.

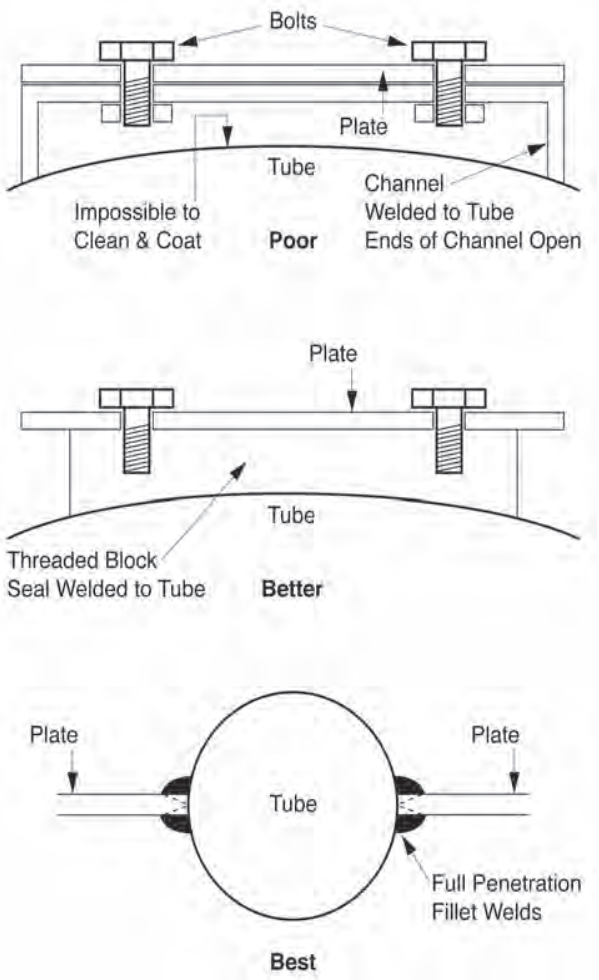


Figure 4. Designs to eliminate the enclosed areas.

Low areas on structures, if not properly sloped and drained, will always be wet longer than well drained areas. Designing a structure to provide positive slope to drains at low points would seem to be the norm, but it is amazing how many roofs on buildings and tanks are designed "flat" without proper slope. In some cases, drains with sufficient local structural support perform well initially, but become ineffective when settlement occurs and they become higher than the area to be drained. This frequently occurs when drains are located at fixed edges of flat roofs.

Partially closed or partially boxed-in areas should also be avoided or sealed to prevent the entry of moisture. **Figure 4** shows corrosion resistant alternatives.

Crevices and Sharp Edges

Many design features can create crevices. Corrosion is almost always more severe in systems with crevices than in those where crevices have been avoided by good design. Crevices may cause accelerated attack through concentration cell corrosion, or by retaining wetness more than surrounding surfaces. Accelerated attack may also occur in crevice areas because they are virtually impossible to protect effectively with coatings.

The number of details that can present sharp edges and corners that are difficult to coat effectively is essentially infinite. **Figure 5** shows how a coating thins at a sharp edge. Sharp edges must be avoided at the design stage, or remedied by grinding after construction at a much higher cost.

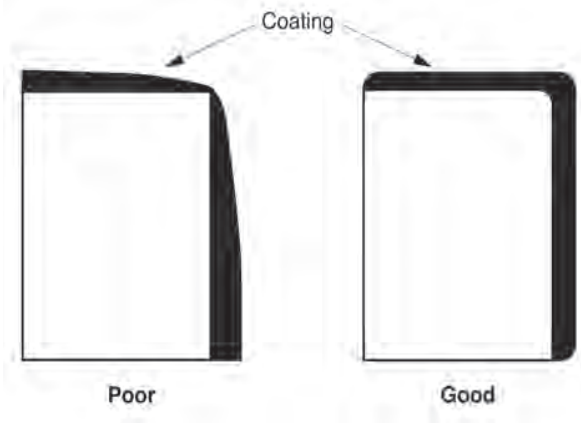


Figure 5. Sharp edges.

One type of feature that creates crevices is the overlapping plate. Thermal expansion and contraction of overlapping plates causes differential movement between the plates, which results in cracking of coatings at the entrance to the crevice between the plates. Bolted flanges also create crevices where corrosion at the joint surfaces often results in premature failure of the external coating.

Back-to-back angles are features that are all too commonly encountered. They create crevices or enclosed areas that result in susceptibility to corrosion and poor coatability. Where back-to-back angles are included in a design, it is difficult to seal or recoat the area between the angles, and corrosion in this area will be a problem when the original coating fails. Solid structural members, boldly exposed, provide a structurally equivalent alternative with greatly improved performance and coatability **(Figure 6)**. Once back-to-back angles are designed into a system, attempts to fill and seal the crevice areas are both costly and usually ineffective, particularly if corrosion is allowed to initiate inside the crevice. Joined flanges present similar problems to those encountered with crevices.

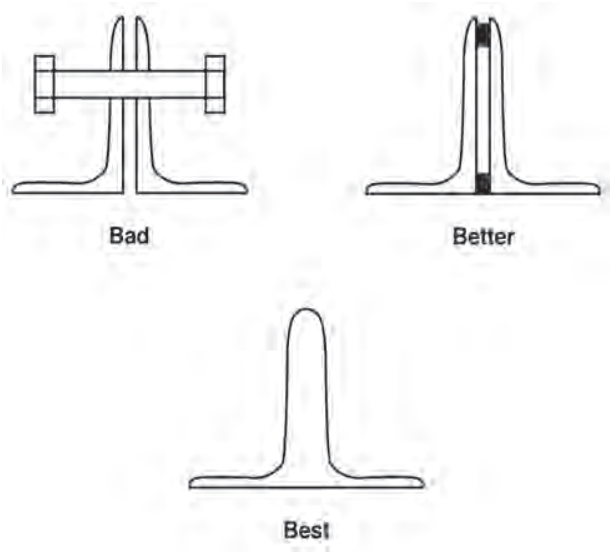


Figure 6. Back-to-back angles. Solid T alternative.

Sheared Edges

Sheared edges are particularly troublesome, since they usually present very sharp corners. Sheared edges consist of deformed material that contains a very large number of small and tight crevices. These crevices can result in concentration cell attack and are particularly difficult to coat due to their small size. Proper grinding or breaking of sharp edges or sheared edges is often necessary in order for a coating to provide adequate protection. Due to surface tension effects in the wet coating, obtaining a uniform coating thickness on edges and corners is difficult in most cases. Relatively recently, edge retentive 100% solids coatings were developed that maintain at least 70% of the dry film thickness that occurs on flat areas.

Fasteners

Fasteners such as nuts and bolts always present sharp corners and form crevices. When feasible, parts should be joined by welding rather than bolting. If fasteners cannot be avoided, making them of a more resistant alloy than the base material should be considered. Stainless steel fasteners in aluminum structures are an example of such a combination. Galvanic corrosion due to the more noble (cathodic) fasteners is usually minimal due to the favorable anode-cathode area ratio. Nonmetallic washers and sleeves can also provide complete electrical isolation.

Poor welding practice can also create crevice areas. Improper welding is a common cause of coating failure. Both the design of the weld and the workmanship of the welder affect the performance of coatings at welded joints. Skip welding, as shown in **Figure 7,** creates a multiplicity of crevices that can cause premature coating failure.

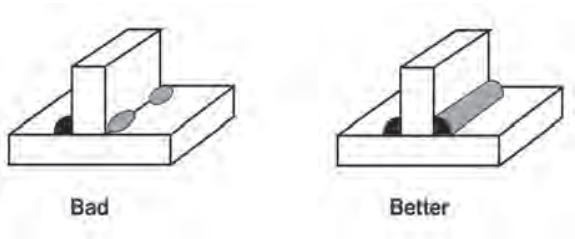


Figure 7. Skip welds.

Welds must be continuous. The welds should also be full penetration welds. As shown in **Figure 8,** a full penetration weld effectively removes the possibility of a crevice at the joint. In cases where full penetration welds are not practical, full “seal” welding as shown in **Figure 9** is an acceptable alternative as long as inspection is provided to insure that a full seal is achieved. Welds also present rough surfaces that should be ground smooth for good coating performance. Weld spatter, arc strikes, and scale must also be removed for good coating performance. Temporary

weld attachments used to aid in construction (e.g., padeyes and spacers) should be removed prior to coating the structure and should be ground smooth and treated like other weld areas in order to achieve full coating performance.

NACE RP-0178-91 gives examples of good requirements for correction of weld defects that can adversely affect coating performance.[1]

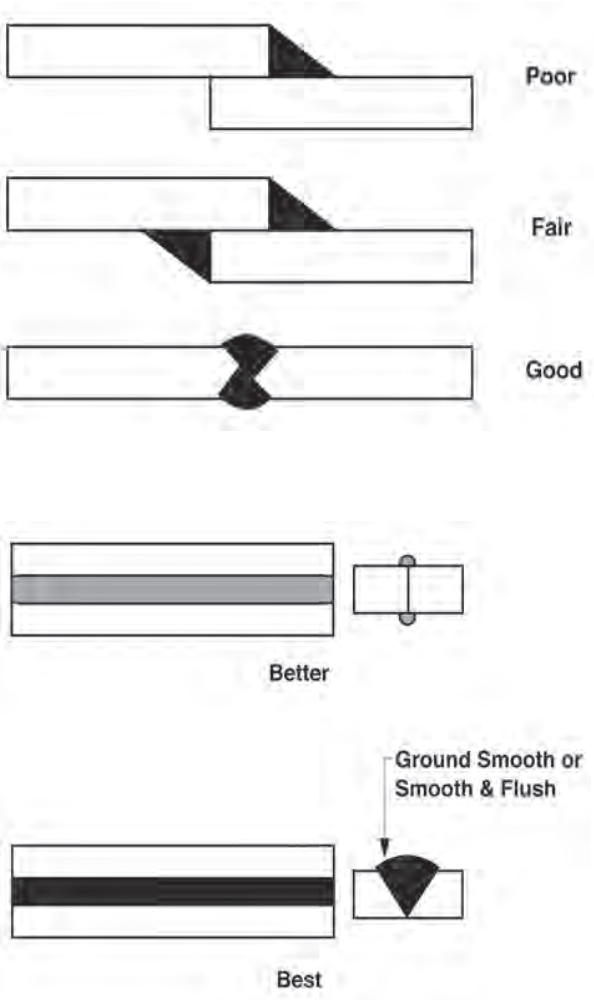


Figure 8. Incomplete and complete penetration welds.

Inaccessible Areas and Areas that are Difficult to Coat

As shown in **Figure 10,** even something as simple as the general location and layout of a piece of equipment can greatly affect the ability to apply and maintain protective coatings. Designing systems that provide easy access for inspection and maintenance requires that the system be considered as a whole.

Interior Corners. Interior corners are difficult to clean properly and keep clean prior to the application of a coating. Even small of amounts of contaminants can interfere with proper bonding of a coating. Interior corners can also cause problems with coatings, since the coating in this area will tend to be much thicker than desired. This can interfere with proper curing of the coating and result in excessive shrinkage and coating disbondment. It is a common practice to coat each wall separately and then turn the spray gun 90° to obtain a horizontal rather than a vertical fan for application of a thinner film to interior corners.

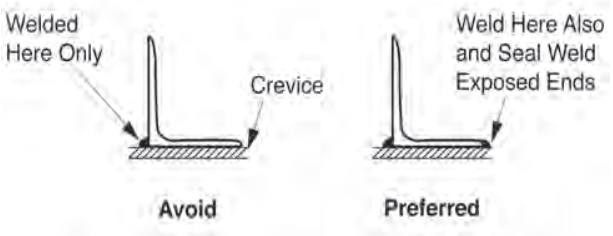


Figure 9. Seal weld.

Pits, Cracks, and Gouges. The performance of a coating depends heavily on proper surface preparation. Abrasive blasting or power tool cleaning is used to prepare the surface of most steel for the application of protective coatings. These surface preparation techniques are most effective on smooth surfaces that are free from sharp edges and sharp corners that cannot be effectively cleaned.



Figure 10. Inaccessible area.

Pits, cracks, gouges, and other surface defects interfere with the effectiveness of these surface preparation methods at removing contaminants and establishing the required surface profile.

These defects must therefore be avoided or repaired prior to abrasive blasting and coating application.

Stray Current Avoidance

For buried and submerged structures, stray current avoidance is important. When a new underground or submerged facility is planned, the environment in which the facility is to be located must be surveyed for stray currents prior to the facility's design and construction. These stray currents must either be eliminated by modification of the source or counteracted by the application of cathodic protection or other means of control. A post-construction stray current survey should also be conducted if there are any systems or equipment in the new facility that could be a source of stray currents.

Design for Inspection and Maintenance

Inspection and maintenance are likely to be required in any system. Good maintenance is often the key to a successful, long-lived system. Coating maintenance may entail either spot repair or complete removal of the old coating, surface preparation, and application of a new coating system. A good design should allow access to all surfaces for all of these maintenance activities. It should also allow access for inspection.

It is easy to say that a structure should be designed for inspection and maintenance; however, it is only by knowing what maintenance is to be performed that the facility can be designed for it. Thus, just as every automobile comes with a maintenance manual, a maintenance guide should be prepared during the design of any new structure or facility. The requirements and guidelines for inspection and maintenance should include local considerations such as climate.

Summary

The corrosion of a structure or system is greatly affected by its design. During the design process, the members of the design team should consider corrosion as an important factor, and produce a design and specifications that properly address all corrosion-related issues.

An important part of the design process is the proper selection of coatings and materials. However, it is also important during the design process to consider other factors such as system geometry, welding and joining details, system layout, surface finish, and, for buried or immersed structures, avoidance of stray currents. The structure or system must also be designed so that required inspection and maintenance can be easily and effectively performed.

References

1. NACE International Standard Recommended Practice RP 0178-91. *Fabrication, Details, Surface Finish Requirements, and Proper Design Considerations for Tanks and Vessels to be Lined for Immersion Service;* NACE: Houston.
2. Pludek, V. Roger. *Design and Corrosiopn Control;* MacMillian: New York, 1978.
3. Landrum, R. James. *Fundamentals of Designing for Corrosion Control;* NACE: Houston, 1989.

About the Authors

James F. Jenkins
James F. Jenkins retired in 1995 after 30 years of service to the U.S. navy in corrosion control for shore and ocean-based facilities. Now a consultant, he is a registered corrosion engineer in the state of California. Mr. Jenkins received his BS degree in metallurgical engineering from the University of Arizona.

Dr. Richard W. Drisko
Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society for Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy's center of exertise on coatings for shore structures. He is a professional corrosion engineer in the state of California, an SSPC certified protective coatings specialist (PCS), and a NACE International certificated corrosion specialist. Dr. Drisko received his BS, MS, and PhD degrees from Stanford.

Chapter 1.3
Mechanisms of Corrosion Control by Coatings

Richard W. Drisko and James F. Jenkins

Introduction

This chapter describes the mechanisms by which coatings may protect steel and other metals from corrosion. Corrosion of metals is an electrochemical reaction that has four basic requirements:

- An anode that corrodes
- A cathode that does not corrode
- An electrolyte external path
- A metallic path to complete the circuit

Protective coatings and other systems that interfere with one or more of these components can be used to control corrosion. Protective coatings provide such interference by three basic mechanisms:

- **Barrier protection—**Most coating films form a barrier to isolate the metal surface from electrolytes in the environment
- **Chemical inhibition—**Chemical components added to the coating may inhibit the anodic or cathodic reactions.
- **Galvanic (Cathodic) protection—**A primer heavily-loaded with zinc particles may provide galvanic protection to steel surfaces, much like a zinc anode does to steel surfaces.

This chapter describes these three basic mechanisms of corrosion control by coatings. It also briefly describes the concept of a total protective coating system.

Barrier Protection

Almost all coatings provide corrosion protection to metals by forming a barrier between the metal and the electrolytes in the environment. Penetration of most films by water and oxygen is relatively rapid, but penetration of salt (ion) solutions is relatively slow. Thus, a barrier coating may provide corrosion control for several years. The actual length of time that a coating provides barrier protection depends upon:

- The inherent permeability of the resin system (in most services)
- The level and type of pigments and additives
- The film thickness
- The quality of coating formulation
- Cleaning of the substrate prior to coating
- The quality of application
- Adhesion of the film to the substrate
- The severity of the environment

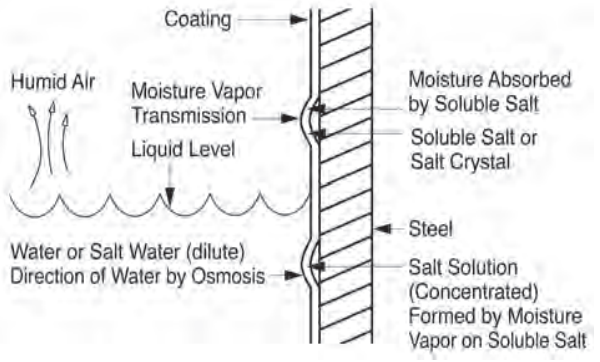


Figure 1. Diagram of osmotic blistering.

No organic coating is completely impermeable to electrolytes; however, some barrier coatings (such as epoxies) perform this function very well, particularly if the metal surface is salt-free and there are no soluble salts in the coating film. Some oxygen-containing binder materials (e.g., oil-based resins) are relatively permeable to electrolytes. When these materials are used in immersion service, differences in salt (ionic) concentrations between solutions under and outside the barrier film may cause migration of water through the film, which results in blistering. **Figure 1** shows an example of osmotic blistering.

In general, the greater the barrier thickness, the greater the protection of metals in most services. Very thick films with limited flexibility, however, may not readily expand and contract with the substrate and may crack and/or disbond from it. **Figure 2** shows an example of cracking.

Leafing-aluminum and natural micaceous iron oxide pigments may orient themselves in a layered fashion overlapping and roughly parallel to the substrate.[1-2] This requires moisture or salt penetration to

pass around the platelets, which effectively increases the barrier thickness. This effect is represented schematically in **Figure 3.**

Other types of protective coatings are also used in special situations. Fused porcelain or fused glass are commonly used to line vessels for heating water and large field erected tanks for water and waste water. Domestic water heaters are usually glass lined. Cement linings are often used for water pipelines and provide corrosion protection to steel both by their barrier action and by chemical inhibition due to the alkalinity of the cement. Tapes or other wraps may also be used to provide a barrier coating.



Figure 2. Cracking.

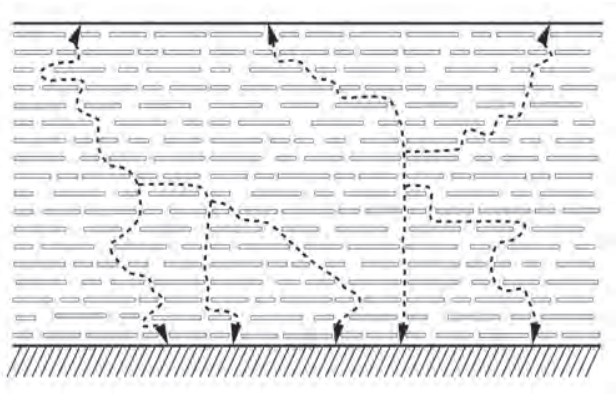


Figure 3. Diagram of a coating containing lamellar micaceous iron oxide.

Chemicals That Inhibit Corrosion

Chemicals that inhibit the anodic or cathodic corrosion reactions at the interface between the metal and the binder may be used to effectively control corrosion. These chemicals may be simply added to the formulation or, as is usually the case, may be inhibitive pigments that are incorporated into the insoluble portion of the coating system. These pigments must be slightly water-soluble so that the corrosion inhibitor is released from the binder at a controlled rate. In order to be effective, the inhibitive chemical must be available in a water soluble form at the surface of the metal or metal oxide. Too low a rate will be ineffective, while too great a rate will result in rapid inhibitor depletion and/or other adverse effects.

The effectiveness of a particular inhibitive pigment in providing corrosion protection varies with the composition of the coating. In atmospheric environments, inhibitive pigments work better with binders that are relatively permeable (e.g., oil-based) than they do with less permeable binders. The effectiveness of inhibitive pigments also depends on the pigment volume concentration (PVC) and critical pigment volume concentration (CPVC). PVC is the ratio of the volume of pigment to the volume of total solids in the coating (i.e., the volume of pigment plus the volume of binder). CPVC is the PVC level at which there is just enough binder to fill all voids between pigment particles in the dry coating film. Coatings with inhibitive pigments usually have less permeability and, consequently, better corrosion protection properties and less coating blistering just below the CPVC. PVC and CPVC are also important factors in the performance of metal primers without inhibitive pigments.

Many inhibitive pigments consist of a chemical mix formed by the fusion of two or more products. Such mixes are assigned formulas based upon elemental composition (the relative amounts of each element present) rather than on compounds actually present. Because of this, the chemistry of these inhibitive pigments is not well known. In addition, the exact mechanisms by which most inhibitive pigments provide corrosion inhibition are usually not well established. Nevertheless, there are a few well known types of inhibitive pigments that have played an important role in protective coating systems. It should be noted that the effectiveness of a particular inhibitive pigment usually varies greatly when used with different generic types of binders.

Red lead is the inhibitive pigment that has been used in coatings for the longest time. It is predominantly lead tetroxide produced by heating metallic

lead in an excess of oxygen. When incorporated into oil-base paints, small amounts of lead and oil react to form lead soaps, which are very effective corrosion inhibitors. Despite its effectiveness, the use of red lead is greatly limited today because of toxicity concerns. When lead-containing paint is removed from substrates, special precautions must be taken to protect the workers, the public, and the environment. **Figure 4** shows a lead-containing paint removal operation on a bridge.



Figure 4. Containment on bridge during removal of lead-containing paint.

Chromate pigments (e.g., zinc chromates and strontium chromates) have been shown to be effective corrosion inhibitors. Corrosion inhibition results directly from the slight solubility of the chromate itself rather than from forming a soap or other chemically inhibitive compound. Like red lead, the use of chromate is greatly limited today because of toxicity concerns.

Zinc phosphate and zinc molybdates are receiving much attention as inhibitive pigments, as lead and chromate pigments are being phased out. They seem to present fewer health concerns.

Borates, phosphosilicates, and other inhibitive pigments provide protection that varies widely with the specific formulation.

Galvanic (Cathodic) Protection

Zinc-Rich Coatings

Zinc-rich coatings may be formulated to provide galvanic protection to steel surfaces. They contain a heavy loading of fine zinc particles, which act as anodes that corrode preferentially to convert steel anode areas to cathode areas. Zinc-rich coatings may be formulated using inorganic or organic binders. Galvanic protection is usually greater for inorganic rather than organic zinc-rich coatings, because binders for the latter are less conductive.[3]

Metallic Coatings

Galvanizing is a thin layer of zinc most commonly applied to cleaned steel by hot dipping into a bath of molten zinc or by electrochemical deposition. It provides corrosion protection by both barrier and galvanic action.

Like galvanizing, thermal spray metallic coatings are also thin layers of metal (most commonly zinc, aluminum, or zinc-aluminum alloy). They are, however, applied by spraying the molten metal onto the cleaned steel surface.

Total Protective Coating Systems

Coating systems usually consist of two or more individual coats. Each coat may provide corrosion control by one or more of the above mechanisms, and/or may provide other desired properties for the system. An example of a protective coating system is shown in **Figure 5.**

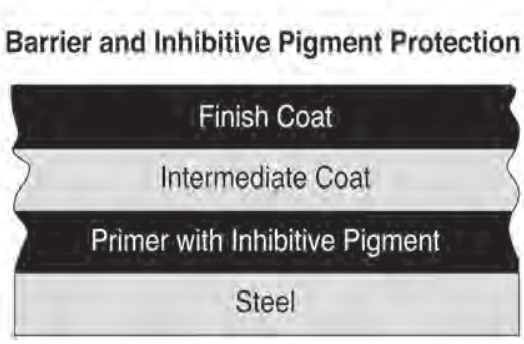


Figure 5. Barrier and inhibitive pigment protection.

The primer must adhere well to the metal substrate and provide a base for good adhesion of additional coats. The primer may also contain an inhibitive pigment or heavy zinc loading to inhibit corrosion of metals, as well as provide greater total thickness for barrier protection.

Intermediate and topcoats provide additional barrier protection. The finish coat, of course, provides the desired color, gloss, and texture, in addition to barrier protection. Exterior finish coats are also formulated to provide protection from weathering (sun and

rain), which slowly degrades the barrier and the protection it provides. For immersion service, the topcoat also must be formulated to be chemically resistant to the immersion fluid. Each coat of a system is usually tinted differently so that it is easier to determine visually when overcoats have imperfections (holidays).

In the study *Minimum Film Thickness for Protection of Hot-Rolled Steel: Results After 23 Years of Exposure at Kure Beach, North Carolina* sponsored by the Federation of Societies for Coatings Technology and conducted by SSPC it was concluded that: [4]

• For all oil and alkyd paints, in all three atmospheric environments tested (industrial, marine, and rural), each additional mil of paint thickness resulted in an increase of about 20 months of paint life

•A critical minimum dry film thickness existed for each generic type of paint

• It is more beneficial to apply sufficient paint thickness at the start of exposure than conduct more frequent maintenance painting

Desirable Film Properties

In order for coating films to provide long-term protection to steel and other metals, they must have properties specifically designed for corrosion control, as well as any other properties necessary for performance in the particular service environment. Depending on the generic type and use, desired film properties may include several of the following:

• Good adhesion
• Low permeability (except for inorganic zincs and unsealed metallizing, which initially provide only galvanic protection)
• A continuous film
• Flexibility
• Resistance to impact and abrasion
• Resistance to water, fuel, chemicals, etc.
• Resistance to biological growth

Adhesion of Coatings

All primer coatings must adhere well to substrates to allow the total system to provide long-term protection; otherwise, early disbondment will occur. Most experts agree that there are three basic components to adhesion: primary chemical bonding, secondary (polar) chemical bonding, and mechanical bonding.[5]

Primary chemical bonding coatings are very rare. Wash primer and siloxane coatings, both to be discussed later, are examples.

Most coatings adhere to metal surfaces by secondary chemical bonding (e.g., hydrogen bonding and van der Waal forces). Organic coating binders with hydroxyl (OH) or (e.g., NH) amine chemical groupings (e.g., oil-base paints and epoxies) have greater polarity and so bond well to substrates.

Mechanical bonding is most commonly attributed to increased bonding area (i.e., more bonding sites). Coatings that penetrate the pores on concrete surfaces may also have mechanical interlock. Mechanical interlock occurs to a much lesser extent on abrasive blasted steel surfaces.

To obtain optimum coating adhesion to a metal, its surface must be free of contaminants and textured (roughened) to increase the area available for bonding. Contaminants tend to increase the distance between the bonding surfaces and reduce the number of bonding sites. **Figure 6** shows an example of a type of adhesion failure that can occur as a result of a coating over a contaminated surface. Abrasive blasting can best provide the necessary cleanliness and texture. More detailed discussions of adhesion of coatings can be found in References 5, 6, 7, and 8.

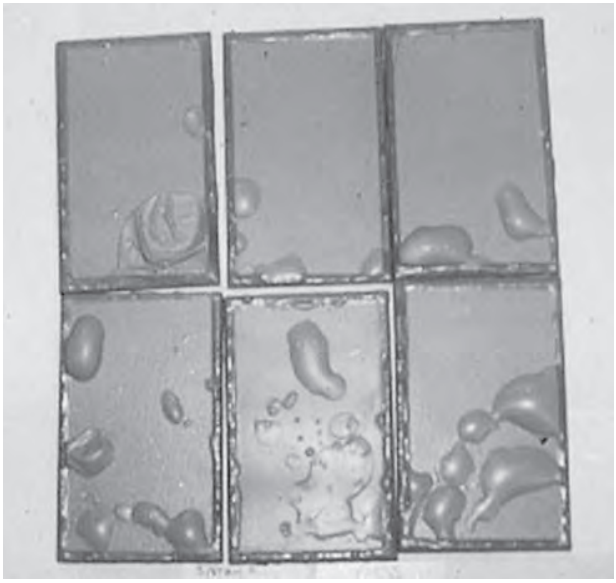


Figure 6. Osmotic blistering caused by residual salt on cleaned steel.

Permeability

Organic coatings vary widely in their permeability to electrolytes and thus in their ability to provide barrier

protection. Low permeability and rapid release of solvent vapors are especially important when providing barrier protection in severe service such as immersion. Film permeability is reduced in films of high cross-link density.

Film Continuity

A highly desirable coating property is the ability to form a continuous film, uniformly thick, and free of discontinuities (holidays). Holidays permit electrolyte to penetrate the barrier, which can lead to accelerated corrosion. If a wet coating has good flow and leveling, it will minimize pinholes and thinner areas that invariably fail first. Holiday detection is usually only considered necessary in immersion and other severe services such as marine piling, tank linings, and buried piping. **Figure 7** shows a worker performing holiday testing of a newly-applied coating.



Figure 7. Holiday testing a newly applied coating.

Flexibility

A desirable coating property is sufficient flexibility, so that the coating film can easily expand and contract with the substrate during temperature variations or stresses without disbonding or cracking. It should be noted that if a rigid topcoat is placed over a flexible undercoat, the topcoat may crack if it is not able to expand and contract with the undercoat.

Hard films (e.g., inorganic zinc-rich coatings) tend to be rigid. Thus, a compromise may have to be made in order to attain a durable film that possesses the appropriate combination of flexibility and high tensile strength.

Resistance to Impact and Abrasion

In many service conditions, resistance to impact and abrasion damage is important. Polyurethane coatings are reported to be the most abrasion-resistant industrial coatings.[6] The U.S. Army Corps of Engineers has found that vinyl coatings impart excellent abrasion resistance to structures on locks and dams. Inorganic zinc coatings, although more brittle, have performed well on the decks of barges and ships and on the boottopping of ships.

Resistance to Weathering

All organic coating binders are subject to deterioration by the sun's ultraviolet light, which can break their chemical bonds. Exterior aromatic coatings such as epoxies, phenolics, and aromatic polyurethanes that have poor resistance to the sun's ultraviolet light are often topcoated with an ultraviolet-resistant finish such as an aliphatic polyurethane or an acrylic.

Chemical Resistance

Interior surfaces of structures used to store water, fuel, or chemicals must be lined with a coating that is resistant to the stored products. Exterior surfaces of dams, off- and on-shore platforms and ship hulls must also be resistant to the severe natural environments and services that they encounter.

Resistance to Biological Growth

The protective coatings used on structures located in tropical and subtropical locations may contain a mildewcide to protect them from biological defacement. All mildewcides used in protective coatings should be approved by the Environmental Protection Agency (EPA) and should pass the American Society for Testing and Materials (ASTM) mildew-resistance tests.

Finish coatings used on ship hulls and other underwater structures may contain antifouling compounds (toxic chemicals) that are slowly released into seawater to control the attachment and growth of marine fouling organism such as barnacles.

Figure 8 shows biofouling on underwater test panels. Heavy fouling growths on the hulls of ships reduces their speed (and maneuverability) and

increases their fuel consumption. For ship hulls, there have also been many attempts to produce smooth, low surface energy coatings that do not permit attachment and growth of fouling organisms. Although none of these has been completely successful at eliminating fouling, some permit only slight fouling adhesion that may be removed relatively easily by movement of the ship through water, or by underwater, low-pressure water blasting using commercially available equipment.[9]



Figure 8. Marine fouling on underwater test panels.

Summary

Protective coatings provide corrosion control by three basic mechanisms:

- Barrier protection
- Chemical inhibition
- Galvanic (cathodic) protection

Coatings with barrier action isolate the substrate from electrolytes in the environment. Thicker coatings in general provide better barrier protection; however, with very thick films, cracking may occur. Leafing or plate-like pigments may be used in barrier coatings to effectively increase barrier thickness.

Inhibitive pigments may be used in coatings to interfere with anodic or cathodic corrosion reactions. These pigments must be carefully selected for effective use with different binder systems. The relative effectiveness of inhibitive pigments depends on the coating composition, PVC, and CPVC. Corrosion and coating blistering are usually minimized when the PVC is at or slightly below the CPVC. The use of lead and chromate inhibitive pigments is being limited because of toxicity concerns. Coatings that provide galvanic protection to steel surfaces include zinc-rich coatings, galvanizing, and thermal spray metallizing. Many of these coatings can provide dual protection (barrier as well as galvanic).

In addition to barrier and corrosion inhibition, other important coating film properties include adhesion, permeability, continuity, flexibility, and resistance to impact, abrasion, weathering, water, fuel, chemicals, and biological growth. Each coat of a coating system provides special requirements for the total protective system. More information on corrosion control by coatings is available in References 5–8.

References

1. Wiktorek, S. A Comparison of Natural and Synthetic Micaceous Iron Oxide. *Journal of Protective Coatings and Linings,* November 1995, pp 25-36.
2. Hendry, C.M. Designed Permeability of Micaceous Iron Oxide Coatings. *Journal of Protective Coatings and Linings,* July 1990, pp 33-42.
3. Smith, Lloyd M. *Generic Coating Types;* Technology Publishing Company: Pittsburgh, 1996, p 152.
4. Morcillo, M. Minimum Film Thickness for Protection of Hot-Rolled Steel: Results after 23 Years of Exposure at Kure Beach, North Carolina. In *New Concepts for Coating Protection of Steel Structures;* D.M. Berger and R.F. Wint, eds., ASTM: West Conshohocken, PA, 1984, pp 95-112.
5. Weldon, Dwight G. *Failure Analysis of Paints and Coatings;* John Wiley and Sons: New York, 2001, pp 9-10.
6 Munger, Charles G. *Corrosion Prevention by Protective Coatings;* NACE: Houston, 1986, pp 53-54.
7. Hare, Clive H. Corrosion and Its Control by Coatings. In *Protective Coatings, Fundamentals of Chemistry and Composition;* Technology Publishing Company: Pittsburgh, 1994, pp 331-359.
8. Hare, Clive H. Trouble With Paint Adhesion. *Journal of Protective Coatings and Linings,* May 1996, pp 77-87.
9. NAVFAC P-990. *Conventional and Underwater Construction and Repair Techniques;* Naval Facilities Engineering Command: Alexandria, VA, 1995, pp 2.23-2.26.

About the Authors

Dr. Richard W. Drisko

Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society for Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy's center of expertise on coatings for shore structures. He is a professinal corrosion engineer in the state of California, an SSPC certified protective coatings specialist (PCS), and a NACE International certificated corrosion specialist. Dr. Drisko received his BS, MS, and PhD degrees from Stanford.

James F. Jenkins

James F. Jenkins retired in 1995 after 30 years of service to the U.S. Navy in corrosion control for shore and ocean-based facilities. Now a consultant, he is a registered corrosion engineer in the state of California. Mr. Jenkins received his BS degree in metallurgical engineering from the University of Arizona.

Chapter 1.4
Properties of Generic Coating Types

Richard W. Drisko and James F. Jenkins

Introduction

This chapter describes the general properties of various generic coating types. It focuses on the properties of protective films and how they contribute to the formation of a total protective system. It also gives examples of generic coating types that form protective films by each of these mechanisms. More detailed information of this type is available in References 1, 2, and 3.

Special attention is given to the ease of formulating different generic types with low VOC (organic solvent) content. Low VOC formulations such as high solids coatings and water-borne coatings are becoming increasingly important because of the need to satisfy VOC restrictions that are enacted to improve air quality.

Non-Convertible Coatings

Non-convertible coatings are not changed chemically during film formation. Their binders are merely deposited from solution or dispersion during the evaporation of organic solvent and/or water.

Lacquers

Lacquers are solutions of natural or synthetic resins (e.g., vinyls, chlorinated rubbers, and acrylics) in organic solvents. Upon coating application and solvent evaporation, the resins are deposited on the surface and are unchanged chemically during the formation of protective films. These durable films have good water and general chemical resistance (especially to acids and alkalis), but, being thermoplastic, poor solvent and heat resistance. Lacquers usually have a low film build but dry so rapidly that they can be quickly topcoated to build up the film thickness. They require an abrasive blasted surface, and, in a few cases, pretreatment wash priming for good adhesion. Applied in multiple coats and easy to topcoat and repair, they can also be formulated for good gloss retention. The good weathering of acrylic lacquers is duplicated in acrylic water-emulsion coatings.

The chief disadvantage of the above lacquers is their high VOC content, which may completely eliminate them from industrial and architectural use.

Advantages
- Rapid drying and recoating
- Good general chemical resistance
- Good in water immersion
- Good gloss retention possible
- Good durability
- Ease of topcoat and repair

Limitations
- High VOC contents
- Poor solvent and heat resistance
- Low film build
- Blasted surface necessary for coating
- Occasional poor adhesion

Bituminous Coatings

Bituminous (asphalt and coal tar) coatings are also thermoplastic, non-convertible coatings. Asphalt is petroleum-based, and coal tar is distilled from coal during the manufacture of coke. Each of these coatings is available in three different forms: enamels, emulsions, and cutbacks.

Bituminous Enamels. Asphalt and coal tar enamels are solid products that must be melted by heating (e.g., asphalt, to 450–500°F [232–260°C]) before they are applied. Both may contain fillers to add reinforcement.

Bituminous Emulsions. Bituminous emulsions consist of fine particles dispersed in water. These may have a little better resistance to exterior weathering than the other two bituminous forms.

Bituminous Cutbacks. Bituminous cutbacks are solutions of the materials in organic solvent, permitting application by conventional means. Thus, they are actually lacquers. **Figure 1** shows an example of a

coal tar cutback in use on a galvanized steel pipeline.



Figure 1. Bituminous coating in use on an underground pipe.

Bituminous coatings have found much use in the past because they are inexpensive and easy to use. They also have good water resistance and can be applied as thick films. However, they weather poorly (become brittle and lose adhesion) in sunlight. They are used less now overall because of toxicity concerns, particularly for coal tar coatings, and their limited durability. Bituminous coatings are still used extensively, however, to protect buried steel structures, such as pipelines.

Advantages
- Low cost
- Ease of application, topcoating, and repair
- Good water resistance
- Good film build
- Low level of surface preparation required

Limitations
- Cutbacks may be high in VOCs
- Poor solvent and heat resistance
- Poor weathering
- Available only in black
- Toxic; need personal protective equipment during application

Water Emulsion (Latex) Coatings

Latex coatings have been and continue to be used successfully to coat wood and masonry structures. The relatively porous nature of their films allows water vapor to pass through them, i.e., they are "breathing" coatings. This makes them less susceptible to blistering. Binder materials must be specially selected for latex coatings to be used on steel.

Water-emulsion coatings have excellent flexibility, relatively low cost, and ease of topcoating and repair. Limitations include poor solvent and heat resistance (as with all thermoplastics), poor performance in immersion and other severe environments, and difficulties in bonding to smooth surfaces. Poor bonding to existing coatings is related to their limited content of organic solvents, and thus limited ability to soften a smooth coating to promote adhesion. Because of this limited adhesion, it is necessary to sand enamels and/or use a surface conditioner or other drying oil product before topcoating with a latex coating. Also, latex coatings do not cure well at temperatures below 50°F (10°C), as the dispersed particles do not coalesce to form a durable film.

Several types of water-borne emulsions (e.g., acrylics, polystyrene, butadiene-modified acrylics, etc.) are also available for use on atmospheric steel surfaces. These products retain the advantages of previously described emulsion coatings, while providing protection to steel structures.

Advantages
- Environmentally acceptable
- Ease of application, topcoating, and repair
- Fast drying for recoating
- Reduced solvent odor
- Excellent flexibility
- Low cost
- Safer (reduced flammability/solvent exposure)

Limitations
- Limited durability in severe service
- Poor chemical and solvent resistance
- Poor wetting of surfaces
- Poor immersion service
- Best cured above 50°F (10°C)
- Poor heat resistance

Convertible Coatings

Convertible coatings are changed by chemical reaction during curing to a higher molecular weight, solid film. The reactions may be between separately packaged coating components or between the coating and oxygen, water, or carbon dioxide from the atmosphere. The higher performance convertible coatings (e.g., epoxy, polyurethane, zinc-rich) usually require a

higher level of cleanliness and greater application skills.

Oil-Base Coatings

Coatings based on drying oils (e.g., linseed, tung, soya, or fish oils) cure by reaction (cross-linking) with oxygen from the atmosphere. Although these films may be completely dry in less than a day, curing slowly continues throughout the life of the coating. Because the oxygen can enter the film only at its surface, the film thickness must be no more than that recommended by the supplier. If applied more thickly, the film may preferentially at the surface leaving the underlying coating soft and uncured and the surface wrinkled **(Figure 2).**

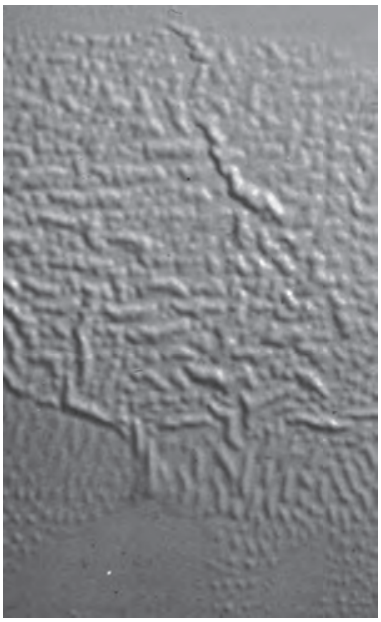


Figure 2. Wrinkling.

Air-oxidizing coatings have limited solvent resistance. However, as they continue to oxidize and cross-link, they become harder, more brittle, and less soluble in solvent, i.e., they attain more thermosetting properties.

Unmodified drying oil coatings can be formulated to have a low VOC content by using low viscosity oils. However, as the oil content is reduced by chemical modification, formulation of low VOC coatings with a low viscosity becomes much more difficult. Thus, the current wide use of alkyd and other modified drying oil products may be curtailed by future VOC limitations.

Oleoresinous Coatings. Oleoresinous (unmodified drying oil) coatings as initially developed were very easily applied, didn't require a high level of surface preparation, and had good flexibility, so that they could readily expand and contract with the substrate. They did, however, have several drawbacks. They were slow to dry, had residual tack, and provided a limited degree of protection. They could not be used in sea water immersion service or on alkaline substrates (e.g., concrete), because they are easily saponified (hydrolyzed) by alkalinity. Drying was accelerated by incorporation of metal driers, but chemical modifications were required to significantly improve film properties.

Alkyd Coatings. Oil-modified alkyd coatings (simply called "alkyd" coatings in this book) use resins formed by the reaction of polyhydric alcohols (e.g., glycerin) and polybasic acids (e.g., phthalic acid) followed by modification with drying oils. They cure much faster than unmodified drying oil formulations to form a harder film and improved resistance properties. They retain the good application properties of the unmodified coatings but with some loss in flexibility.

Silicone Alkyd Coatings. Silicone alkyd coatings were developed by modifying oil-modified alkyd resins with silicone (typically 30% of total resin) to provide greater gloss retention and weather and heat resistance. They are frequently used as finishes for alkyd systems to increase gloss retention and general performance.

Epoxy Ester Coatings. Epoxy ester coatings are a modification of drying oils with epoxy resin to improve performance, particularly chemical resistance. However, the expense of this improvement was a loss of gloss retention in exterior (ultraviolet) exposure. These products should not be confused with the two-component epoxies that normally provide a higher level of performance.

Uralkyd Coatings. Uralkyd (oil-modified polyurethane) coatings have properties similar to those of alkyds, but form a harder film, so that they can be used on wood floors or furniture. They usually also have decreased drying time and enhanced resistance to chemicals, moisture, and weathering.

Oleoresinous Phenolic Coatings. Oleoresinous

phenolic (oil-modified phenolic) coatings are made by cooking phenolic resins with drying oils. They have good water resistance and can be used in water immersion. However, they tend to discolor with age and become hard and brittle.

Advantages
- Ease of application, topcoating, and repair
- Good flexibility possible
- Good surface wetting and adhesion
- Good gloss retention possible
- Relatively inexpensive
- From renewable source

Limitations
- Anticipated lower VOC limits
- Poor chemical and solvent resistance
- Poor water immersion resistance
- Poor alkali resistance
- Long time for complete curing

Epoxy Coatings

Epoxy coatings are the most commonly used two-component convertible coatings today. One component is commonly called the base and the other, the curing agent, although they are both best described as co-reactants. By modifying the epoxy component and/or the co-reactant, a variety of products with differing properties can be obtained.

Epoxy coatings bond well to abrasive blasted steel and clean concrete and are very durable in most environments. Their films are hard and relatively inflexible. Thus, they cannot expand or contract much without cracking. They chalk freely in sunlight, some losing over a mil of thickness a year. An aliphatic polyurethane finish coat is frequently applied over an epoxy coating to impart resistance to the sun's ultraviolet light .

New high-solids epoxy products are available that are wedge retentive. Their coating thicknesses at edges is at least 70% of that on adjacent flat surfaces.

Epoxy-Polyamide Coatings. Epoxy-polyamide coatings are probably the most widely used epoxy because of their good water and corrosion resistance and their relative tolerance to moisture and incompletely cleaned surfaces. The polyamide curing agents are actually resinous products with attached amino groups. This makes the cured films somewhat softer and more resilient and flexible than those of amine-cured epoxies but having less chemical, particularly acid, resistance. They are used mostly extensively on ship hulls, water and fuel tank interiors, and marine steel pilings **(Figure 3).**



Figure 3. Applying an epoxy-polyamide coating to sheet piling in a cofferdam.

Amine-Cured Epoxies. Amine-cure epoxy coatings are hard, tightly-bonded, chemically resistant products that are used extensively to line chemical storage tanks and in other severe environments. An oily, amber film of amine may rise to the surface of the coating, especially when applied in cold, damp weather. It then reacts with carbon dioxide and water in the air to form a glossy product. This "amine blush" must be removed before topcoating to permit good topcoat adhesion. Amine curing agents are usually toxic and may cause skin irritation. Thus, special safety precautions must be taken during their use.

Cycloaliphatic amine-cured epoxy coatings are very high-solids products with a high film build, short pot life, and rapid curing. It has good low-temperature application and curing properties.

Amine Adduct Epoxies. Amine adduct epoxy coatings are products in which the amine curing agent has been partially reacted with a relatively low molecular weight epoxy resin. This reduces the health hazards, lessens the tendency to blush, and makes mixing ratios less critical, since a greater volume of curing agent is used. Cured products have properties similar to those of amine-cured epoxies.

Ketimine Epoxies. Ketimine epoxy coatings utilize a

"blocked" ketimine curing agent formed chemically by reaction between a primary amine and a ketone. After mixing of components and application, moisture from the atmosphere reacts with the ketimine to regenerate the amine and the ketone. The ketone is merely lost by evaporation, but the amine reacts with the epoxy component as normally occurs with amine-curing epoxies. The low viscosity of the amine curing agent permits formulation of high-solids products. Ketimine epoxies also have long storage lives, pot lives, and curing times.

Phenolic Epoxy Coatings. Phenolic epoxy coatings are specially formulated to produce hard, dense, chemically resistant films. Indeed, they have the best combination of chemical, solvent, and heat-resistance of all epoxies. It should be noted that "phenolic epoxies" comprise a whole family of hybrid coatings made by reacting phenolic resins with epoxy resins. Depending on the relative proportions of the two resins and consequently their method of curing, these may be called "phenolic epoxies" or "epoxy phenolics."

Novolac Epoxy Coatings. Novolac epoxy coatings have the best combination of chemical, solvent, and heat resistance of all the epoxies. These high molecular weight, highly cross-linked products, however, are hard, dense, and brittle.

Epoxy Mastic Coatings. Epoxy mastic coatings are high-solids, high-build epoxy coatings, usually at least 5 mils (125 micrometers) dry film thickness, and often aluminum filled. Since they have good wetting properties, they are "surface tolerant" and can often be applied successfully over incompletely cleaned steel. Because of their relatively weak solvents, they are compatible with most other coatings. They may be formulated for use with various amine-based curing agents.

Advantages
- Low VOC formulations possible
- Good solvent and water resistance
- Generally good chemical resistance
- Tough, durable, slick film formed
- Good adhesion
- Good abrasion resistance possible
- Wide range of properties available

Limitations
- Limited pot life
- Poor resistance to ultraviolet light
- Limited flexibility
- Cure best above 50°F (10°C)
- Recoat window limit
- Amine curing agents toxic
- Amine-cured coatings subject to amine blush

Coal-Tar Epoxy Coatings

Coal-tar epoxy coatings are basically combinations of epoxies and coal tar that take advantage of the good properties of both. The coal tar reduces cost, improves water resistance, and provides for greater film build. However, because of the coal tar, these products tend to become brittle in sunlight, causing loss of adhesion. There is also concern about toxic effects of certain constituents in the coal tar. They are used today mostly on steel piling, tank linings, and buried piping.

Advantages
- Low VOC formulations possible
- Good water resistance
- Good film build
- Good abrasion resistance
- Relatively low cost

Limitations
- Toxic; need personal protective equipment during application
- Limited pot life
- Poor resistance to ultraviolet light
- Limited recoat window
- Toxicity of coal tar
- Available only in black or dark red

Polyurethane Coatings

Polyurethane (sometimes simply called "urethane") coatings are usually two-package systems, one an isocyanate component and the other a polyol component. These coatings are available in a variety of formulations, giving rise to a variety of properties, (e.g., they may be hard/brittle or elastomeric). Low-temperature curing is achievable for polyurethane coatings, and they perform well in most environments. The toxicity of the isocyanate component is, however, of great concern, and personal protective equipment, including respirators, must be used when applying

polyurethane coatings.

Two basic chemical types of polyurethanes are aliphatic and aromatic. Aliphatic polyurethanes have excellent weathering in sunlight. Aromatic polyurethanes chalk and discolor in sunlight, but they have better chemical resistance in immersion. Both types can readily be formulated to be low in VOCs. Because the isocyanate component may react with water, polyurethanes are moisture sensitive during storage and application. Also, the gloss of polyurethane coatings may drop when the wet film is exposed to high humidity.

Advantages
- Low VOC formulations available
- Good water resistance
- Good hardness or flexibility possible
- Aliphatics have good gloss and color retention
- Aromatics have good chemical resistance
- Good durability
- Good abrasion resistance
- Low-temperature curing achievable

Limitations
- Toxic; need personal protective equipment during application
- Skilled applicator needed
- Limited pot life
- Blasted surface required when used as primer
- More expensive than epoxies

Another type, moisture-curing polyurethanes, is available as a one-component product that cures by a series of reactions, initiated by the reaction of water with a portion of the isocyanate to produce an amine and carbon dioxide. The amine then react with other isocyanate groups to form a urea.[3] The relative humidity must be within a certain range for them to cure properly. A minimum relative humidity of 30 to 50% is normally required for complete curing. For some products, the maximum relative humidity is 75%, while others can be used in up to 99% relative humidity. As with oil-modified polyurethanes, moisture-curing polyurethanes are frequently used as clear or pigmented coatings for wood floors.

Polyurea Coatings

The relatively new polyurea two-component thermosetting coatings are somewhat similar chemically to polyurethanes. They are produced by the reaction of an isocyanate with an amine-terminated co-reactant rather than a polyol, as with polyurethanes. Polyureas can be used by themselves or as a hybrid with polyurethanes. They cure very rapidly to form soft to hard elastomers for use on concrete floors and containments and have the advantages of other 100% solids coatings.

Polyester and Vinyl Ester Coatings

Polyester and vinyl ester films are formed by reactions of multiple components. In both cases, unsaturated thermosetting resins (as pre-polymers) dissolved in an unsaturated polymer (usually styrene), upon the addition of a peroxide catalyst, undergo an addition reaction to form a solid film.[3] These films can have relatively high thicknesses (up to 80 mils; 2 mm). They frequently are reinforced with fiberglass or glass flakes **(Figure 4).** They have excellent chemical resistance, especially acid resistance, and good solvent and water resistance.

Polyester and vinyl ester films are frequently used as special linings such as on tank bottoms. Because it only takes a small amount of the peroxide catalyst to greatly accelerate curing, the proportioning specified by the manufacturer must be carefully followed.

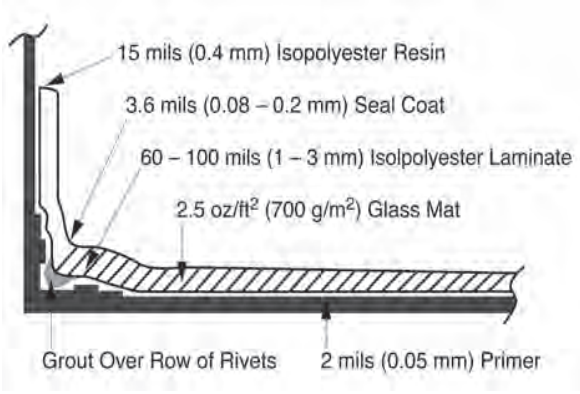


Figure 4. Diagram of a fabric-reinforced troweled lining. These linings combine chemical resistance and physical durability. The reinforced cloth is rolled into the fresh basecoat and saturated with catalyzed resin.

Advantages
- Low VOC formulations available
- High film build
- Good abrasion resistance
- Good water resistance

• Good solvent and chemical resistance
• Temperature resistant formulations available

Limitations
• Limited pot life
• Skilled operator needed
• Blasted surface required
• Hazardous peroxide component
• Special application equipment required

Siloxanes

Siloxanes, sometimes called siloxiranes, are relatively new two-component thermosetting coatings. They have a silicone-oxygen backbone that can be modified by combining with organic binders, notably epoxies. Coatings with epoxy silane binders have good chemical, weather, and heat resistance. They usually have 80–85% solids and are applied at 4–4 mils (75–100 µm).

Siloxanes have a relatively short pot life (e.g., 4 hours at 80°F [27°C]) but may take several days to fully cure unless heated. They are relatively expensive, but this may be offset by a fewer number of coats for protection or longer service life. They have been used successfully on bridges, anchor chains, stacks, and chemical process equipment.

Advantages
• Low VOC formulations available
• Good chemical/weather/heat resistance
• Good general Industrial use

Limitations
• High level of surface preparation required
• Relatively Relatively short pot life
• Relatively slow final cure
• Relatively high cost per coat

Pretreatment Wash Primers

Pretreatment wash primers for steel and aluminum (e.g., DOD-P-15328 and SSPC Paint 27) are used to promote adhesion or provide temporary corrosion protection before applying a full coat of primer. They are two-component products: polyvinyl butyral in alcohol solution with a corrosion inhibitor (basic zinc chromate) and a solution of phosphoric acid. Upon mixing, the components react with each other and with the metal to form a tightly adhering film. They are applied at 0.3 to 0.5 mils (7.5 to 12.5 µm) and dry fast (in less than a half hour) to provide good temporary protection from corrosion. Pretreatment wash primers are very high in VOCs, but they usually have a temporary exemption from VOC regulations.

Advantages
• Promote adhesion of primers
• Provide temporary corrosion protection
• Fast Drying

Limitations
• When applied too thickly, film may fail cohesively
• High in VOCs
• Contains toxic chromate pigment
• Uses are limited

Phenolic and Epoxy Phenolic Coatings

Phenolic resins are generally based on the reaction of a phenol with formaldehyde. Phenolic coatings are usually heat-cured in multiple thin coats to provide products with good adhesion and resistance to water, chemicals, and heat. They discolor during the heat-curing and have poor resistance to exterior weathering because of the aromatic group in the phenol molecule. Baked phenolic coatings are used to line cans, drums, piping, and tanks.

Epoxy phenolics are epoxy modifications of phenolic coatings. They are hard but flexible and resistant to abrasion, water, solvents, chemicals, and heat. Like phenolics, they also discolor during heat-curing and have poor resistance to exterior weathering. They are available as air-dry or heat cured-formulations. The uses of epoxy phenolic coatings are similar to those of phenolic coatings.

Advantages
• Hard coatings
• Good chemical resistance
• Good heat resistance
• Good solvent resistance

Limitations
• Require heat to cure
• Discolor during heat curing
• Poor exterior weathering
• Low film build

Zinc-Rich Coatings

In zinc-rich coatings, the zinc loading must be

high enough that the zinc particles are in electrical contact with each other and with the steel surface. A combination of zinc particles of different sizes provides a greater, more uniform loading; however, there are differences of opinion as to how much zinc loading is required for satisfactory performance. Thus, in documents such as SSPC Paint 20 and 29, the zinc content requirements are different. Indeed, some of the zinc may be replaced with other conductive pigments (e.g., di-iron phosphide) to provide the necessary electrical continuity. The zinc in both inorganic and organic zinc-rich coatings is attacked by acid or alkali.

Inorganic Zinc-Rich Coatings. Inorganic zinc-rich coatings are tough, abrasion-resistant silicates containing very high loadings of zinc dust. They usually cure by reaction with moisture or carbon dioxide in the atmosphere. Most types of inorganic zinc-rich coatings, particularly the water-borne products, can be formulated to be acceptably low in VOCs.
Inorganic zinc-rich coatings form relatively porous films that initially protect steel by galvanic protection. As the zinc is sacrificed (reacts with the atmosphere), its corrosion products fill these “pores” or voids to form a barrier coating. If this barrier is broken by impact, galvanic protection will again take over until the break (up to 0.125 inch; 3.18 mm wide) is healed by filling with zinc corrosion products. Their alkalinity of inorganic zinc-rich coatings also improves the resistance of steel to corrosion.

Inorganic zinc-rich coatings require greater steel surface cleanliness than do most other generic coating types. Water-borne inorganic zinc-rich coatings are the most sensitive of the inorganic zinc-rich coatings to surface contaminants, particularly oil or grease.

Inorganic zinc-rich coatings must be applied by a skilled applicator using a constantly agitated container to keep the heavy zinc particles suspended. Films of inorganic zinc-rich coatings are brittle and may crack when applied too thickly **(Figure 5).** Thus, they are generally applied at less than 5 mils (125 µm) dry film thickness, although some products can successfully be applied at greater thicknesses.

When topcoating inorganic zinc-rich films, small bubbles may form in the wet topcoat from escape of air or solvent vapors entrapped in the porous binder. Many painters attempt to minimize this problem by applying a mist coat (thin, quick coat) and

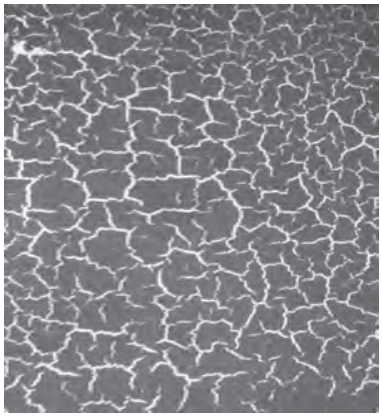


Figure 5. Mudcracking.

allowing it to dry, before applying a full topcoat. However, inorganic zinc-rich coatings perform well without a topcoat in a variety of services. Thus, in a marine environment and elsewhere where color and gloss are not important, it is often best not to topcoat them. Inorganic zinc-rich silicate coatings frequently do not bond well to each other, and it is safest to repair them using organic zinc-rich coatings.

Advantages
- Low VOC formulations available
- Excellent abrasion resistance
- Excellent heat resistance
- Good good atmospheric durability
- Useful as shop primer
- Fast dry
- Can be used untopcoated
- Provides galvanic in addition to barrier protection

Limitations
- Very clean, blasted surface required
- Skilled applicator, agitated coating required
- Difficult to topcoat
- Attacked by acid and alkali
- High initial cost
- Limited color selection

Organic Zinc-Rich Coatings. Organic zinc-rich coatings utilize an organic resin rather than an inorganic silicate binder for film formation. They protect steel galvanically (to a lesser level than inorganic zinc-rich coatings), as well as by barrier protection. Organic zinc-rich coating films may form by simple solvent evaporation (e.g., those that utilize phenoxy, vinyl or

chlorinated rubber resins) or by chemical reaction of components (e.g., those that utilize epoxy or polyurethane resins). Epoxies are the most commonly used binders.

Organic zinc-rich coatings require an alkali-resistant binder because of the alkalinity produced in the cathodic reaction (in this case, on the surface of the protected steel). Organic zinc-rich coatings are usually topcoated to extend their service lives.

Film properties of organic zinc-rich coatings are similar in most respects to those of zinc-free organic coatings using the same resin. Organic zinc-rich coatings do not require as high a level of cleanliness of blasted steel surface as do zinc-rich inorganic coatings, and they are easier to topcoat. They can be used to repair damaged galvanizing or inorganic zinc coatings on steel.

Advantages
- Good atmospheric durability
- Relatively easily topcoated
- Moderate surface preparation required
- Can be used to repair galvanizing or inorganic zinc coatings on steel

Limitations
- Requires constant agitation during application
- Attacked by acid and alkali
- High initial cost
- Normally requires topcoat
- Lower abrasion and temperature resistance than inorganic zinc-rich products

Metallic Coatings

There are two generic types of metallic coatings, those that are anodic to the underlying metal (called here “anodic metallic coatings”) and those that are cathodic to the underlying metal (called here “cathodic metallic coatings”). Both of these generic types provide barrier protection, but they differ in their ability to provide corrosion protection when they are damaged or contain localized defects.

Anodic Metallic Coatings. When an anodic metallic coating (i.e., one high in the galvanic series) is damaged or defective and the underlying metal is exposed, the underlying metal will act as a cathode and have a reduced rate of corrosion. The coating itself will have an accelerated rate of corrosion, but this effect will be minimal if the area of any defects or damage is small relative to the overall surface area, i.e., if the anode/cathode area ratio is favorable. Zinc and aluminum coatings on steel are examples of metallic coatings that are anodic to the steel and provide effective protection even when damaged.

The effectiveness of anodic metallic coatings depends on their thickness and their ability to provide a barrier. In general, hot dip coatings are thicker, and thus are more effective barriers than electroplated coatings. Thermal spray coatings are less effective barriers as they are more porous. The barrier properties of anodic metallic coatings can sometimes be improved by topcoating. For example, electroplated anodic coatings are frequently topcoated with a paint and thermal spray coatings are commonly sealed with paint. These combinations of an anodic metallic coating with paint can provide control of corrosion for long periods and can be much more effective than either the metallic coating or the paint when used alone. The use of the metallic coatings without topcoat is also limited by the resistance of the zinc or aluminum to the exposure environment.



Figure 6. Galvanized guardrail.

In galvanizing, the zinc layer provides barrier protection to the steel **(Figure 6).** However, if the barrier is compromised (i.e., if a discontinuity forms in the barrier), galvanic (cathodic) protection will protect the steel from corrosion. The amount of protection provided by the layer of zinc is directly proportional to its thickness.

In thermal spray metallizing, a thin, relatively porous coating of metal, most commonly zinc, aluminum, or zinc-aluminum alloy wire is melted in a hot flame or electric arc and sprayed onto clean steel

(Figure 7). When metallized structures are to be in severe service such as immersion, additional corrosion protection is almost always obtained by sealing the metallizing with a low-viscosity coating. This fills the pores to provide barrier protection.



Figure 7. Thermal spray metallizing in the field.

Cathodic Metallic Coatings. When a cathodic metallic coating is damaged or defective and the underlying metal is exposed, the underlying metal will act as an anode and have an accelerated rate of corrosion. In this case, the anode/cathode area ratio is unfavorable and the acceleration of the rate of attack of the underlying metal can be very high.

Nickel and chromium coatings on steel are examples of metallic coatings that are cathodic with respect to the steel. Where defects occur or where such coatings are damaged, rapid corrosion of the underlying metal can occur. The effectiveness of cathodic metallic coatings depends on the completeness and durability of the barrier that they provide. Cathodic metallic coatings are often selected because of their resistance to highly corrosive environments.

Summary

There are many different generic coating types, which vary widely in their physical and chemical properties. Non-convertible coatings (those that are not changed chemically during film formation) include: lacquers, bituminous coatings, and water emulsion (latex) coatings.

Convertible coatings (those that are changed chemically during film formation) include: oil based coatings, epoxies, coal-tar epoxies, polyurethanes, polyureas, siloxanes, polyester and vinyl ester coatings, phenolics and epoxy phenolics, inorganic zinc-rich coatings, and organic zinc-rich coatings.

Pretreatment wash primers, used to promote adhesion or provide temporary corrosion protection, are also convertible coatings.

There are many factors that contribute to the satisfactory performance of a protective coating. These include surface preparation or application characteristics, resistance to exposure conditions, esthetic considerations, safety and environmental considerations, cost, and maintainability. While some generic coating types are clearly best for certain uses, each coating type has its advantages and disadvantages.

References

1. Hare, Clive L. Protective Coatings. In *Fundamentals of Chemistry and Composition;* Technology Publishing Company: Pittsburgh, 1994.
2. Munger, Charles G. *Corrosion Prevention by Protective Coatings;* NACE: Houston, 1986.
3. *Generic Coating Types;* Lloyd M.Smith, ed., Technology Publishing Company: Pittsburgh, 1996.
4. *Journal of Protective Coatings and Linings Tips*: *Tip 10 Waterborne Coatings; Tip 11 Generic Coating Systems and Their Uses; Tip 28 Zinc-Rich Coatings; Tip 45 Polyurethane Coatings; Tip 47 Epoxy and Coal Tar Epoxy Coatings;* Technology Publishing Company: Pittsburgh.

About the Authors

Richard W. Drisko

Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society for Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy's center of expertise on coatings for shore structures. He is a professional corrosion engineer in the state of California, an SSPC certified protective coating specialist (PCS), and a NACE International certificated corrosion specialist. Dr. Drisko received his BS, MS, and PhD dgrees from Stanford.

James F. Jenkins

James F. Jenkins retired in 1995 after 30 years of service to the U.S. Navy in corrosion control for shore and ocean-based facilities. Now a consultant, he is a registered corrosion engineer in the state of California. Mr. Jenkins received his BS degree in metallurgical engineering from the University of Arizona.

Chapter 1.5
Organic Coatings: Composition and Film Formation

Richard W. Drisko and James F. Jenkins

Introduction

This chapter discusses the various mechanisms of protective film formation. By necessity, it also includes a discussion of the components of protective coatings and their functions in providing the protective film.

Components of Organic Coatings

Liquid-applied organic coatings have three basic components: binder, solvent, and pigment **(Figure 1).** To be sure, not all organic coatings contain all three components; however, binders are always necessary for film formation. For example, there are clear, pigment-free coatings and also solvent-free (100% solids) coatings, but never binder-free organic coatings. In multi-packaged systems, the binder, solvent, and pigment are divided into parts as necessary for best storage and later use.

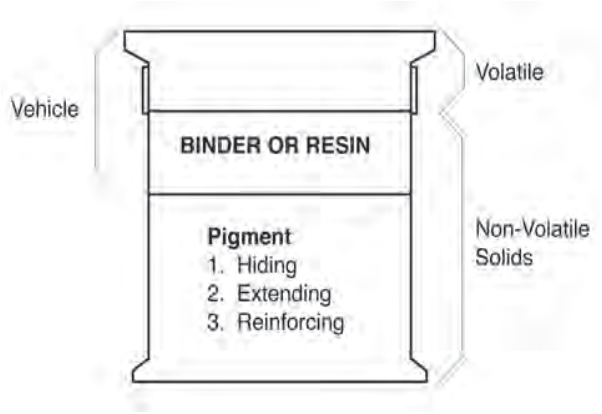


Figure 1. Basic components of coatings.

Liquid-applied coatings are sometimes described as having two basic components: the vehicle and the solid phase. The vehicle or liquid component is made up of the solvent and dissolved binder. The solvent is then called the volatile vehicle and the binder is called the nonvolatile vehicle. The solid phase is made up of the insoluble pigment and insoluble film additives. Since the pigment is heavier than the vehicle, it tends to settle to the bottom of containers upon prolonged standing.

Because only the solvent portion of coatings is lost during most curing reactions, the remaining binder and pigment are sometimes called the coating solids. The percent of coating solids by volume directly affects the coating film thickness and thus the level of barrier protection provided.

Liquid-applied organic coatings are supplied in three basic forms: solvent-borne, water-borne, and solvent/water-free. Solvent/water-free coatings are typified by the so-called 100% solids epoxy systems which have no solvent evaporation.

Binder

The binder, often called polymer or resin, is the film-forming component of the coating. It is usually a high molecular weight polymer (i.e., a large molecule with repeating structural units). Examples of common binders are alkyd, acrylic, and epoxy polymers.

The binder wets the surfaces of pigment particles and binds them to each other and to the substrate. The binder is responsible for most of the coating properties. Because of this, generic coatings are generally classified by their type of binder. Important properties imparted to the coating by the binder include:

- Mechanism and time of curing
- Performance in different environments
- Adhesion to various substrates
- Compatibility with other coatings
- Flexibility and toughness
- Exterior weathering
- Ease of application, topcoating, and repair

Solvent

Organic solvents are used to dissolve binder materials and/or reduce coating viscosity to permit easier coating application. They may also control leveling, drying, durability, and adhesion. Binders that are more insoluble require stronger solvents or more solvent to dissolve them. Solvent blends rather than single solvents are generally used to control evapora-

tion and film formation.

As coatings containing organic solvent dry, the solvent evaporates into the atmosphere. Virtually all of the volatile organic compounds (VOCs) that comprise the organic solvent portion of coatings react in sunlight to form ozone, an air pollutant. In certain geographical areas in the U.S. and elsewhere, there are restrictions on the VOC content of coatings. This is necessary to assist in reducing existing air pollution to an acceptable level. In water-borne coatings, the binder is dispersed in water using wetting agents to obtain a stable dispersion. They frequently also contain organic co-solvents to obtain desired film formation, drying properties, or other performance properties.

Pigment

The pigment is the heavier, solid portion of the coating. Inorganic pigments derived from natural earth materials such as red iron oxide tend to be more resistant to deterioration (i.e., fading) by the sun's ultraviolet light than synthetic organic pigments. Pigments can impart to coatings such important properties as:

- Opacity
- Color
- Corrosion resistance
- Flow properties for ease of application
- Ultraviolet (UV) radiation and moisture resistance
- Level of gloss
- Reinforcement of film and film build
- Adhesion

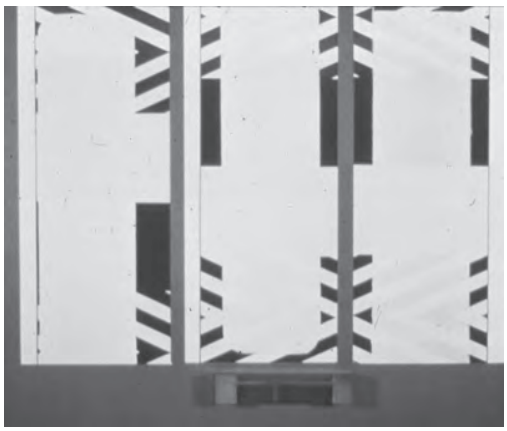


Figure 2. Opacity tests at different coating thicknesses.

Opacity. Two of the chief functions of the pigment are to provide opacity (hiding) to obscure the underlying substrate or coating and to protect the organic binder from deterioration by the sun's ultraviolet light ("chalking"). (All organic coatings chalk to some degree in sunlight.) Titanium dioxide is a very opaque white pigment that is widely used to impart opacity to coatings with white and light tints. As shown in **Figure 2,** opacity increases with increasing coating thickness.

Color. Pigments may provide a variety of color tones. In addition to providing an aesthetic pleasing appearance, color may be used for safety, fire, or other coding (e.g., identification of products in piping).

Corrosion Resistance. Inhibitive pigments may be incorporated into primers to provide corrosion protection. Their effectiveness varies with the type of binder and with the pigment volume concentration (PVC) and the critical pigment volume concentration (CPVC). However, certain inhibitive pigments (lead and chromate), once used extensively, are seldom used today in the United States because of health and environmental concerns. These have been replaced with less toxic pigments, such as zinc oxide, zinc phosphate, and others.

Zinc pigment particles may also be incorporated into coatings to provide corrosion protection. For example, so-called zinc-rich coatings with a heavy loading of fine zinc pigment particles may be used to provide galvanic (cathodic) protection to steel.

Flow Properties. Extender or filler pigments (talc, silica, etc.) are used to control viscosity, wet film leveling, and settling of coatings. These pigments are relatively inexpensive but impart relatively little opacity.

Weather and Moisture Resistance. In addition to protecting the binder of the finish coat from the destructive effects of sunlight, the pigment increases the coating barrier thickness and requires penetrating moisture to detour around it to reach the substrate. This is especially true with pigments like micaceous iron oxide and flake aluminum that tend to leaf over each other much like shingles on a roof.

Level of Gloss. The PVC of coatings can vary widely. There can be little or no pigment (PVC close to zero), or the PVC can approach the CPVC. At the CPVC, there is just enough binder to fill all the voids between pigment particles in the dry film. The level of gloss of a

coating will vary with its PVC. The lower the PVC, the higher the coating gloss. Thus, localized resin-rich areas of finish coatings, such as may occur in areas of significantly greater film thickness, often have "hot spots" (glossier areas).

The fineness of the dispersion of the pigment (formerly called the "fineness of grind") also affects gloss. With a finer the dispersion of the pigment in the vehicle, the coating gloss is greater.

Reinforcement. Fiber, flakes, and other types of pigment can be used to reinforce the coating film and to increase its thickness.

Additives

Additives impart special properties to the coating. They are considered to be part of the binder or pigment component depending on whether they are present in the liquid or solid phase (i.e., soluble or insoluble in the liquid phase).

Examples of additives incorporated into the wet paint during manufacture are:

- Wetting agents to aid in dispersing water-borne coatings
- Additives to prevent settling, skinning, or other deterioration of the wet paint during storage
- Biocides for stability in cans during storage
- Driers to accelerate the curing of oil-base coatings
- Plasticizers to impart flexibility to the cured film
- Mildewcides to control the growth of mildew on the dry film
- Rheological modifiers to improve application properties

Examples of additives that may be incorporated into the wet coating or dropped later into the wet film to impart special properties are:

- Fine aggregates to provide a non-slip surface
- Fine glass beads to reflect light

Mechanisms of Film Formation

Terms Commonly Used to Describe Films and Their Formation

Liquid coatings are converted into solid films by a process called curing. Curing is defined by SSPC's *Protective Coatings Glossary* as "the process of changing the properties of a paint from its liquid state into a dry, stable, solid protective film by chemical reaction with oxygen, moisture, or chemical additives, or by application of heat or radiation."[1] If this definition is followed strictly, coating films that are deposited from solution or dispersion by evaporation of organic solvent or water without chemical change upon drying do not cure. In any event, the reader should not confuse the words "drying" and "curing." "Drying" is merely loss of solvent and/or water, which may or may not result in the formation of a protective film. "Curing," on the other hand, always produces a protective film.

Two other terms used to describe organic films are "thermoplastic" and "thermosetting." As originally used in the plastics industry, the term "thermoplastic" referred to materials that could generally be softened by heating and would harden (or become more brittle) when cooled. The term "thermosetting" referred to materials that underwent a chemical change when heated and, once cured, would not be softened by heating.

Organic coatings are more easily classified as either non-convertible or convertible. A non-convertible coating contains a resin that does not change chemically during film formation. A convertible coating contains a resin or resin-forming component that undergoes chemical changes during film formation.

Coatings that cure by the same basic mechanism tend to be compatible with each other, but not with coatings that cure by other mechanisms. All commonly used coatings utilize one of the following basic mechanisms in their protective film formation:

Non-Convertible

- Evaporation of organic solvent
- Coalescence of latex particles
- Phase change

Convertible

- Air oxidation (polymerization) of unsaturated drying oils
- Chemical reaction of components
- Reaction with moisture

It should be noted that water-borne zinc-rich coatings are unusual in that their films cure by the inorganic binder reacting with carbon dioxide in the air.

Film Formation and Coating Solubility

As thermosetting coatings cross-link to

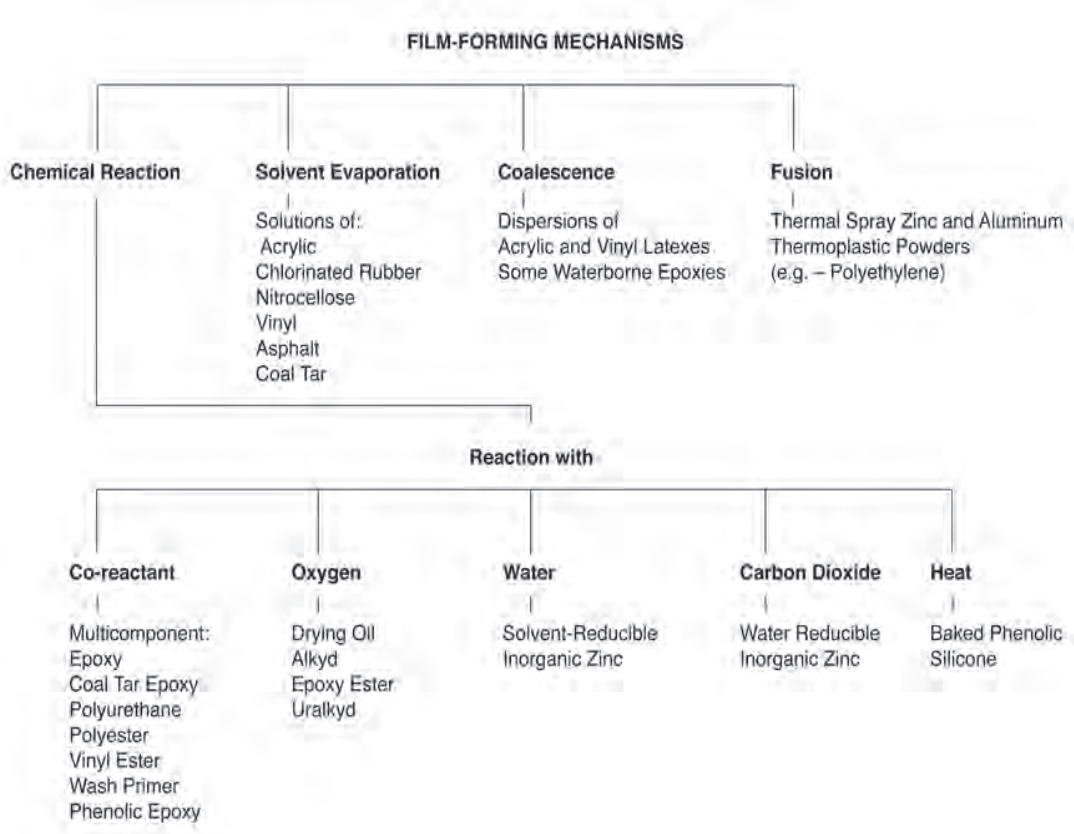


Figure 3. Mechanisms of film formation (curing).

become much greater in molecular weight, they tend to become less soluble in organic solvents. Solubility in a strong solvent such as methyl ethyl ketone (MEK) can be used to distinguish between some general coating types as shown below:

Coatings Soluble in MEK
- Lacquers
- Latex Products
- Oil-Base Products (initially)

Coatings Slightly Soluble in MEK
- Chemically reacting products
- Oil-Base Products (after much aging)

The various mechanisms of film formation (curing) are summarized in **Figure 3.** This figure shows the different curing mechanisms and gives examples of coatings that cure by each mechanism. More detailed information on film formation for various types of protective coatings is presented below and in Reference 2.

Non-Convertible Coatings

Two common types of thermoplastic (non-convertible) coatings are “lacquers” and “latex” or “emulsion paints.” Both of these types of coatings form protective films that can be dissolved in organic solvent. It should be noted that the terms “lacquer,” “latex,” and “emulsion,” are not very precise; however, their use is common. A third type of non-convertible coating is one that forms a film as a result of a phase change.

Coatings That Form Films by Solvent Evaporation. Lacquers are made by dissolving solid resins in an appropriate solvent. After lacquers are applied, the solvent evaporates to deposit the resin in a thin film **(Figure 4).** Since no chemical change occurs to the binder, lacquers are easy to topcoat with another coat of the same material. When a lacquer is topcoated, the organic solvent in the topcoat softens the undercoat, permitting the topcoat to slightly penetrate the undercoat.

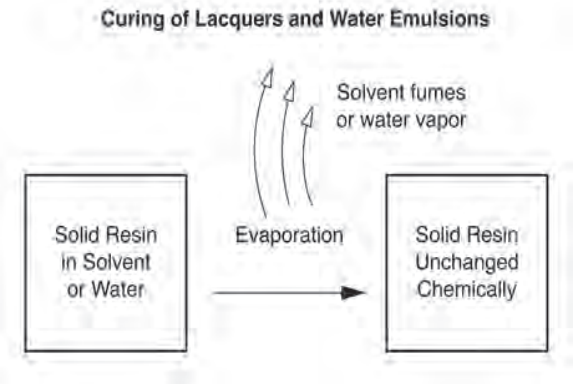


Figure 4. Curing lacquers and water emulsions.

Coatings That Form Films by Water Evaporation. Latex (emulsion) coatings are dispersions of binder and pigment in water **(Figure 5).** After application to a substrate, the dispersed particles coalesce as the water evaporates. These coatings usually contain some organic coalescing solvent to control film formation and ease of application. Two binders that are often used to form latex dispersion coatings are acrylics and vinyls (polyvinyl acetates). Latex films are relatively flexible but of limited durability, so that they are not normally used for severe service such as immersion.

Besides latex coatings, there several other types of water-borne coatings (coatings with water as the main carrier), generally classified as:

- Water-soluble
- Water-reducible
- Water-dispersible

Of these types, only the latter two may be practical for protection of metals. In severe environments, they are typically less durable than corresponding solvent-borne types. Currently available water-soluble coatings are not durable enough for this type of service.

Water-reducible coatings (which contain a solvent blend that can be thinned with water) and water-dispersible coatings may be used in geographic areas where the VOC (organic solvent) content of coatings is restricted. For example, alkyd and epoxy formulations are available in either water-reducible or dispersion forms, and may be used where low VOC content is required. The alkyd films cure by air oxidation, and the epoxies cure by chemical reaction between components.

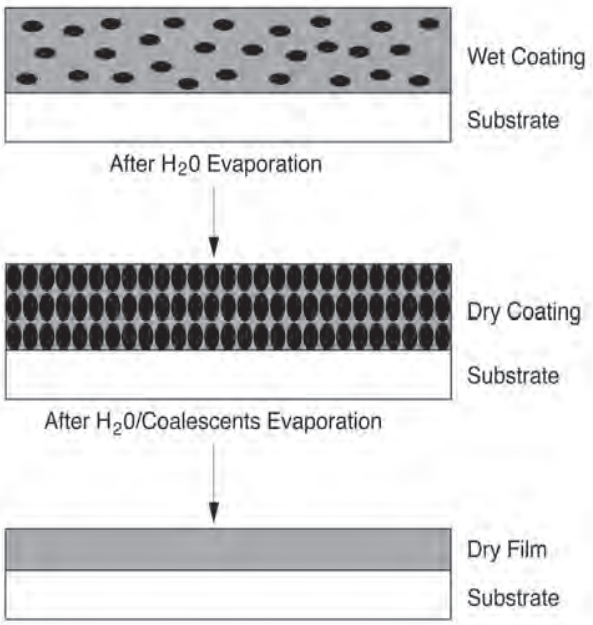


Figure 5. Film formation process in latex emulsion paint.

Coatings That Cure by Phase Change. Some coatings are heated until they fuse (melt) and then applied hot. When they cool, they harden to form a film. Examples are hot-applied coal tar pitch coatings and thermoplastic powder coatings.

Convertible Coatings

There are many different types of convertible coatings. In general, after curing, these are insoluble in common organic solvents. However, as discussed below, certain types of convertible (thermosetting) coatings such as air-oxidizing coatings (oil-base paints) are solvent-soluble after initial curing, becoming less soluble only with additional time, as polymer cross-linking continues.[3]

Coatings That Cure by Air-Oxidation of Drying Oils. In coatings that cure by air oxidation of drying oils (usually vegetable oils), film formation takes place as oxygen from the air reacts with unsaturated fatty acids in the drying oils **(Figure 6).** This causes cross-linking, which forms a higher-molecular weight solid product. Metallic driers such as cobalt and manganese salts of organic acids are usually incorporated into formulations of drying oil coatings to accelerate this normally

slow curing reaction.

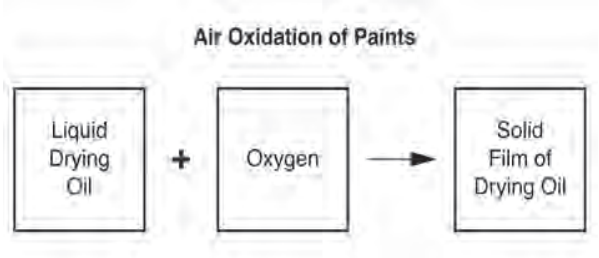


Figure 6. Air oxidation of paints.

Coatings that cure by air-oxidation of drying oils include:

- Unmodified drying oils
- Oil-modified alkyds
- Silicone alkyds
- Epoxy esters
- Oil-modified polyurethanes (uralkyds)
- Oleoresinous phenolics

Coatings that cure by air-oxidation of drying oils wet surfaces very well and so do not require as high a level of surface cleanliness as do other coatings. Their films generally provide good protection in mild atmospheric environments, but they have limited durability in chemical environments, particularly alkaline environments.

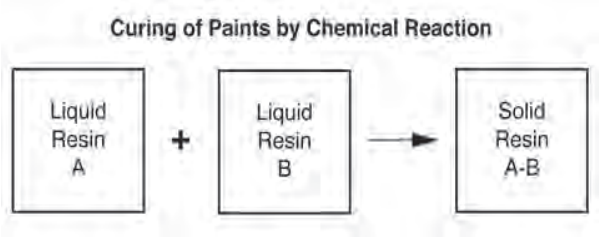


Figure 7. Curing paints by chemical reaction.

Coatings That Cure by Chemical Reaction Between Components. Coatings that cure by chemical reaction of components are usually the most durable but have more stringent surface preparation and application requirements than other generic types. They are generally packaged in two or more separate containers that are mixed together to initiate their curing reaction. Components must be combined in the specified proportions for which they were formulated and in the manner specified by the supplier in order to achieve complete curing to a film with optimum properties **(Figure 7).** Sometimes, an "induction period" (also referred to a "sweat-in time") is required after mixing and before application to permit the reaction to occur for a short time before application. After mixing, there is always a "pot life" during which the coating must be applied. After that time, the curing reaction will have advanced so far that the coating cannot be properly applied or develop adequate bonding to the substrate, which may be a prepared metal or concrete surface or a previously applied coating.

Common examples of coatings that cure by chemical reaction of separately packaged components are:

- Epoxies
- Coal tar epoxies
- Polyurethanes
- Polyesters
- Polyureas
- Siloxanes

Polyurethanes are also available in a one-component form (so-called moisture curing polyurethanes) that cure by reaction with moisture in the atmosphere.

Some thermosetting coatings (e.g., baked phenolics and powder coatings) require heat for curing.

Convertible coatings usually have good chemical and solvent-resistance, but they are difficult to topcoat when fully cured, because topcoat solvent cannot "bite" into them to bond tightly. Topcoats therefore should be applied to convertible coatings before the undercoat within the topcoating time window specified by the manufacturer.

Inorganic zinc-rich coatings also cure by chemical reaction, and are thus classified as convertible coatings. There are, however, various inorganic zinc-rich formulations, which cure by different mechanisms.[4-5] Some of these are described here:

- Post-cured water-borne alkali silicate formulations cure by water evaporation followed by neutralization with acidic solutions sprayed over them
- Self-cured water-borne alkali silicate formulations cure by water evaporation followed by reaction with carbon dioxide in the atmosphere
- Alkyl silicates cure by solvent evaporation followed by hydrolysis with water from the atmosphere. Thus, on very dry days, they may have to be sprayed with a fine mist of water, after solvent evaporation, to

promote curing

Organic zinc-rich coatings may be convertible or non-convertible, depending on the mechanism of curing of their organic binders. For example, zinc-rich epoxies and polyurethanes cure by chemical reaction and are thus convertible, while zinc-rich vinyls and chlorinated rubbers cure by solvent evaporation and are thus non-convertible.

Summary

The three basic components of coatings are solvent, binder, and pigment. The binder is the film-forming component of the coating. The solvent is used to dissolve the binder materials and/or modify coating viscosity. The pigment is the solid portion of the coating. It can impart a variety of performance properties to the coating. A coating may also contain additives that impart other special properties to it.

There are many ways to describe coating films. Those that form protective films by simple evaporation of organic solvent or water without chemical change may be called non-convertible or thermoplastic. They are generally solvent soluble and include lacquers and latex coatings.

Those coatings that form protective films by chemical change may be called convertible or thermosetting. The chemical change may be air oxidation of unsaturated drying oils, reaction with another coating component or water or carbon dioxide in the air. Some types of chemical change require heating. Convertible products include modified and unmodified drying oils, epoxies, coal tar epoxies, polyurethanes, polyesters, polyureas, siloxanes, and inorganic zinc-rich coatings. Their cured films are generally solvent insoluble.

References

1. *Protective Coatings Glossary;* Drisko, Richard W. ed.; SSPC: Pittsburgh, 2000.
2. Hare, Clive H. The Chemistry of Film Formation. In *Protective Coatings, Fundamentals of Chemistry and Composition;* Technology Publishing Company: Pittsburgh, 1994.
3. Drisko, Richard W. Total Protective Coatings Program. In *Proceedings of SSPC '96.*
4. Munger, Charles G. *Corrosion Prevention by Protective Coatings;* NACE: Houston, 1986, pp 72-73.
5. SSPC Paint Specification No. 20. *Steel Structures Painting Manual, Vol. 2;* SSPC: Pittsburgh, 1995, p 281.

About the Authors

Dr. Richard W. Drisko

Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society for Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy's center of expertise on coatings for shore structures. He is a professional corrosion engineer in the state of California, an SSPC certified protective coating specialist (PCS), and a NACE International certificated c orrosion specialist. Dr. Drisko received his BS, MS, and PhD degrees from Stanford.

James F. Jenkins

James F. Jenkins retired in 1995 after 30 years of service to the U.S. Navy in corrosion control for shore and ocean-based facilities. Now a consultant, he is a registered corrosion engineer in the state of California. Mr. Jenkins received his BS degree in metallurgical engineering from the University of Arizona.

Chapter 1.6
Cathodic Protection of Coated Structures

James F. Jenkins and Richard W. Drisko

Introduction

This chapter describes the mechanisms and applications of cathodic protection systems for corrosion control. It also describes how cathodic protection is utilized in conjunction with coatings. Cathodic protection is a technique that can be applied to structures that are exposed to a continuous bulk electrolyte, i.e., structures that are immersed in water or buried in soil. These structures are usually coated, and the coating used can the influence the design and performance of the cathodic protection system. Likewise, the cathodic protection system can affect the performance of the coatings.

Cathodic protection has been used for over 150 years to protect submerged metal surfaces and for over 75 years in the control of underground corrosion. In 1824, Sir Humphrey Davy described how he determined the nature of the corrosion that was attacking the copper sheeting used to prevent fouling of the hulls of the Royal Navy, and how he attached zinc and iron anodes to control the corrosion. This technology was developed further in the late 1800s when iron ships were introduced.

Cathodic protection systems for underground structures were developed in the early 20th century to control corrosion caused by the newly developed electric systems used to propel railways and provide power for other sources. Cathodic protection for underground structures was developed further in the 1920s to protect the great number of long-distance pipelines that were installed during this period, primarily for the transportation of crude oil and petroleum products. Today, cathodic protection is widely used to protect ships, waterfront structures, underground pipelines and tanks, and the interiors of water storage tanks.

The use of cathodic protection combined with protective coatings has proven to be both effective and practical for the control of corrosion. This combination of corrosion control measures is now required by law for some systems such as underground pipelines and tanks containing hazardous materials, where leaks can cause severe environmental damage or hazards to people and property.

Mechanism of Cathodic Protection

To understand how cathodic protection works, it is necessary to return to the electrochemical cell that is responsible for corrosion activity on metals. In this electrochemical cell, depicted in Figure 1, an electrical current flows through the metallic path between the anode and the cathode. This current is a product of the anodic reaction:

$$M^o \rightarrow M^+ + e^-$$

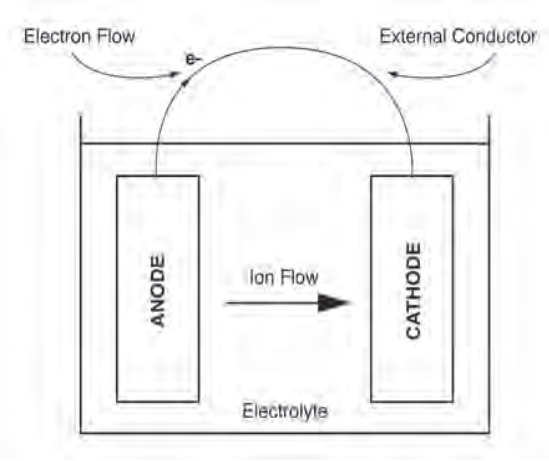


Figure 1. Electrochemical cell.

Cathodic protection prevents this current from flowing by applying counteracting electrical currents to both the original anode and cathode areas. The counteracting electrical current causes the surface of the metal to become more negative than it that would be from the previous anodic reaction; and, since electrons can only flow from a more negative to a less negative site, this inhibits the anodic reaction. (In order for the anodic reaction shown above to proceed, the electrons produced must be able to flow away from the reaction site.) Thus, with cathodic protection, the entire surface of the metal acts as a cathode and corrosion is

reduced or can even be effectively stopped. This mechanism of corrosion protection is depicted in **Figure 2.**

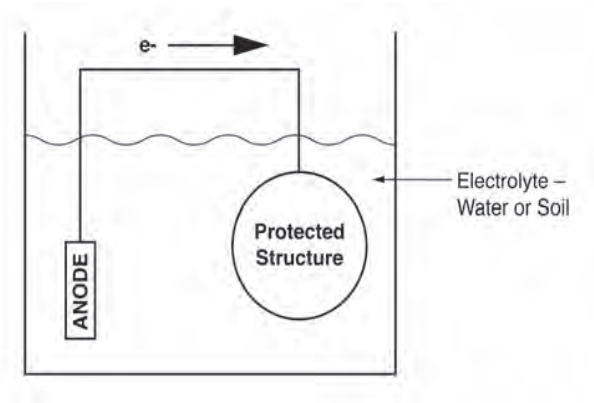


Figure 2. The electrochemical cell in cathodic protection. The protected structure acts as a cathode.

In cathodic protection systems, the counteracting electrical current can be supplied by the corrosion of a metal that is more active than the metal being protected. This is commonly called a galvanic anode or sacrificial anode cathodic protection system. The counteracting electrical current can also be supplied by an external power source.

The electrochemical cell in cathodic protection. The protected structure acts as a cathode. No corrosion on protected structure as electrons that would be produced by corrosion reaction ($Fe^{o} \rightarrow Fe^{++} + 2e^{-}$) cannot flow from structure to anode due to voltage gradient.

This is commonly called an impressed current cathodic protection system. Although these two types of systems contain different components, they both control corrosion activity by the same mechanism, i.e., by controlling corrosion activity at anodic sites on the structure being protected. The different types of cathodic protection systems are discussed later in this chapter.

It should be noted that both types of cathodic protection systems discussed here require that the structure being protected be immersed in an electrolyte. This is necessary in order for the protective current to flow from the cathodic protection system to the structure being protected. Under immersion conditions, such as on ship hulls and the interior of water storage tanks, the water provides this electrolyte path. Underground, moist earth provides the electrolyte path. Since air is not an effective electrolyte, structures exposed to the atmosphere cannot be effectively protected by the types of cathodic protection systems described in this chapter. However, some coatings can provide a type of localized cathodic protection in the atmosphere, where moisture from the atmosphere serves as the electrolyte.

Cathodic Protection and Protective Coatings

Coatings are almost always used in conjunction with cathodic protection systems in both underground and immersion conditions. When coatings are used, the amount of electrical current required for cathodic protection is reduced dramatically. This applies to both sacrificial anode and impressed current systems. Even a coating in poor condition can cut current requirement by 80% to 90%. This reduction in current reduces the cost and extends the life of the cathodic protection system. It can also reduce undesirable side effects such as stray currents, which can occur when large amounts of current are required.

Cathodic protection can have both beneficial and adverse effects on the performance of protective coatings, depending on the situation encountered.

Beneficial Effects of Cathodic Protection on Coatings

One beneficial effect when coatings are used in conjunction with cathodic protection is that holidays present in the coating and the coating deterioration that inevitably occurs with time do not result in local metal loss. In addition, because corrosion at holidays and defects is controlled, there is no undercutting of the coating at these areas.

Adverse Effects of Cathodic Protection on Coatings

If the cathodic protection system is not properly designed and operated, or if the coating system is not properly selected to be compatible with cathodic protection, three problems may arise:

Deterioration of Coatings with Limited Alkali Resistance. Deterioration of coatings (saponification) may occur, if they are not sufficiently resistant to the alkaline conditions present at cathodic areas. Since the entire exposed surface of the cathodically protected metal acts as a cathode, the hydroxide (OH^{-}) ions produced by the cathodic reaction will cause the

surface of the structure being protected to become more alkaline. If the coating used is not resistant to this alkalinity, it can be damaged and can fail. Oil-based paints such as alkyds are particularly susceptible to damage by the alkalinity produced by cathodic protection systems. This damage can occur even under normal operation of the cathodic protection system.

Disbonding of Coatings by Hydrogen Evolution. Disbonding of coatings may result from the generation of hydrogen at the metal-coating interface where there is excessive protective current. If the amount of current applied is excessive, hydrogen can be generated on the surface of the structure being protected. This can cause disbondment and premature failure of the coatings used. However, if the cathodic protection system is properly designed and operated, the evolution of hydrogen can be prevented.

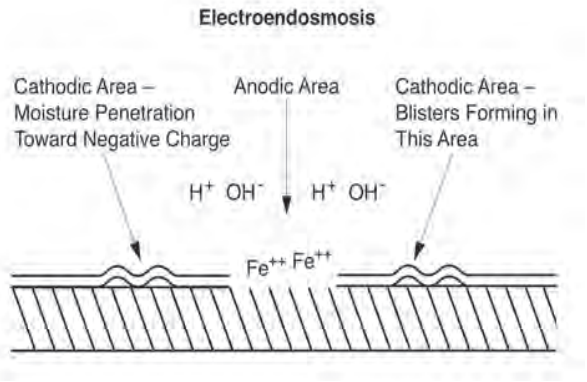


Figure 3. Mechanism of electroendosmosis.

Electroendosmosis. Deterioration of the coatings may result from electroendosmosis.[1] The flow of current at the surface of a coated structure can also cause an increased ion flow, called "electroendosmosis," in some coatings **(Figure 3).** Electroendosmosis can cause failure of coating systems that are not resistant to this form of coating damage. In general, the less permeable coatings such as epoxies are more resistant to electroendosmosis than the more permeable coatings such as oleoresinous phenolics.

Specific tests, such as American Society for Testing and Materials (ASTM) G8, G9, G19, G42, G80, and G95 can be used to evaluate the resistance of coatings to damage such as alkalinity damage, cathodic disbondment, and electroendosmosis.[2-7]

Types of Cathodic Protection Systems

Sacrificial Anode Systems

As described above, a sacrificial anode system uses the corrosion of a more active metal to control the corrosion of a less active metal. The most commonly used metals for galvanic anodes are magnesium, aluminum, and zinc. Magnesium and zinc are most commonly used underground; all three are commonly used in fresh water and seawater. The anodes can be either directly attached to the structure to be protected, as shown in **Figure 4,** or located a small distance away, as shown in **Figure 5.** Directly attached anodes are most commonly found under immersion conditions and remote anodes are most commonly used underground.

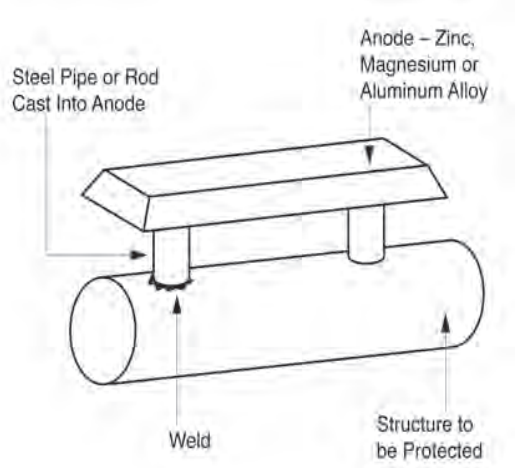


Figure 4. Sacrificial anode attached to structure to be protected.

Since the anodes are consumed in providing the protective current, they have a limited life. In the case of ships and many other immersion conditions, the consumed anodes are removed and new anodes are installed periodically. In underground systems, new anodes are installed when the old ones are consumed. This is determined by a reduction in current output.

Impressed Current Systems

Impressed current cathodic protection systems are similar to sacrificial anode systems in that the electrical currents used for corrosion control flow from one or more anodes to the structure to be protected. However, in impressed current systems, direct current electrical power is used to control the magnitude and

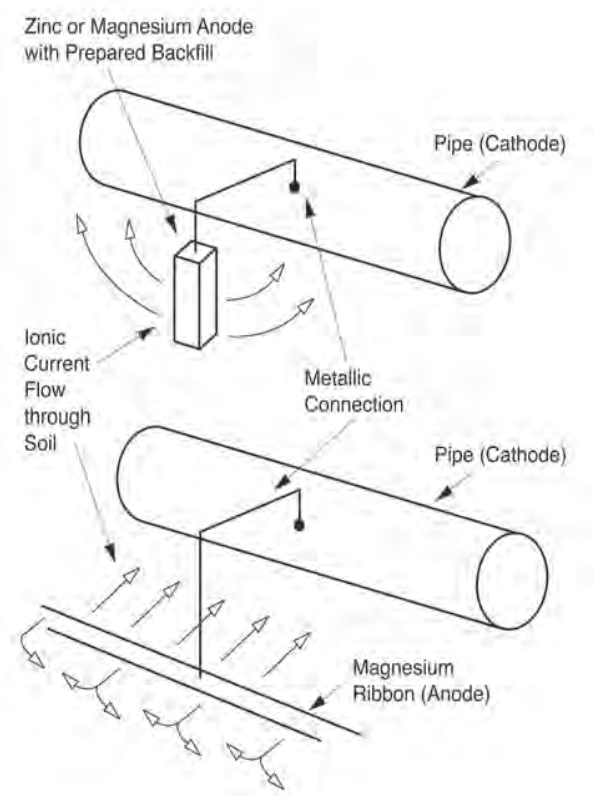


Figure 5. Sacrificial anodes a short distance from protected pipe.

direction of the current flow used for cathodic protection; thus materials that are less active than the material to be protected can be used as anodes. Such materials include graphite, high silicon cast iron, platinum, and ceramics, all of which can act as an anode with a minimal amount of corrosion. Graphite and high silicon cast iron are commonly used in underground installation. High silicon cast iron, platinum, and ceramics are commonly used in fresh water and seawater applications.

Rectifiers **(Figure 6)** that convert alternating current grid power to direct current are most commonly used to supply and control the current in impressed current cathodic protection. However, solar power, wind energy and batteries are used in special circumstances, especially where grid power is not readily available.

Figure 7 shows an impressed current system for protection of an underground pipeline. **Figure 8** shows an impressed current system for the protection



Figure 6. Rectifier for cathodic protection system.

of a ship. **Figure 9** shows an impressed current system for protection of pier piling. Many variations on these installations as well as other types of installations are found in the field.

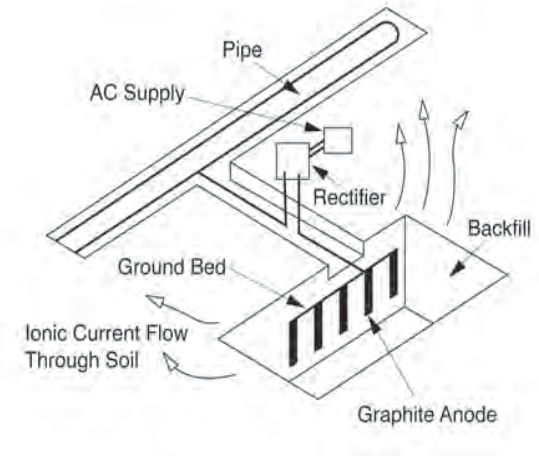


Figure 7. Impressed current system for protection of an underground pipeline.

Cathodic Protection Criteria

Since both sacrificial anode and impressed current cathodic protection systems are electrical circuits, electrical measurements can be used to evaluate their activity. By the measurement of electrical potentials at various locations within the circuit, the effectiveness of the system can be measured. Both theory and practice have shown that several criteria can be used to determine whether or not the cathodic protection system is effectively controlling corrosion. The electrical criteria are also used to adjust the system so that the structure being protected receives adequate but not excessive current, and to diagnose problems within the system. Although the equipment

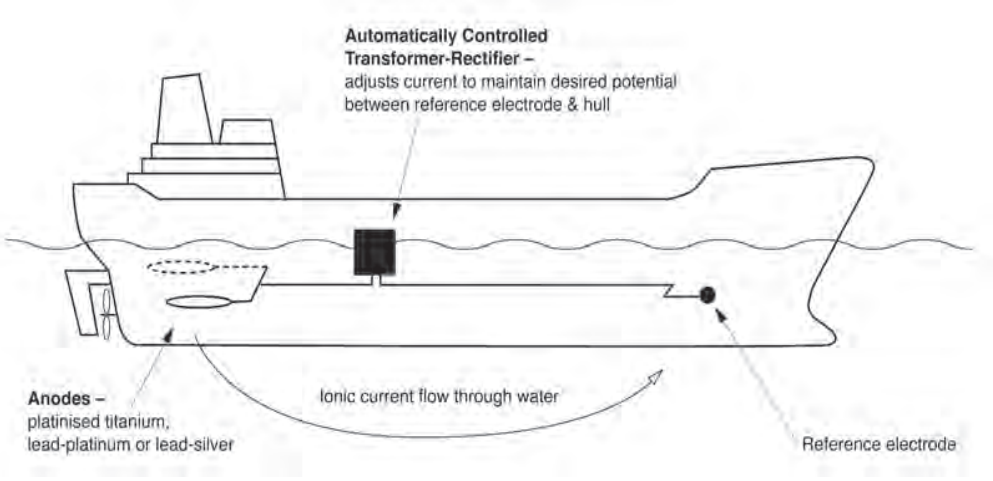


Figure 8. Impressed current system for the protection of a ship hull.

and techniques used to perform these tests and the evaluation of the measurements are relatively simple, they are beyond the scope of this text. References 8 and 9 give a good overview of cathodic protection testing.

Cathodic Protection System Design and Installation

Methods for the design of cathodic protection systems can be complex, but all are aimed at answering three basic questions:

- How much current is required?
- How can that current be most economically provided?
- How should the protective current be distributed over the structure?

Current Requirement

The amount of current required for cathodic protection can either be based on past experience or on actual measurements. The amount of current required to protect a specific exposed area can be estimated based on past experience. The current required to protect the new structure is then calculated based on its overall exposed area. Another method requires that the structure to be protected be installed and electrical measurement be performed to directly determine the required current for protection.

How to Provide Estimated Current

Sacrificial Anodes. If sacrificial anodes are to be used, an anode material must be chosen and the number and size of anodes required must be determined. Anode life can also be calculated. The material used and size of the anodes can then be adjusted to provide the required current for the desired anode life at the least overall cost.

The choice of anode material and the number and size of anodes required will depend on the corrosivity of the environment, a property that is a function of resistivity of the electrolyte (i.e., the ability of the electrolyte to inhibit the flow of electrical charge). The resistivity of liquids and moist earth can be easily measured, and can be used to calculate the output from a single anode of a given size and material. The number of anodes required is then obtained by dividing the total required current by the output from a single anode.

Anode life can be calculated based on the amount of active material present in the anode and the current provided. (The weight of anode material being consumed is proportional to the amount of current being provided.)

Impressed Current Systems. If an impressed current system is to be used, the system is designed as a simple direct current circuit. The most important variables in this circuit are the resistances of its components, in particular the resistance of the anode component, which is dependent on the number and size of anodes used and the resistivity of the environment. A low overall resistance is desirable, since this will reduce the amount of voltage required to provide

the required current. For a given current requirement, a lower overall resistance and resultant lower voltage will result in lower power costs.

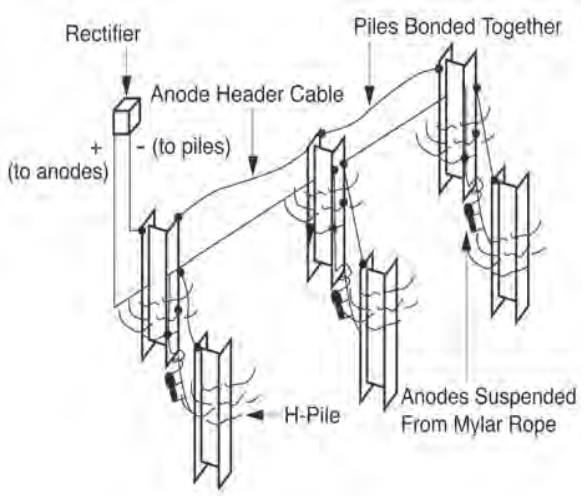


Figure 9. Impressed current system for protection of pier piling.

In underground anode installations, an electrically conductive material such as coke breeze is placed around the anodes. This can reduce their electrical resistance somewhat by increasing their effective size. Further reduction of the resistance of the anodes requires the installation of more or larger anodes. If more or larger anodes are necessary, their expense must be balanced with the increased cost of the rectifier and power costs associated with higher voltages. As in the case of the sacrificial anode system, these factors are balanced in the overall design of the system to minimize cost while maintaining effective protection.

System Configuration

The details of the configuration of sacrificial anode systems can vary considerably. Figure 5 shows a typical configuration of a sacrificial anode for the protection of a pipeline. In this system, a resistive shunt is placed in the wire from the anode to the pipeline, allowing the current to be easily measured. This, along with potential measurements, allows for easy inspection of the system to determine if it is operating properly.

Figure 7 shows a typical configuration of an impressed current system for the protection of an underground pipeline. In this case, the distance between the anodes and the pipeline is much greater than it is in the sacrificial anode system described above. The remote location of the anodes is desirable in this case where one anode bed is used to protect a very long section of pipe because it allows for more even distribution of the current along the pipeline. It should be noted that the rectifier is located close to the anode bed. This is commonly done to minimize the length of the wire between the anodes and the rectifier, which can suffer rapid anodic corrosion if its insulation is damaged, a typical mode of failure of impressed current cathodic protection systems.

Inspection and Maintenance of Cathodic Protection Systems

Cathodic protection systems require periodic inspection and maintenance. In the case of sacrificial anode systems, the requirements are minimal. A typical inspection program will involve electrical measurement of the potential of the structure at several points within the system every six to twelve months. In many cases, “test stations” for performing these measurements are installed as a permanent part of the system. Potential readings obtained from test stations can indicate problems within the system and the need for a more thorough survey consisting of potential measurements at more points on the structure and current output measurements on the anodes of the system. The most common cause of problems in sacrificial anode systems is consumption of the anodes and breakage of the wires from the anodes to the structure.

Impressed current systems require more frequent inspections. A typical inspection program will involve monthly inspections of the rectifiers to determine the amount of current and voltage being provided. At intervals of from six months to one year, these readings need to be augmented by structure potential measurements at selected points within the system. As in the case of sacrificial anode systems, evaluation of these readings is used to determine if problems exist within the system and if additional tests are required.

Summary

Cathodic protection is a method of corrosion control in which an applied electrical current is used to make cause the structure to be protected to act as a cathode. The structure to be protected must be

exposed to a bulk electrolyte such as by burial in soil, encasement in concrete, or immersion in water. Cathodic protection can be more readily used to protect coated structures than bare structures. This is because only the uncoated portions of the structure, such as holidays, require protection and the intact coating acts as an electrical insulator, reducing the amount of current required.

Cathodic protection, properly applied, can benefit the performance of coatings. However, if improperly applied, cathodic protection can have adverse effects on coatings.

There are two types of cathodic protection systems. In the sacrificial anode system, an active metal is used as an anode, and the potential between the active metal and the structure being protected forces the protective current to flow. In the impressed current system, an external power source is used to force the protective current to flow, and less active materials can be used as anodes, thus increasing anode life.

Cathodic protection systems must be properly designed, installed, operated, and maintained to provide adequate control of corrosion without causing damage to the structure being protected or the coatings on it. Properly designed, installed, operated, and maintained cathodic protection systems, particularly when combined with protective coatings, are an effective and widely used form of corrosion control.

References

1. Hare, C. H. Non-Osmotically Induced Blistering Phenomena on Metal. *Journal of Protective Coatings and Linings*, March 1998, p 17.
2. ASTM G-8. *Test Method for Cathodic Disbonding of Pipeline Coatings;* ASTM: West Conshohocken, PA.
3. ASTM G-9. *Test Method for Water Penetration into Pipeline Coatings;* ASTM: West Conshohocken, PA.
4. ASTM G-19. *Test Method for Disbonding Characteristics of Pipeline Coatings by Direct Soil Burial;* ASTM: West Conshohocken, PA.
5. ASTM G-42. *Test Methods for Cathodic Disbondment of Pipeline Coatings Subjected to Elevated Temperatures;* ASTM: West Conshohocken, PA.
6. ASTM G-80. *Test Method for Specific Cathodic Disbonding of Pipeline Coatings;* ASTM: West Conshohocken, PA.
7. ASTM G-95. *Test Method for Cathodic Disbondment of Test of Pipeline Coatings (Attached Cell Method);* ASTM: West Conshohocken, PA.
8. Morgan, J. H. *Cathodic Protection, 2nd Edition;* NACE: Houston, 1987.
9. Peabody, A.W. *Control of Pipeline Corrosion;* NACE: Houston, 1967.

About the Authors

James F. Jenkins

James F. Jenkins retired in 1995 after 30 years of service to the U.S. Navy in corrosion control for shore and ocean-based facilities. Now a consultant, he is a registered corrosion engineer in the state of California. Mr. Jenkins received his BS degree in metallurgical engineering from the University of Arizona.

Dr. Richard W. Drisko

Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society for Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy's center of expertise on coatings for shore structures. He is a professional corrosion engineer in the state of California, an SSPC certified protective coatings specialist (PCS), and a NACE International certificated corrosion specialist. Dr. Drisko received his BS, MS, and PhD degrees from Stanford.

Chapter 1.7
Coating Galvanized Steel

Richard W. Drisko

Introduction

Galvanizing is merely a coat of zinc metal. It has been used for more than 150 years to protect steel from corrosion. Typical examples of galvanized structures are highway guard rails and antenna towers. The thickness of the zinc layer and the prevailing weather influence the period of corrosion protection galvanizing provides.

The zinc can be applied to steel by hot dipping, electrodeposition, thermal spraying, sheradizing (tumbling cleaned steel items such as fasteners with powdered zinc), application of zinc-rich coatings, and other methods. Hot dipping cleaned steel into molten zinc has the unique feature of forming a metallurgical bond between the zinc and the steel. A typical hot dip galvanizing consists of three zinc-iron alloy layers plus the surface layer of metallic zinc.

More recently, galvanizing has been coated with conventional organic coatings, a duplex system, to enhance its appearance and to extend the period of corrosion control.[1] Tall galvanized structures, such as towers and tanks, may require alternating bands of orange and white to meet Federal Aviation Agency (FAA) criteria for visibility. This chapter describes currently used methods of preparing galvanized steel surfaces for coating and applying protective coatings to them.

Mechanisms of Protecting Steel by Galvanizing

There are two basic mechanisms of protecting steel by galvanizing: barrier and galvanic protection. Barrier protection by the impermeable zinc coating isolates the underlying steel from the electrolytes that are necessary for corrosion to occur. In galvanic protection (a type of cathodic protection), the more chemically active zinc sacrifices itself by preferential corrosion to protect the steel. It converts all the anodes on the exposed steel to cathodes.

The length of protection time zinc coatings provide is directly proportional to the weight of the zinc.[2] The weight of galvanizing is generally specified in ounces of zinc metal/ft.^{2} Typically, electrogalvanizing has less than 0.3 oz./ft.^{2} of metal substrate (equivalent to 0.5 mil; 13 micrometers dry film thickness), while hot dip galvanizing has a minimum of 2 oz./ft.^{2} (3.4 mils; 27.4 micrometers). Hot dip galvanizing on structural steel typically has a weight of 2.1 to 2.9 oz./ft.^{2} (3.5 to 5.0 mils; 89 to 127 microns dry film thickness) of zinc. One half of this thickness is zinc metal and the other half is zinc-iron alloy layers.

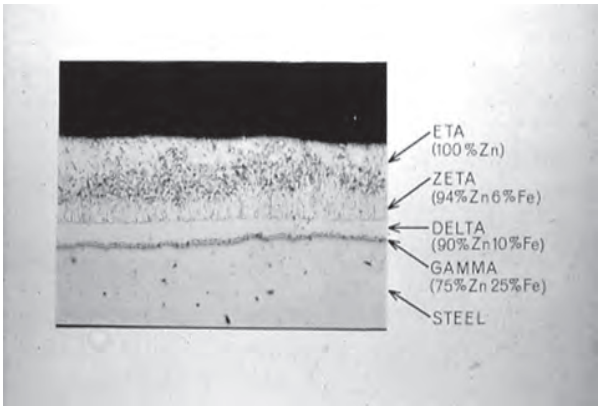


Figure 1. Galvanizing layers.

Hot Dipping

Steel surface preparation is the most important component of successful galvanizing. The vast majority of galvanizing failures are associated with inadequate or improper surface preparation. The typical three-step process for cleaning and treating the surface of uncoated steel for hot dipping consist of:

- **Caustic Cleaning.** Uncoated steel is dipped into a solution of hot alkali to remove grease, oil, and dirt. (Coated steel must be abrasive blasted to remove the coatings. Abrasive blasting cleans the steel surface so that it does not require alkali cleaning or acid pickling before fluxing.)
- **Acid Pickling.** After rinsing the alkali-cleaned steel, it is dipped into a dilute solution of hot sulfuric acid or an ambient temperature solution of hydrochloric acid.
- **Fluxing.** After rinsing pickled steel, it is ready for fluxing to remove any remaining oxides, prevent their

formation prior to hot dipping, and enhance adhesion of the zinc. In the dry galvanizing process, the cleaned steel is dipped into an aqueous solution of zinc ammonium chloride and then thoroughly dried before immersion in the molten zinc. In the wet galvanizing process, a blanket of molten zinc ammonium chloride is used for fluxing.

During the actual hot dipping, the cleaned metal is completely immersed in 98% pure molten zinc metal maintained at a temperature of 850°F (450°C). The requirements for the purity of the zinc metal are found in ASTM A 123.[3]

Articles too long for complete immersion in the molten zinc can be double-end dipped to provide a continuous zinc coating. Also, special facilities are available for continuous galvanizing of sheet metal rolls and wire. Cables consisting of stranded galvanized wires are used extensively for guy lines and other industrial purposes.

Inspecting Galvanizing and Repairing Defects

Inspection

After the hot dipping process, the coated items are inspected to determine whether they meet all industry standards:

- **Visual.** Bare spots, runs, surface irregularities, flux inclusions, etc.
- **Dry Film Thickness.** Using gauges and methods described in SSPC-PA 2[4]
- **Adhesion.** Using the equipment and methods described in ASTM A 123 and ASTM A 153[3, 5]

Touch-Up of Repairable Galvanizing

Defects may arise in the hot dipping process or in later shipment and handling. ASTM A 123 defines the amount of bare spots and other imperfections on galvanizing that can be repaired by touch-up to achieve an acceptable condition.[3] Methods of defect repair include:

- Metallizing with zinc.
- Zinc-rich organic coatings. Described in SSPC-Guide 14.[6]
- Soldering with zinc-based alloys. Zinc-based alloys in stick or powder form are applied to the defect area preheated to about 650°F (315°C).

Additional information concerning the "galvanizing process can be found in various AGA publications from which information was taken for the description of galvanizing in this chapter.[7]



Figure 2. Galvanizing bath.

Surface Treatment for Storage

While galvanizing may provide many years of protection to steel in open atmospheric service, wet storage staining may occur on galvanized articles (e.g., a stack of galvanized steel siding) stored in a damp exterior exposure where there is limited air circulation. This condition is caused by the accelerated (crevice) corrosion of the zinc to form white oxidation products, mostly zinc hydroxide. Galvanizers may provide protection from wet storage stain by applying a thin film of oil to the galvanizing or by formation of a chromate conversion coating. Both treatments must be addressed before a coating is applied. Thus, purchasers of galvanized steel to be coated should specify that these surface treatments not be given to their products.

Oil Coating. The presence of oil contamination can be detected using the water-break test.[8] A mist of water is sprayed on the surface of the galvanizing. If the water

gathers in lens that last about 25 seconds before they flow out (break), the surface is clean. If the water gathers up into droplets, the surface is contaminated.

A coating or trace contamination of oil can be removed by solvent cleaning (SSPC-SP 1).[9] This specification includes cleaning with mineral spirits and high-flash naptha or with an alkaline solution of pH 11 to 12.

Chromate Conversion Coating. The presence of a zinc conversion coating on galvanizing can be detected by spot testing according to ASTM B 201.[11] If detected, it can be removed by light sanding or sweep blasting or by allowing the galvanizing to weather for six months.



Figure 3. Rusting and streaking through galvanizing.

Removing Wet Storage Stain

Wet storage stain must be removed from galvanizing before it is coated. Light brushing of the stain using a soft bristle brush and a mild ammonia solution will usually remove light or mild staining. For more severe cases, more vigorous brushing with weak acids such as acetic or citric acid at pH 3.5 to 4.5 may be necessary. Strong mineral acids should not be used, because they will rapidly attack the zinc.

The Changing Surface Composition of Galvanized Surfaces

The surface of zinc begins to change immediately after galvanizing by corrosion to form a passive zinc oxide layer. In the presence of moisture, the oxide layer is converted into zinc hydroxide. This layer, in turn, slowly reacts with carbon dioxide in the air to form a stable, tightly-bonded layer of zinc carbonate. The recommended surface treatment of galvanizing for coating varies with its age and thus surface chemical composition.[11-12]

Treating New and Partially Weathered Galvanizing for Coating

Prior to surface treatment of new and partially weathered galvanizing for coating, any surface irregularities (rough edges, high spots, etc.) are usually removed by hand or power tool cleaning to permit a more uniform, continuous coating application.[13-14] However, too smooth a surface may result in limited coating adhesion.

Surface treatment and coating application is best done in a shop under controlled conditions. Some paint shops merely clean the surfaces of new galvanizing prior to coating. Other applicators feel that one or more of the treatments described here is necessary to achieve good coating adhesion and performance. Applicators routinely coating galvanized steel should determine the procedure that is best.

Mechanical Treatments to Prepare Galvanized Surfaces for Coating

- **Hand and Power Tool Cleaning.** Hand and power tool cleaning can be used to remove light surface contaminants. However, it does not produce a surface profile to enhance adhesion of coatings.
- **Sweep Blasting.** Sweep blasting is defined as a fast pass of the abrasive blasting pattern over a surface to remove loose material and to roughen the surface sufficiently to successfully accept a coat of paint.[15] This can be used effectively on galvanizing if the abrasive and the blasting conditions are selected to avoid excessive loss of zinc metal. These are described more fully in ASTM D 6386.[11]

Chemical Treatments

There are three basic treatments for preparing clean galvanized surfaces for coating by controlling corrosion of the zinc surface and providing a substrate that will result in better coating adhesion. Old remedies such as washing with vinegar should be avoided.

- **Zinc Phosphate Conversion Treatment.** A zinc phosphate conversion coating can be obtained by reacting new galvanizing with an acidic zinc phosphate solution containing an oxidizing agent and accelerators. Brush, spray, or immersion application can be used successfully. After application, a period of 3 to 6

minutes should be allowed before rinsing. Some shops routinely use commercial phosphate treatment products on galvanizing before coating.

• **Acrylic Passivation Treatment.** Acrylic passivation is accomplished by treating the cleaned surfaces with an acidic acrylic solution. The 0.04 mil (1 µm) coating provides passivation to the zinc and promotes coating adhesion.

• **Wash Primers.** Polyvinyl butyral wash primers such as SSPC-Paint 27 have been used as pretreatment for galvanizing before coating for many years. The acid in the wash primer neutralizes the alkalinity in the zinc corrosion products and etches the surface to promote adhesion. It is best applied by spraying, because it is more difficult control film thickness when brush, dip, or roller coating. There are several concerns about the use of wash primers. These include:

–Criticality of the coating film thickness. The dry film thickness should be between 0.3 and 0.5 mils (8 and 13 micrometers). If less, the protection may be significantly reduced; if more, cohesive failure may occur.

–Presence of toxic chromate pigment.

–High VOC content.

Surface Treatment of Fully Weathered Galvanizing

Fully weathered galvanizing has a stable surface texture suitable for coating. Complete weathering may require only six months in a severe marine atmospheric environment, or up to two years in a mild environment. Fully weathered galvanizing requires only that the surface be cleaned of loose contaminants before coating. Some applicators prefer power washing with warm water at a pressure less than 1450 psi (10 MPa) to avoid damage to the zinc carbonate protective film. Others feel that sweep blasting is more convenient and that the loss of zinc is minimal.

Old uncoated galvanizing may have pinpoint rusting and rust streaking. The exposed rust should be removed from the steel by hand or power tool cleaning and the rust streaking removed by power washing.

If uniform corrosion of the zinc occurs, a reddish-brown layer of zinc-iron alloy may be exposed. This indicates that all of the pure zinc has been lost, and coating for additional protection is appropriate.

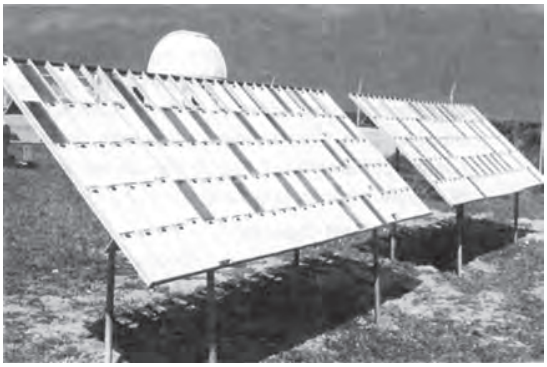


Figure 4. Exposure racks in Bermuda with coated galvanized steel test panels.

Coating Systems for Galvanizing

Two generic coating systems were shown in long-term exposure studies to perform well in severe marine atmospheric environments. Obviously, they will protect steel even longer in milder atmospheric environments.[16]

Epoxy Primer with Ultraviolet-Resistant Finish Coats

A system of one coat each of epoxy polyamide primer and aliphatic polyurethane performed well for more than 5 years in two different marine atmospheric environments (Bermuda and Cape Canaveral, Florida). The aliphatic polyurethane provided excellent resistance to ultraviolet light.

An alternative system using an acrylic latex finish coat rather one of aliphatic polyurethane also performed well. Application of a tightly bonded acrylic finish coat, however, was more difficult than with the polyurethane finish.

Acrylic Latex System

Two coats of an acrylic latex also performed well in the above study, but not quite as well as the epoxy primer systems. This system had the advantages of being easier to apply and touch-up.

Other Coating Systems

Alkyd and Other Drying Oil Systems. At one time, standard alkyd systems, including those containing zinc dust/zinc oxide pigmentation (e.g., TT-P-641), were used extensively on galvanizing. These systems failed relatively quickly because the naturally occurring alkalinity on the zinc surface saponified (hydrolyzed)

the drying oils in the coatings. Pretreatment with wash primer did increase performance slightly but not to the levels of the two systems previously described.

Lacquers. Vinyl, acrylic, and chlorinated rubber lacquer coatings have been successfully used on galvanizing in the past. However, because of their high contents of volatile organic compounds (VOCs), they are seldom used today.

Bituminous (Coal Tar and Asphalt). Bituminous (coat tar and asphalt) coatings are not recommended for exterior service because they become embrittled by the sun's ultraviolet light. They are, however, quite suitable for burial service.

Maintenance of Coatings on Galvanizing

As far as possible, coatings applied to galvanized structures should receive periodic maintenance, so that the underlying zinc remains protected:

- If only chalking or soiling occurs on the organic coating, it can readily be cleaned by detergent washing and coated with a compatible (usually the same) finish coating. It is usually not necessary to sweep blast the weathered coating for good topcoat adhesion. A coat of acrylic latex can be used to restore the appearance of a weathered coating to an acceptable condition.
- If the organic coating peels, the loose coating must be removed before repairs can be made. Careful sweep blasting can usually accomplish this without too much loss of zinc. The maintenance coating must be compatible with the existing finish coat and any exposed zinc.
- If corrosion of the galvanizing has exposed rusted steel, the rust must be removed by hand or power tool cleaning or by localized abrasive blasting. Again, the maintenance coating must be compatible with all exposed substrates.

References

1. Eijnsbergen, J.F.H. *Duplex Systems—Hot-Dip Galvanizing Plus Painting;* Elsevier Science: Amsterdam, 1994.
2. Brevort, Gordon H. Inorganic Zinc-Rich Coatings vs. Galvanizing. *Modern Steel Construction,* December 1995.
3. ASTM A 123. *Zinc (Hot-Dip) Coatings of Iron and Steel Products;* ASTM: West Conshohocken, PA.
4. SSPC-PA 2. *Measurement of Dry Coating Thickness With Magnetic Gages;* SSPC: Pittsburgh, 1996.
5. ASTM 153. *Zinc Coating (Hot Dip) on Iron and Steel Hardware;* ASTM: West Conshohocken, PA.
6. SSPC-Guide 14. *Guide for Repair of Imperfections in Galvanized or Inorganic Zinc-Coated Steel Using Organic Zinc-Rich Coatings;* SSPC: Pittsburgh, 1999.
7. American Galvanizers Association, 6881 South Holly Circle, Suite 108, Englewood, Colorado, 80112.
8. *The Inspection of Coatings and Linings;* Bernard R. Appleman, ed.; SSPC: Pittsburgh, 1997, p 380.
9. SSPC-SP 1. *Solvent Cleaning;* SSPC: Pittsburgh, 2000.
10. ASTM B 201. *Practice for Testing Chromate Coatings on Zinc and Cadmium Surfaces;* ASTM: West Conshohocken, PA.
11. ASTM D 6386. *Standard Practice for Preparation of Zinc (Hot-Dip Galvanized) Coated Iron and Steel Products and Hardware Surfaces for Painting;* ASTM: West Conshohocken, PA.
12. Smith, Lloyd M. Cleaning and Painting Galvanized Steel. *Journal of Protective Coatings and Linings*, April 2001, pp 51-55.
13. SSPC-SP 2. *Hand Tool Cleaning;* SSPC: Pittsburgh, 2000.
14. SSPC-SP 3. *Power Tool Cleaning;* SSPC: Pittsburgh, 2000.
15. *Protective Coating Glossary;* Drisko, Richard W. ed., SSPC: Pittsburgh, 2000.
16. Drisko, Richard W. Research News: A Five-Year Study Of Environmentally Acceptable Coatings for Galvanized Steel. *Journal of Protective Coatings and Linings,* September 1995.

About the Author

Dr. Richard W. Drisko

Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society for Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy's center of expertise on coatings for shore structures. He is a professional corrosion engineer in the state of California, an SSPC certified protective coatings specialist (PCS), and a NACE International certificated corrosion specialist. Dr. Drisko received his BS, MS, and PhD degrees from Stanford.

Chapter 2.1
Overview of Steel Surface Preparation

H. William Hitzrot

Introduction

Preparing steel surfaces for coating involves removing physical surface defects and contaminants and providing a surface profile satisfactory for good primer adhesion. It has been shown that steel surface profile and cleanliness have a direct relationship to coating adhesion in laboratory and field performance.[1]

Coating failures associated with inadequate surface preparation are described in separate chapter of this book.

As new surface preparation requirements for VOC-conforming coatings and new surface preparation techniques arise, so does the need for industry to utilize this information. This chapter provides an overview of surface preparation of steel for coatings. Other chapters provide more specialized information.

What Is Steel Surface Preparation?

Surface preparation is defined as any operation or series of operations performed on a steel surface to remove physical defects and surface contaminants in preparation for subsequent fabrication, repair, and/or painting.

Examples of surface preparation include removing surface defects, pre-cleaning, removing chemical contaminants, abrasive blast cleaning, waterjetting, and power tool cleaning. Surface preparation also includes meeting a specified degree of surface cleanliness as well as providing a surface profile compatible with subsequent fabrication, repair, and/or painting.

Why Is Surface Preparation Important?

The life of any steel coating system is directly impacted by the quality of the prepared surface. Thus, the better the surface preparation, the longer the life of the coating system. This also implies that the coating system generally dictates the type and extent of the surface preparation. Therefore, when selecting surface preparation procedures, always consider the requirements of the subsequent coating system.

Establishing a Surface Preparation Protocol

Thoroughly examine the steel surface before initiating any surface preparation and establish its conditions to define the things that need to be addressed in the surface preparation protocol.

Pre-cleaning

Pre-cleaning before surface preparation removes loose or soluble surface contaminants. Determine what, if any, pre-cleaning is required by considering these things:

- If the steel surface shows evidence of oil or grease contamination, treat these areas according to SSPC-SP 1, *Solvent Cleaning.*[2]
- In areas where industrial pollution is prevalent or salt contamination is likely either from ocean spray or deicing salts, the steel should be treated by low-pressure washing according to SSPC-SP 1 or high-pressure washing according to SSPC-SP 12/NACE 5 as appropriate to remove the contamination.[2, 3]
- Pre-cleaning also includes removing dirt, snow, ice, and water prior to mechanical cleaning.

Removing Surface Defects

Before initiating blast cleaning, examine the steel for surface defects, such as weld spatter, rough welds, “scabs,” and sharp edges that can cause premature coating failures if not removed. Also, if these defects are not removed, subsequent abrasive blast cleaning will exaggerate the defect, creating an even more difficult coating problem. Typical surface defects and suggested surface preparation include:

- Weld spatter is composed of little beads of steel and slag that adhere to the steel after welding. It is best removed with hand grinders per SSPC-SP 2 *Hand Tool Cleaning.*[4]
- Scabs, burrs, and sharp edges are rolling mill defects that occur on structural steel surfaces and are best removed with hand grinders or chipping hammers as described in SSPC-SP 2. If not removed, abrasive blast cleaning will exaggerate these defects, requiring

repair and reblasting of the area. Weld-up and grinding may be necessary to correct some defects.

• Grinding rough welds, weld undercuts, and other localized surface repairs can also be accomplished with the hand-tool surface preparation procedures outlined in SSPC-SP 2. Weld-up and grinding may be required to correct some defects, especially porosity and undercutting.

Abrasive Blast Cleaning

Abrasive blast cleaning is the accepted surface preparation method for cleaning large areas of steel. The primary advantage of this method is that it is fast and cost-effective and creates a roughened surface suitable for good adhesion of most coating systems. Abrasive blast cleaning removes mill scale, rust, paint, and other tough, brittle contaminants that respond well to the impact cleaning of abrasive particles.

Blast cleaning does not effectively remove oil, grease, or chemical contaminants, such as salts and chlorides. Therefore, no blast cleaning procedure should proceed until all of these contaminants have been removed during pre-cleaning. If oil, grease, and chemical contaminants are not removed, blast cleaning will spread these contaminants widely over the entire surface, contaminate the abrasive, and make subsequent contaminant removal much more difficult.

The abrasive blast cleaning parameters that affect surface preparation are:

• **Abrasive particle size:** Generally speaking, the larger the average abrasive particle size, the larger the profile produced on the blast-cleaned surface. Conversely, smaller average particle sizes produce smaller surface profiles. This assumes the use of proper techniques.

• **Abrasive velocity:** The greater the nozzle pressure or wheel-speed propelling the abrasive particle, the faster the cleaning rate.

• **Abrasive density:** The greater the density or mass of an abrasive particle, the more effective it will be in removing dense, thick coatings. Dense abrasives also produce a deeper profile.

• **Abrasive shape:** Angular abrasive particles generate an angular profile, while rounded-to-spherical particles generate a more scalloped-to-peened surface profile.

• **Abrasive hardness:** Choosing the proper abrasive hardness depends on the type of cleaning involved. For example, water is used to remove soluble salts; corn cobs and walnut shells are used to clean a coating surface without removing the coating; and metallic and nonmetallic hard abrasives are used to remove hard, tough surface contaminants such as mill scale, rust, and old paint. Generally, the tougher the surface contaminant, the harder the abrasive.

For more information on specific abrasive characteristics and their impact on surface preparation consult the chapters about metallic and nonmetallic abrasives in this book and SSPC-SP COM, *Surface Preparation Commentary for Steel and Concrete Substrates.*[5]

Wet Abrasive Blast Cleaning and Waterjetting Methods

Methods of surface preparation using water may or may not include abrasive. SSPC and NACE International have defined four levels of water cleaning and waterjetting based on nozzle pressure. These levels are defined in **Table 1** and discussed in depth in a separate chapter.

Table 1. Levels of Water Cleaning and Waterjetting.

Low Pressure Water Cleaning (LP WC)	Less than 34 MPa (less than 5,000 psi)
High Pressure Water Cleaning (LP WC)	34 to 70 MPa (5000 to 10,000 psi)
High Pressure Waterjetting (HP WJ)	70 to 210 MPa (10,000 to 30,000 psi)
Ultra High Pressure Waterjetting (UHPWJ)	Over 210 MPa (over 30,000 psi)

Low-pressure water cleaning (LP WC) is used as part of the pre-cleaning operation to remove water-soluble contaminants. High-pressure water cleaning, high-pressure waterjetting, and ultrahigh-pressure waterjetting are generally used in maintenance cleaning of previously painted surfaces.

Surface Cleanliness Standards

SSPC and NACE International have established a set of standards and reference photographs to define the various levels of surface cleanliness. A summary of these standards appears in **Table 2.**

It is clear from the range of standards shown that steel surface preparation involves the full spectrum of surface cleaning operations, including

Table 2. Surface Cleanliness Standards.

Title	SSPC Designation	Scope
Solvent Cleaning	SSPC-SP 1	Removal of oil, grease, dirt, soil, salts, and contaminants by cleaning with solvent, vapor, alkali, water, emulsion or steam
Hand Tool Cleaning	SSPC-SP 2	Removal of loose mill scale and loose paint to the degree specified, by hand chipping, scraping, sanding, wire brushing and grinding.
Power Tool Cleaning	SSPC-SP 3	Removal of loose mill scale and loose paint to the degree specified, by power tool chipping, descaling, sanding, wire brushing and grinding
White Metal Blast Cleaning	SSPC-SP 5/ NACE 1	A white metal blast cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dirt, dust, mill scale, rust, coating, oxides, corrosion products and other foreign matter.
Commercial Blast Cleaning	SSPC-SP 6/ NACE 3	A commercial blast cleaned surface when viewed without magnification shall have at least two-thirds of the surface free of all visible rust, mill scale, paint and foreign matter.
Brush-Off Blast Cleaning	SSPC-SP 7/ NACE 4	A brush-off blast cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dirt, dust, loose mill scale, loose rust and loose coating. Tightly adherent mill scale, rust and coating may remain on the surface.
Near White Blast Cleaning	SSPC-SP 10/ NACE 2	A near white blast cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dirt, dust, mill scale, rust, coating, oxides, corrosion products and other foreign matter except for slight staining.
Power Tool Cleaning To Bare Metal	SSPC-SP 11	This specification covers cleaning the surface to bare metal as opposed to SSPC-SP 2, which requires only removal of loose mill scale, rust and paint.
Cleaning Of Steel Using High & Ultra High Pressure Waterjetting	SSPC-SP 12/ NACE 5	This standard provides requirements for the use of high- and ultra high-pressure waterjetting to achieve various degrees of surface cleanliness. This standard is limited to the use of water only without the addition of solid particles into the water stream.
Industrial Blast Cleaning	SSPC-SP 14/ NACE 8	An industrial blast cleaned surface, when viewed with out magnification, shall be free of all-visible oil, grease, dust and dirt. Traces of lightly adherent mill scale, rust, coating residue are permitted to remain on 10% of each unit area (9 inches^2) of surface.
Commercial Grade Power Tool Cleaning	SSPC-SP 15	A commercial grade power tool cleaned surface, when viewed without magnification, shall be free of all visible oil, grease, dust, dirt, rust, costing, oxides, mill scale, corrosion products and other foreign matter. Random staining shall be limited to no more than 33% of each unit area (9 inches^2) of surface.
Guide and Reference Photographs for Abrasive Blast Cleaned Steel	SSPC-VIS 1	Explanatory text and photos illustrating previously painted and unpainted surfaces cleaned to SSPC-SP 7/NACE 4, SSPC-SP 14/NACE 8 (painted steel only), SSPC-SP 6/NACE 3, SSPC-SP 10/NACE 2 and SSPC-SP 5/NACE 1.
Visual Standard for Power- and Hand-Tool Cleaned Steel	SSPC-VIS 3	Explanatory text and photos illustrating previously painted and unpainted surfaces cleaned to SSPC-SP 2, SSPC-SP 3, and SSPC-SP 11. SSPC-SP 2 surfaces were cleaned using hand tools, SSPC-SP 3 and SSPC-SP 11 surfaces were cleaned using a variety of power tools.
Guide and Reference Photographs for Steel Surfaces Prepared by Waterjetting	SSPC-SP 4/ NACE VIS 7	Explanatory text and photos illustrating previously painted and unpainted surfaces before and after cleaning by waterjetting per SSPC-SP 12/NACE 5 to cleanliness levels WJ 1, 2, 3 and 4. An appendix illustrates three levels of flash rusting which may appear on surfaces cleaned with wet surface preparation materials.
Guide and Reference Photographs for Steel Surfaces Prepared by Wet Abrasive Blast Cleaning	SSPC-SP 5/ NACE VIS 9	Explanatory text and photos illustrating unpainted rusted surfaces with moderate and severe pitting before and after cleaning by wet abrasive blasting methods to WAB 6 (roughly equivalent to SSPC-SP 6/NACE 3) and WAB 10 (roughly equivalent to SSPC-SP 10/NACE 2) with three levels of flash rusting on each cleaned surface.

removing dirt and soil, oil and grease, chemical contaminants, mill scale, rust and paint—all of which require a different approach. It is important, therefore, to thoroughly examine the steel surface and determine what surface preparation procedures will be required to meet a given cleanliness level:

• Evidence of oil and grease (SSPC-SP 1)
• Spot welding produced weld spatter and some rough welds (SSPC-SP 2)
• Steel structure in an industrial area with evidence of chemical contaminants on the surface. (SSPC-SP 1 water washing or steam cleaning)
• Steel surface must be blast cleaned to meet a commercial level of cleanliness. (SSPC-SP 6/NACE 3 *Commercial Blast Cleaning*)[6]

By devising and following a surface preparation protocol, the job will proceed smoothly and minimize future surface preparation-related problems.

Surface Profile

Generating a surface profile is a consequence of any surface preparation method involving abrasive blast cleaning. It is important to know the profile requirements of the coating system to be applied to the blast-cleaned surface. For example, if the coating system requires a 2 mil profile, the blast cleaning abrasive used should generate a 2 mil profile. Test panels can be prepared prior to blasting to be certain that a given abrasive media will generate the required profile.

If surface preparation involves blast cleaning to remove an existing coating system, remember that there is an existing blast cleaned profile under the original coating. Subsequent blast cleaning to remove the original coating will change but not remove that original profile. Any new coating system should be compatible with the altered, potentially deeper profile of the reblast-cleaned surface.

Profile Measurement

The two most commonly used methods for field measurement of surface profile of blast-cleaned steel are ASTM D 4417, Method A (comparator) and C (replica tape).[7] In Method A, the blasted steel surface is visually compared to standards prepared with various profile depths. In Method C, a composite plastic tape is impressed into the steel surface profile forming a reverse image that is measured with a micrometer. These techniques are described in more detail in the inspection chapter of this book.

Environmental Impact on Surface Preparation

Such factors as job location, presence of hazardous materials, and abrasive disposal can influence the surface preparation method:

• If surface preparation occurs inside a production facility, power-tool cleaning methods may be required to minimize disruptions.
• If the job is located in a residential area and the coating being removed contains hazardous materials, containment is required during blast cleaning to minimize the environmental impact.
• If abrasive disposal after blast cleaning is a problem, use of a recyclable abrasive is dictated.

It is evident from these examples that job location plays an important role in any surface preparation process. Carefully review the surrounding environment before establishing a surface preparation protocol.

Summary

Because the life of a coating system depends on the quality of the surface preparation, it is essential to establish a surface preparation protocol that will meet the requirements of the subsequent coating system. The surface preparation protocol should begin with a careful examination of the entire project to determine the answers to these questions:

• What pre-cleaning is required?
• Are there surface defects to be removed?
• What mechanical cleaning methods—abrasive blast cleaning, high-pressure water, power tools—will be required to accomplish the job?
• What degree of SSPC specified surface cleanliness is required?
• What type of abrasive or method of mechanical cleaning will clean the steel and generate sufficient surface profile to meet the coating system requirements?
• Can the proposed surface preparation protocol comply with the environmental constraints of the job location?

Once the surface preparation protocol is established, it is then time to begin the job.

References

1. Schwab, Lee K.; Drisko, Richard W. Relation of Surface Profile to Coating Performance. In *Corrosion Control by Coatings;* Henry Leidheiser, Jr., ed., NACE: Houston, 1981.
2. SSPC-SP 1. *Solvent Cleaning;* SSPC: Pittsburgh.
3. SSPC-SP 12/NACE 5. *Surface Preparation and Cleaning of Steel and Other Hard Materials by High- and Ultra High-Pressure Waterjetting Prior to Recoating;* SSPC: Pittsburgh and NACE: Houston.
4. SSPC-SP 2. *Hand Tool Cleaning;* SSPC: Pittsburgh.
5. SSPC-SP COM. *Surface Preparation Commentary for Steel and Concrete Substrates;* SSPC: Pittsburgh.
6. SSPC-SP 6/NACE 3. *Commercial Blast Cleaning;* SSPC: Pittsburgh and NACE: Houston.
7. ASTM D 4417. *Test Method for Field Measurement of Surface Profile of Blast Cleaned Steel;* ASTM: West Conshohocken, PA.

Acknowledgements

The author and SSPC gratefully acknowledge the participation of Joe Brandon, Carl Mantegna, Hugh Roper, and Don Sanchez in the peer review process for this document.

About the Author

H. William Hitzrot

Bill Hitzrot, prior to his retirement, was an active member of SSPC for about 30 years, chair of the abrasives committee and member of the SSPC Board of Governors. He was also an active participant in the Chesapeake Chapter of SSPC. Bill retired as vice president of Chesapeake Specialty Products, a manufacturer of steel abrasives and iron oxides for industrial use. He remains active in SSPC assisting in updating publications and training programs in the areas of surface preparation and abrasives.

Chapter 2.2
Hand and Power Tool Cleaning of Steel Surfaces

Preston S. Hollister and R. Stanford Short (Original Chapter)
Florence Mallet and Brian Harkins (2002 Revision)

Hand Cleaning

Hand cleaning is one of the oldest processes for preparing surfaces prior to painting. Generally, it is used only when power operated equipment is not available, when the job is inaccessible to power tools, or when the job is small. The standard for hand tool cleaning is SSPC-SP 2.

Hand tool cleaning is a method of surface preparation often used for normal atmospheric exposures, for interiors, and for maintenance painting when using paints with good wetting ability. Hand cleaning will remove loose rust, loose paint, and loose mill scale but will not remove all residue of rust or intact mill scale. For cleaning small, limited areas prior to maintenance priming, hand cleaning will usually suffice.

It is important to follow the good practices in order to minimize failures or to avoid unnecessarily stringent specifications for the preparation of surfaces that will be exposed in mild environments. Care in hand tool cleaning is also especially important if the prime coat is to be applied by spray, because a sprayed coating may bridge gaps and crevices, whereas brushing works the paint into these areas.

Prior to hand tool cleaning, oil and grease, along with any salts, must be removed as specified in SSPC-SP 1, *Solvent Cleaning*. On welded work, particular care should be taken to remove as much welding flux, slag, and fume deposit as is possible since these are notorious in promoting paint failure on welded joints. All loose matter should be removed from the surface prior to painting. Blowing it off with clean, dry, oil-free compressed air, brushing, or vacuum cleaning are satisfactory methods.

Determining the degree of cleaning required to comply with SSPC-SP 2 is often very difficult. The problem lies in establishing whether a residue is “adherent” or “loose.” The specification considers the residue adherent if it cannot be lifted with a dull putty knife, a somewhat subjective criterion.

One possible solution is to establish a standard of cleaning through use of a specified cleaning procedure in which the type of tool, force, speed, etc., are stipulated. The surface for the standard (or the control) should be a flat portion of the surface actually to be cleaned.

This standard establishes a standard of cleanliness, but not a production rate. As long as the surface is cleaned as well as that in the standard cleaning, the actual production rate is not in question. The standard is of value in resolving differences of opinion as to whether or not the surface has been properly cleaned. If mutually agreed upon, SSPC-VIS 3, ISO 8501-1, or other visual references may be used to supplement the cleaning criteria of SSPC SP 2.

Tools needed include wire brushes, non-woven abrasive pads, scrapers, chisels, knives, chipping hammers, and, in some instances, conventional coated abrasives. Specially shaped scrapers or knives are sometimes necessary.



Figure 1. Tools used in hand cleaning operations. An oblong wire brush is shown to the right of goggles and gloves; wide-blade hand scraper; hand chipping hammer; long-handled, wide-blade scraper; hammer and chisel used for removing rust scale.

In close areas, tools must be shaped so they can enter areas to be cleaned. Further limitations are also found with hand tools when tight mill scale or rust must be removed. These can be cracked on impact

and removed with scrapers, abrasive paper, or non-woven abrasive pads, but this is a very slow and impractical method except for small areas. There is danger that deep markings in the metal from impact tools will leave a burr on the metal surface that may interfere with coating systems performance.

Tools

Dried or caked soil and other such contaminants are generally removed with loose mill scale and rust by scraping, brushing with non-woven abrasive pads, wire brushing and hand chipping. It is important that any surface contaminant, such as gobs of oil or grease, is not distributed over the entire surface through cleaning operations. Some tools used for hand cleaning are illustrated in **Figure 1.** Wire brushes may be of any practical shape and size. Two general types are the oblong with a long handle and the block. Bristles are of spring wire. Brushes should be discarded when they are no longer effective because of lost or badly bent bristles. Non-woven abrasives are used in simple pad form or applied to a backup holder with handle **(Figure 2).** They can be cut to fit various applicators.

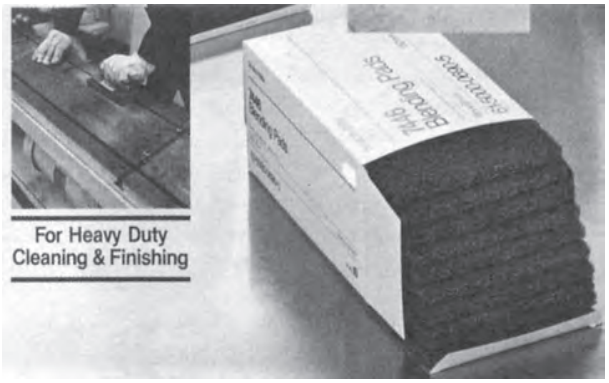


Figure 2. Nonwoven abrasive pad attached to plastic backup holder. Courtesy 3M.

Scrapers may be of any convenient design. **Figure 3** shows practical scrapers used by maintenance crews. Scrapers should be made of tool steel, tempered, and kept sharp to be effective. Some scrapers are made by sharpening the ends of 1-1/2 to 2-inch (4 – 5 cm) wide flat files or rasps and fastening them to a handle. The handle may be up to 5 feet (1.5 m) long to increase the area that can be reached. Other chipping and scraping tools made from old files or rasps have both ends sharpened.

Hand-chipping hammers are advisable in maintenance work where rust scale has formed. A chipping hammer is about 4 to 6 inches (10 – 15 cm) long with two wedge-shaped faces at either end of the head, one face perpendicular to the line of the handle and the other at right angles to the first face. Typical tools are illustrated in **Figure 3.**

Auxiliary equipment includes dust brushes, brooms, various sizes of putty knives and conventional paint scrapers, coated abrasives, and safety equipment such as goggles and dust respirators.

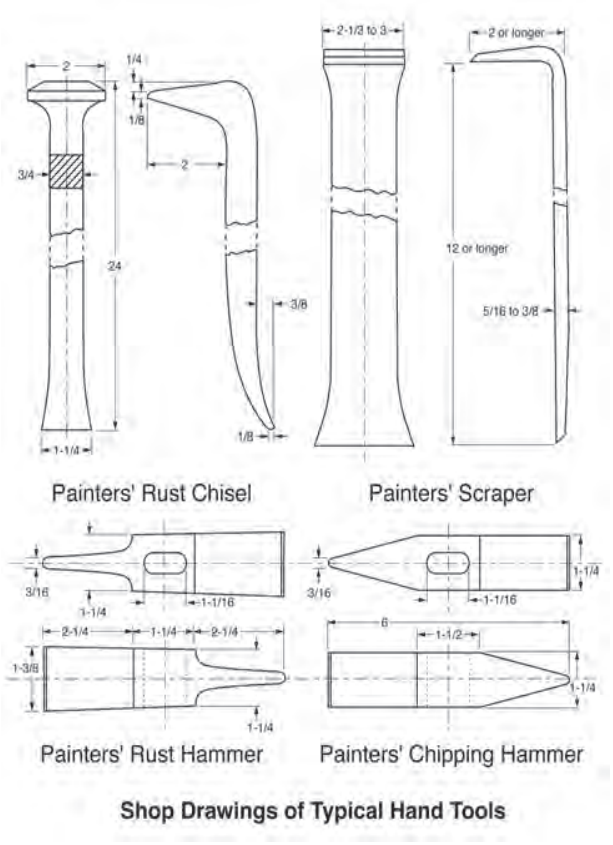


Figure 3. Typical hand tools.

Procedures

Hand-cleaning operations vary depending on the job. Rust scale forms in layers. It is removed first usually by hand chipping and hammering. Where rust scale has progressed to the point where thickness of the metal has been diminished, use extreme care to prevent heavy sledges from puncturing the metal. Deep marking of the surface must be avoided. Burrs interfere with performance of the coating system. After rust scale, oil, grease, and similar contaminants are

removed, all loose and non-adherent rust, loose mill scale, and loose or non-adherent paint are removed by a suitable combination of scraping and nonwoven abrasive or wire brushing. The cleaning method depends on the surface. Loose, voluminous rust is easily removed by scraping with thin, wide-blade scrapers and then wire or nonwoven abrasive brushing. Tightly adherent rust is generally removed with a heavy scraper.

Hand-cleaning painted surfaces removes all loose non-adherent paint in addition to any loose rust or scale. If paint is thick, edges of the old paint should be feathered to improve the quality of the paint job. After cleaning, the surface is brushed, swept, dusted, and blown off with compressed air to remove all loose matter.

Power Tool Cleaning

Use of portable power tools—pneumatic and electric — is common for cleaning operations. Through careful selection and use of the great variety of power tools and accessories, many cleaning operations can be accomplished rapidly and produce satisfactory surface conditions with reasonable labor costs and good paint life.

The specifications governing power tool cleaning are SSPC-SP 3, SSPC-SP 11, and SSPC-SP 15. Each of these requires removal of all oil, grease, dirt, etc. in accordance with SSPC-SP 1, *Solvent Cleaning,* before cleaning with power tools. SSPC-SP 3, *Power Tool Cleaning,* requires removing loose paint and rust and is specified when rigorous surface preparation is not required, such as a dry interior. When the highest degree of power tool cleaning is needed, SSPC-SP 11, *Power Tool Cleaning to Bare Metal* is specified. SSPC-SP 15, *Commercial Grade Power Tool Cleaning,* requires the removal of all paint, rust, mill scale, and other foreign matter except for some staining and debris in the bottom of pits. This degree of power tool cleaning is between SSPC-SP 3 and SSPC-SP 11. These three standards are described in more detail below.

SSPC-SP 3 Power Tool Cleaning

Similar to hand tool cleaning, power tool cleaning removes loose rust, loose mill scale, and loose paint. Intact materials may remain. Power tools use electrical and pneumatic equipment to provide faster cleaning. They include sanders, wire brushes or wheels, chipping hammers, scalers, rotating flaps (rotopeen), needle guns, and right angle or disk grinders. Some have high efficiency particulate air filter (HEPA) vacuum lines attached to reduce air pollution and collect debris produced in the cleaning operation.

Power tools clean by impact, abrasion, or both. Cleaning metal surfaces is less expensive using power tools than using hand tools. Also, less particulate contamination of the environment occurs than from abrasive blasting.

Thus, power tools are used frequently for spot cleaning of damaged coatings, where contamination of adjacent areas by abrasive is unacceptable, and when a surface-tolerant coating such as oil-based paint is to be used.

SSPC-SP 11 Power Tool Cleaning to Bare Metal

Power tool cleaning to remove tightly adherent materials produces a surface that is visibly free from all rust, mill scale, and old coatings, and which has a surface profile. It produces a greater degree of cleaning than SSPC-SP 3, *Power Tool Cleaning,* which does not remove tightly adherent material, and may be considered for coatings requiring a bare metal substrate.

The surfaces prepared according to this specification are not to be compared to surfaces cleaned by abrasive blasting. Although this method produces surfaces that “look” like near white or commercial blast, they are not necessarily equivalent to those surfaces produced by abrasive blast cleaning as called for in SSPC-SP 10/NACE 2 (near-white) or SP 6/NACE 3 (commercial).

SSPC SP 11 helps to bridge the gap between the marginal surface preparation described in SP 2 (hand tool), SP 3 (power tool), and SP 7/NACE 4 (brush-off) and the more thorough cleaning described in SP 6/NACE 3 (commercial), SP 10/NACE 2 (near white), and SP 5/NACE 1 (white metal). It gives the specifier an opportunity to select a method of cleaning suitable for certain coatings in areas where abrasive blasting is prohibited or not feasible.

Examples of circumstances where this specification may be applied are:

- Touch-up of welded or damaged areas of erection assemblies
- Reducing volume of hazardous waste produced by abrasive blasting
- Cleaning around sensitive equipment or machinery

SSPC-SP 15 Commercial Grade Power Tool Cleaning

This degree of cleaning is more thorough than SP 3 but not as thorough as SP 11. As in the other power tool specifications, removing oil, grease, and dirt in accordance with SSPC-SP 1 is a prerequisite. Unlike SP 3, SSPC-SP 15 requires the removal of all paint, rust, mill scale, and other foreign matter. SP 15 does allow random staining on 33% of each unit area, i.e., an area of about 9 inch^2 (6400 mm^2), whereas SP 11 does not allow such staining. Both SP 15 and SP 11 allow slight residue in the bottom of pits if the original surface was pitted and both require a 25 micrometer (one mil) minimum profile.

SP 15 is used when SP 3 is not adequate but the added expense of providing SP 11 is not warranted and abrasive blast cleaning is not practical. The tools used to produce an SP 15 surface are the same ones used to produce SP 11.

Impact Cleaning Tools

Needle scalers, chipping guns, and scaling hammers exemplify impact cleaning tools. These tools utilize reciprocating action of multiple steel rods, chisels, or steel cutting heads to impact the work area, removing paint, rust, or other mill scale, as well as profiling the work surface.



Figure 4. Selection of needle scalers. Courtesy Trelawny Surface Preparation USA.

A needle scaler **(Figure 4)** is a de-scaling tool with a bundle of steel needles housed and positioned forward of the striking piston. The piston strikes an anvil that in turn projects all needles forward, propelling them individually against the work surface. Needle scalers are excellent for use on irregular surfaces and hard-to-reach areas. The continually self-adjusting needles conform to nearly any surfaces. Needle scalers are most effective on brittle and loose surface contaminants and may be used on many different applications. Needles are available from 2 mm diameter for light scaling work requiring small profiling to 3 and 4 mm diameter for heavy scaling work. Tips may be flat, chisel, and pointed. Chisel and pointed tip needles are most effective for removing high-build coatings and produce a more extensive/aggressive surface profile. Needle scalers may also be equipped with vacuum shrouding and are viable options for removing lead-based paint or for general coatings removal in a dust free environment.

Chisel scalers can be adapted for scraping and chipping. This type of tool is useful when heavy deposits of rust scale, mill scale, thick old paint, weld flux, slag, and other brittle products must be removed from metal. Chisel scalers are shown in **Figures 5a and 5b.** Chisels have different shapes and are made of various materials. Chisel scalers are often not as effective as needle scalers for removing coatings and provide no surface profile.



Figure 5a. Inline chisel scaler. Courtesy Trelawny Surface Preparation USA.

Piston scalers, also called scaling hammers or knuckle busters, work in a similar fashion, but the piston is the striking component. The smaller dimension of the tools permits use in operations with limited access. This type of tool is available in single and multiple piston types and is ideal for removing high-build coatings or laminar rust. The pistons are available with two types of heads—cruciform for heavy de-scaling and bush hammer for light duty. Sample scaling hammers are shown in **Figure 6.**

Cleaning surfaces with impact scalers is comparatively slower than other methods but is a very economical approach for small areas and spot work. Impact scaling is a viable technique when consider-

able rust scale or heavy paint formation must be removed and when using larger more bulky equipment is logistically impossible.



Figure 5b. Pistol grip chisel scaler. Courtesy Trelawny Surface Preparation USA.



Figure 6. Scaling hammers. Courtesy Trelawny Surface Preparation USA.

Impact cleaning tools are available with various handles and throttle styles. They should be selected for specific operations with consideration for operator safety, convenience, and preference. This minimizes fatigue and improves worker productivity.

These tools may be used to remove tight mill scale and surface rusting and can even create a profile on the surface for better adhesion of the new coating. Tools must stay sharp or they may drive rust and scale into the surface. This is the reason to use chisel or pointed tip needles rather than a blunt needle. The cutting action of sharp chisels is valuable for shaping sharp edges to a rounded or less sharp surface so paint does not pull away. It also removes imperfections from the surface. When working on steel, the operator must keep the tool moving at all times to create an even and regular profile on the work surface and avoid burrs.



Figure 7. Nonwoven abrasive products are available in (from right to left) disc, wheel, and cup wheel forms. Courtesy 3M.

Rotary Cleaning

Rotary power tools tend to do the work much more rapidly than impact tools when the work surface is flat and regular.

Cleaning Media. There are three basic types of cleaning media for rotary power tools: nonwoven abrasives, wire brushes, and coated abrasives. Nonwoven abrasives and rotary wire brushes can be used to remove old paint, light mill scale, rust, weld flux, slag, and dirt deposits. Wire brushes can be composed of differently shaped and sized wire bristles that may be crimped or knotted. Nonwoven abrasive products **(Figure 7)** can be composed of various grades of abrasive in various densities. Wire brushes and nonwoven abrasives come in cup and radial (wheel) form. Nonwoven abrasives also are available in disc form. Selection should be based on trials. Surface condition affects the efficiency of cleaning.

Nonwoven abrasives are particularly advantageous in removing coatings because of lowered susceptibility to loading, as compared to coated abrasives.

Coated abrasives are used in several converted forms **(Figure 8).** Discs and flap wheels are used to remove loose mill scale, old paint, etc. similar to wire brush applications, but can also remove base metal. Loading from old paints may make such applications uneconomical for discs.



Figure 8. Coated abrasive flap wheel used for surface preparation. Courtesy 3M.

Tools. Tools for the three media may be straight, or in-line, machines **(Figure 9),** or vertical or right-angle machines **(Figures 10, 11).** The straight or in-line machine style is used with radial wire brushes, coated abrasive flap wheels, and nonwoven abrasive wheels. The vertical machine style is suited for cup-wire brushes, coated abrasive discs, nonwoven abrasive discs, and cup wheels. The type of machine varies with job conditions. It is advisable to have both types on hand and generally both are used on field jobs.



Figure 9. Several examples of the straight or inline tool. Courtesy ARO Corp.

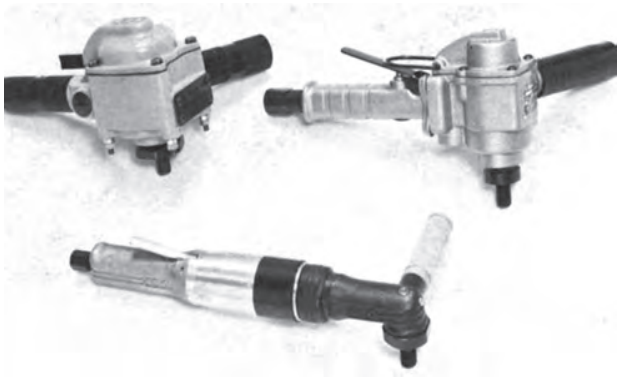


Figure 10. Three air-powered vertical or right-angle tools. Courtesy ARO Corp.



Figure 11. A nonwoven abrasive disc in use on a right-angle power tool for cleaning a steel beam. Courtesy Trelawny Surface Preparation USA.

Operator fatigue is an important factor in power tool cleaning. An operator's preference should be considered in selecting a machine. In some cases, where much overhead work is to be done, small lightweight machines may be used.

The machine should be compatible with the size and speed rating of the cleaning media and should produce enough power to perform the opera-

tion efficiently. Most air-powered machines contain governors to limit the free operating speed. Governors respond to tool load resulting from thrust applied to the work surface and supply more air to the motor, increasing power output and maintaining its rated speed while under load. Electrically driven machines operate at a fixed speed.

Nonwoven abrasive wheels are recommended where base metal should not be removed but where wire brushes are not aggressive enough. These wheels wear at a controlled rate. Fresh working abrasive provides a constant rate of surface cleaning with minimal loading. Nonwoven abrasive wheels are useful in removing light mill scale. In many applications, nonwoven abrasives are a quicker and more effective alternative to wire brushes or coated abrasives.

In power-wire brushing it is possible to cut through some mill scale by using the toe of a very stiff brush and bearing down hard. It is impractical to remove tight mill scale by power wire brushing. Generally, removing only loose mill scale and rust is required. Too high a speed must not be used and the brush must not be kept on one spot for too long or detrimental burnishing may occur. Under such circumstances the surface is smooth and develops a polished, glossy appearance that provides a poor anchor for paint.



Figure 12. Four types of cutters or "stars," a heavy-duty rotary peening flap, and a rotary hammer. Courtesy Desco Manufacturing Co.

Rotary Impact Tools

Rotary impact tools operate on the same basic principle as other impact tools, through cutting or scraping action, but these tools use a centrifugal principle where cutters or hammers are rotated at high speed and thrown against the surface.

Rotary chipping tools use three major types of media: cutter bundles (or stars), rotary hammers, and heavy-duty rotopeen flaps **(Figure 12).** Each type of abrasive media requires a specific rotational speed that matches the media characteristics. A rotary tool is set to run at a specific RPM (revolutions per minute) and cannot be changed. It is important to match the correct tool with each abrasive to avoid premature wear of the abrasive or dangerous situations.



Figure 13a. Example of a hub loaded with 3M rotopeen flaps. Courtesy Trelawny Surface Preparation USA.



Figure 13b. Example of a tool using a heavy-duty flap. Courtesy Trelawny Surface Preparation USA.

Cutter bundles or stars consist of hardened steel star-shaped washers free to rotate individually on spindles that orbit a powered axis. The scraping is

suited for grinding concrete, surface preparation, coating removal, and for generating non-slip surfaces. It is a fast and economical method to remove high-build coatings.

Rotary hammers are a series of free swinging hammers that, through impact on a surface, can be used for removing thermoplastics, coatings, heavy rust, and scale. This method leaves very little profile once the surface is clean.

One process ("heavy-duty" roto peen) employs flexible flaps to the end of which tungsten carbide shot is attached. These flaps are loaded on a hub and are slung via centrifugal force against the work piece thus fracturing old coatings or mill scale and providing a "peened" finish. This process will leave a good anchor pattern for coatings. It can also generate a non-slip surface **(Figures 13a and 13b).**

Safety

Safety is a very important consideration when using tools. Prescribed safety practices are published by various organizations, including the American National Standards Institute, the National Safety Council, the Occupational Safety and Health Administration, and the Environmental Protection Agency. Safety procedures are covered in depth in a separate chapter of this book.

Suggested Reading

Chong, Shuang-Ling; Yao, Yuan. Performance Testing of Moisture-Cured Urethanes on Power Tool-Cleaned Steel Surfaces. In *Proceedings of SSPC '98,* pp 110-116.

Fabian, Ralph L. Applicator Training Bulletin: Power Tool Cleaning. *Journal of Protective Coatings and Linings,* February 1998, pp 21-24.

Finch, Dallas. Contractor Overcomes Tight Schedule, Cold Weather to Finish Ship Restoration. *Journal of Protective Coatings and Linings,* January 1998, pp 86-91.

Henry, Craig; Bennett, Burke; Carter, Paul. Tools and Methods of Hand Tool Cleaning. *Journal of Protective Coatings and Linings,* January 1998, pp 59-61.

Power Tool Cleaning for Steel. *Protective Coatings Europe,* July 1998, pp 41-44.

About the Authors

Preston S. Hollister

Preston Hollister has worked as a technical service engineer in the building services and cleaning products division of 3M.

R. Stanford Short

R. Stanford Short retired as manager of engineering standards and services at the Aro Corporation.

Florence Mallet

Florence Mallet is currently president of Trelawny Surface Preparation USA. She previously headed the U.S. division of Trelawny for the Fulton Group, a corporation headquartered in Liverpool, England. Ms. Mallent received a BA degree in management in 1983 and an MBA in finance in 1986 from Temple University.

Brian Harkins

Brian Harkins is the vice president of marketing and product development for Trelawny Surface Preparation USA. Mr. Harkins joined Trelawny as product development manager in 1992 and assumed his current position in 1997. He received a BS degree in engineering from St. Joseph's University in 1987.

Chapter 2.3
Nonmetallic Abrasives

H. William Hitzrot (original chapter)
James Hansink (2002 revision)

Introduction

Nonmetallic abrasives used for blast cleaning may be classified as mineral abrasives, slag and other by-products, and manufactured abrasives. Physical data is summarized in **Table 1.**

Types of Abrasives

Mineral Abrasives

Minerals are–by definition–naturally occurring inorganic substances. Mineral quartz sands and flint sand are the most commonly used abrasives in U.S. markets. Sands are a low-cost, readily available source of abrasive and have been used for the blast cleaning of steel since the inception of this technique. Sand particles **(Figure 1)** may range from sharply angular to almost spherical, depending on the source. Silica sands are an effective abrasive for blast cleaning new steel and for maintenance cleaning.

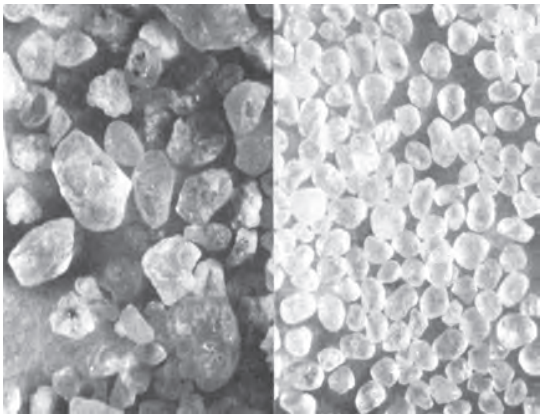


Figure 1. Silica sand abrasive (X8 magnification–8 diameters).

Exposure to dust formed during blasting with quartz-rich sands has been linked to silicosis and other serious lung-related health problems. In recent years, some companies and selected government agencies have urged the use of blast media containing less than 1.0% percent crystalline silica.

Non-quartz sands may also be used for blast cleaning. The most common of these include almandite garnet, specular hematite, staurolite, and olivine—used either by themselves or in various combinations. These sands are tough and dense and are often used in finer particle sizes than the lighter silica sand. An example of a heavy mineral sand is shown in **Figure 2.** Non-quartz heavy mineral sands are effective blast cleaning media for nearly all new steel and maintenance applications.

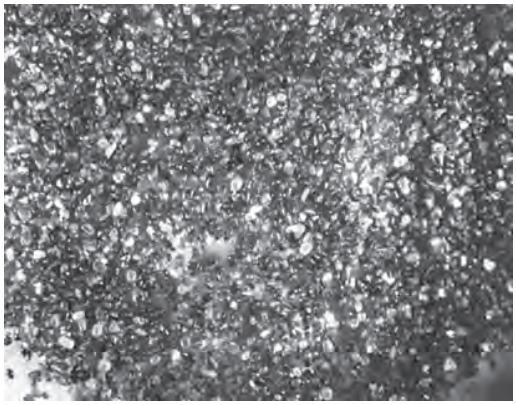


Figure 2. Heavy mineral sand abrasive (X8 magnification).

Quarried rock and crushed aggregate containing no quartz is a relatively new addition to the abrasive field. Its blocky shape and relatively low cost make it an attractive substitute for local silica sands where it is available. Volcanic basalt is the most common source material.

Garnet **(Figure 3)** is a tough, angular-to-subrounded abrasive that is especially suitable for blast cleaning steel parts and castings, i.e., cleaning in a closed system that permits recycling the abrasive. Available in a range of sizes, it can be recycled a number of times because of its toughness. Historically, the perceived high cost of garnet restricted its use to specialty cleaning applications, but this is no longer the case.

Zircon is another tough, rounded abrasive

Table 1. Physical Data on Nonmetallic Abrasives.

	Hardness (Mohr Scale)	Shape	Specific Gravity	Bulk Density (lbs/ft^3)	Color	Free Silica Weight %	Degree of Dusting	Reuse
Naturally Occurring Abrasives								
Sands								
Silica	7	ang-sb rnd	2.6	100	white	90+	high	poor
Heavy Metal	5-8		3-4	128	variable	<5	medium	good
Flint	6.5-7		2.6	80	gray-white	90+	medium	good
Garnet	7-8		4	145	pink	nil	low	good
Zircon	7.5		4.5	184	white	nil	low	good
Novaculite	7	angular	2.5	100	white	90+	low	good
Spec. Hematite		angular	5.2	200	gray	nil	medium	good
Olivise		ang-sb ang	3.5	180	green	nil	medium	poor
By-Product Abrasives								
Slags								
Boiler	6	angular	2.8	80-90	black	nil	high	poor
Copper	6	angular	3.3	100-120	black	nil	medium	good
Nickel	6	angular	2.7	84	green	nil	high	poor
Walnut Shells	3	cubic	1.3	44	brown	nil	low	poor
Peach Pits	3	cubic	1.3	44	brown	nil	low	poor
Manufactured Abrasives								
Silicon Carbide	9	angular	3.2	±105	black	nil	low	good
Aluminum Oxide	8	blocky	4.0	±120	brown	nil	low	good

(Figure 4). Its fine size limits its use to specialty blasting to remove fine scale, leaving a smooth, matte finish. Like garnet, it has higher density and greater hardness than silica sand and is considerably more costly. Zircon is also less widely available than most other media.

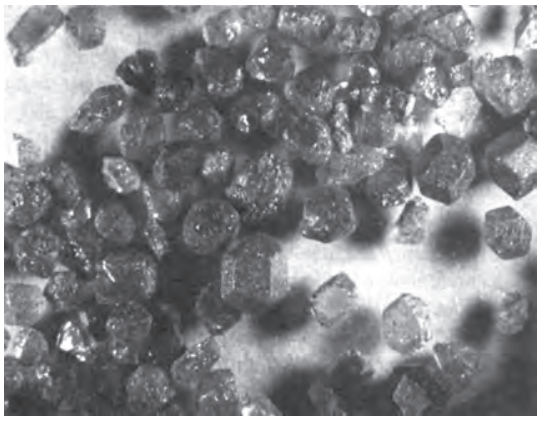


Figure 3. Garnet abrasive (X8 magnification).

Novaculite, a very pure, siliceous rock, is ground to fine sizes for specialty blast cleaning. It leaves a satin luster finish and is most commonly used to clean precision tools and castings and in other special applications.

Slag By-Product Abrasives

This group is the most common substitute media for quartz sand in general blast cleaning. The relative low cost, availability in a variety of sizes and packaging options, and low (less than 1%) free silica content make it well-suited for blast cleaning large steel structures, both for new construction and maintenance cleaning. The natural desire to conserve materials and other environmental concerns has given further impetus to converting slag by-products into commercial abrasives.



Figure 4. Zircon abrasive (X8 magnification).

Chief among the by-products used as abrasives are slags from two sources: metal smelting

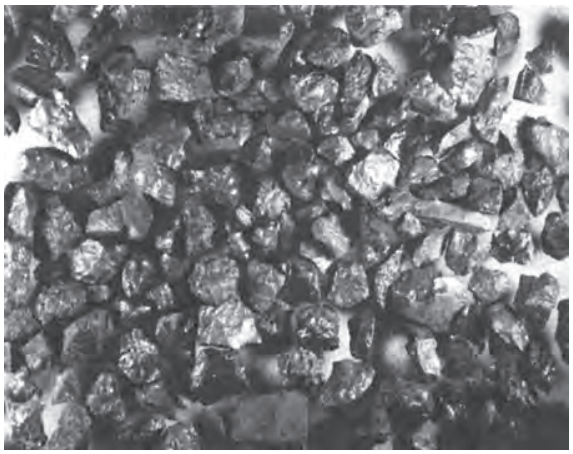


Figure 5. Copper slag abrasive (X8 magnification).

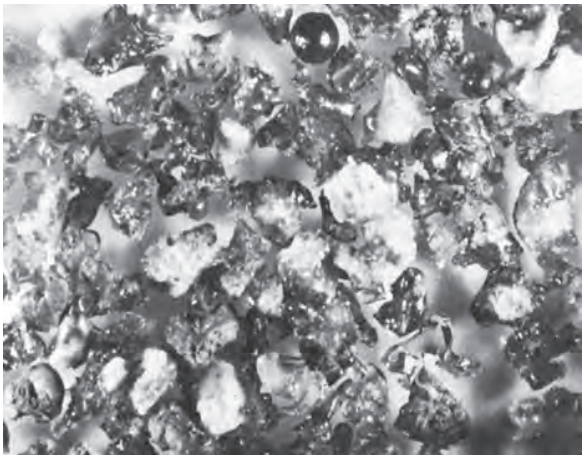


Figure 6. Nickel slag abrasive (X8 magnification).

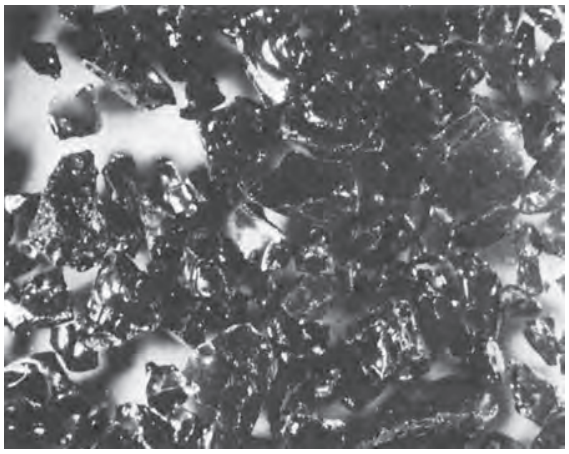


Figure 7. Coal-fired, boiler-bottom ash (X8 magnification).

(Figures 5 and 6) and electric power generating (bottom ash) **(Figure 7).** Smelting and boiler slags are generally glassy, homogeneous mixtures of various oxides, which give them uniform physical properties important for abrasive applications. These abrasives have a sharply angular shape suitable for efficient blast cleaning of both new steel and corroded or painted steel surfaces. Slags are available in the full range of abrasive sizes—coarse (8 sieve) to fine (100 sieve).

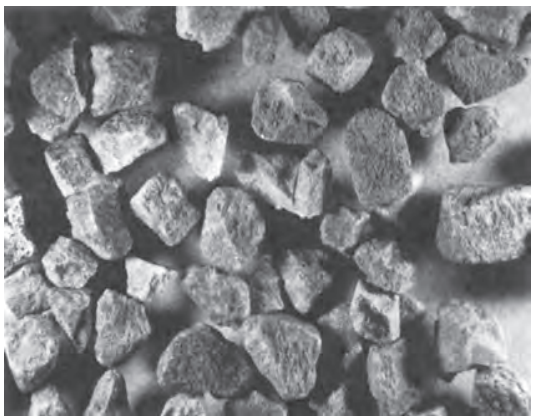


Figure 8. Walnut shell abrasive (X8 magnification).



Figure 9. Corncob shell abrasive (X8 magnification).

Not all slags can be used as abrasives. They need to be tough, have a bulk density of 80 to 100 lb/ft.^{2}, and exhibit a minimum amount of breakdown on impact in order to be effective.

A second by-product abrasive is vegetable media, including walnut shells **(Figure 8)** and peach pits. Tough but lightweight with a bulk density of 42-47 lb/ft^2, such shells are excellent for removing paint, fine scale, and other surface contaminants without altering the metal substrate. Shell products are available from

10 to 100 sieve. Corncobs **(Figure 9)** are another agricultural product used for specialty cleaning to remove surface contaminants, such as grease and dirt, without destroying or altering the paint or metal substrate. Corncobs are also available in a full range of sizes.

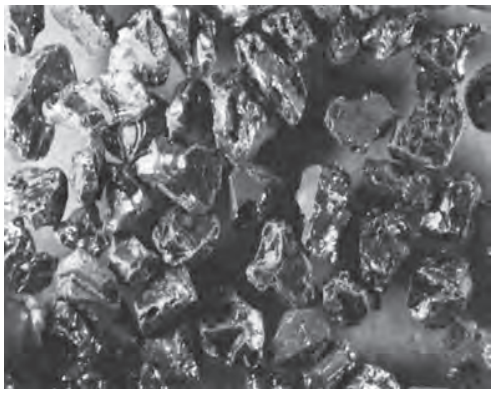


Figure 10. Silicon carbide abrasive (X8 magnification).

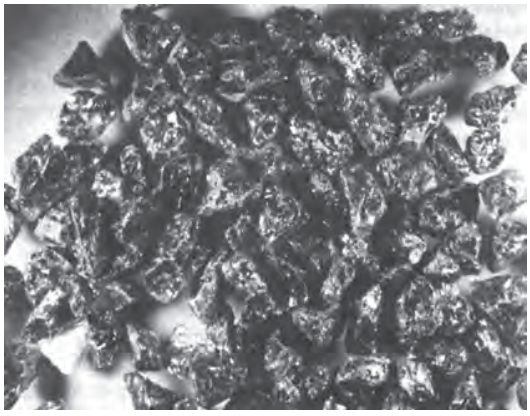


Figure 11. Aluminum oxide abrasive (X8 magnification).

Manufactured Abrasives

Nonmetallic, manufactured abrasives are made from a wide variety of raw materials and can be produced for specific abrasive properties, such as toughness, hardness, or shape. Some examples are silicon carbide **(Figure 10),** a tough angular abrasive for specialty etching; aluminum oxides **(Figure 11)** for blast cleaning materials such as stainless steel; and glass beads **(Figure 12)** for peening and cleaning small, delicate parts and molds. In recent years, a range of softer manufactured products designed to remove dirt, grease, and light corrosion has been introduced. These include dry and wet ice, sodium bicarbonate, and plastic grains.

Since production can require a great deal of energy, manufactured abrasives may be more costly than by-product slags and quartz sand. For this reason, such abrasives are not commonly used for bulk cleaning jobs where the abrasive cannot be recovered for reuse. The tough, durable nature of most manufactured abrasives makes them particularly adaptable to recycling as many as 20 times. Consequently, net cost can be comparable to that of the by-product abrasives.

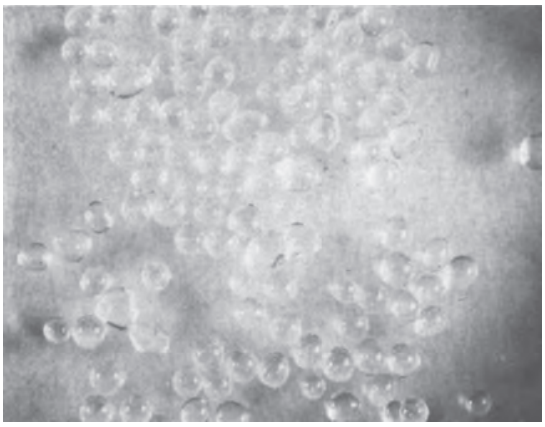


Figure 12. Glass bead abrasive (X8 magnification).

Choosing the Right Abrasive

The variety of materials available make it necessary to know how to select the proper abrasive appropriate for a given job. An abrasive has four parameters that determine its performance: shape, hardness, density, and size. It is important to know how each of these parameters affects surface preparation.

Shape (Angular Versus Round)

Because of their scouring action, angular-to-subangular particles are best suited for removing soft friable surface contaminants such as paint, rust, and dirt. **Figure 13** illustrates scouring. Round particles may be better suited for removing brittle contaminants like millscale or oxidized coatings. Spherical particles are also used to produce a peening action when little or no change in surface configuration is permitted.

Hardness and Durability

Hard, tough particles are best suited for blast cleaning jobs where the primary objective is to remove surface contaminants. Harder particles leave less residue on the surface, and tough, durable particles

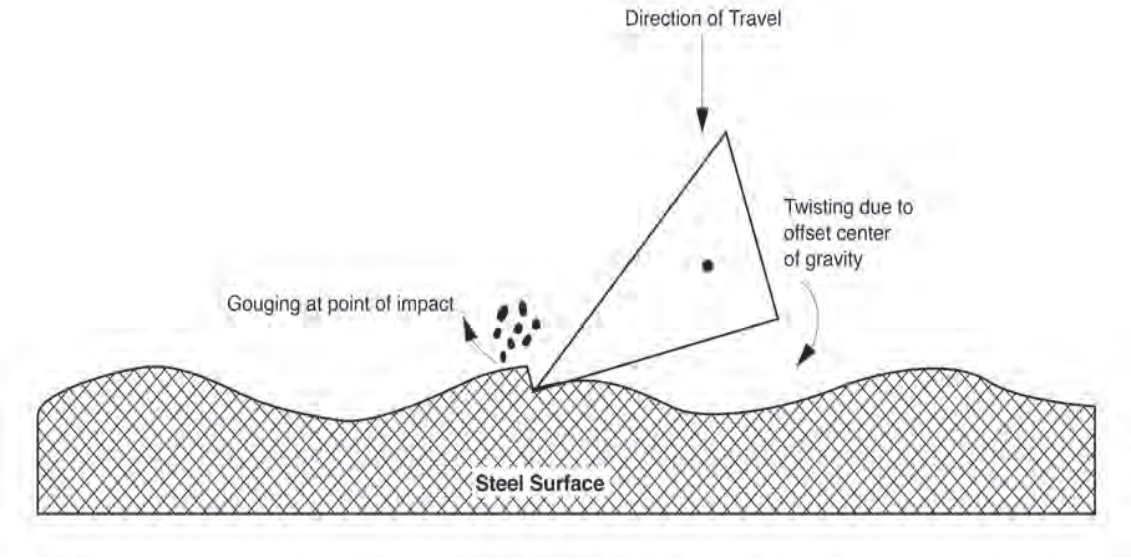


Figure 13. Impact of angular abrasive particle on steel surface.

minimize dusting. Grains with especially good durability—like some garnets—may survive impact to be collected and reused several times.

Soft abrasives remove light contaminants without disturbing the metal substrate or, in some cases, the coating system. Walnut shells and corncobs are soft enough for cleaning valves or turbine rotor blades and for removing grease from motors and dirt or other deposits on paint films.

Coating System

Most coating manufacturers recommend a minimum surface texture on the abrasive-cleaned surface for good coating adhesion – commonly about 2.0 mils (50 µm). The coating system will therefore also influence the choice of abrasive for surface preparation.

Cleanliness

Not all abrasives yield the same degree of surface cleanliness. An abrasive sized to be effective for a commercial blast (SSPC-SP 6) may not be able to economically provide a near-white (SSPC SP 10) or white-metal (SSPC-SP 5) blast-cleaned surface. It is important to know whether an abrasive can meet the specified degree of cleanliness efficiently.

Environmental Constraints

Safety and environmental requirements affect the choice of abrasive. The need to minimize dust or airborne free silica may require replacing sands with by-product slags or other minerals or replacing open blasting with an enclosed operation.

Enclosed blasting is often associated with abrasive reclamation and reuse. This dictates the selection of a durable, higher quality media. Although the most commonly recycled abrasives are the ferrous/steel media, manufactured and naturally occurring abrasives that exhibit excellent durability can also be considered for recycling. The carbide and alumina abrasives and naturally occurring garnets and heavy mineral sands can be reused many times.

Abrasive Evaluation Tests

This section discusses certain key physical and chemical properties of abrasives:

Size consist is defined as the size distribution of abrasive particles and is best determined by sieve analysis, as outlined in ASTM D 451. A consistent range of abrasive particle sizes must be maintained to produce a consistent surface and cleaning rate.

Abrasive breakdown is a measure of a particle breakdown after impact. The greater the particle breakdown, the poorer the cleaning rate. That is, if most of the particle energy is dissipated, little energy is left for removal of surface contaminants. Some manufacturers list a breakdown value, and standard test procedures have been established in California. Regardless of the abrasive used, breakdown is most strongly affected by operator skill.

Dust generation is the amount of dust generated by an abrasive on impact. Excessive dust

can create visibility problems during blasting and cause environmental problems at the job site. Dust generation may be minimized by the use of well-trained and supervised operators and well-maintained equipment.

The **pH values** of an abrasive should be nearly neutral when the abrasive is mixed with water. Some suppliers note the pH on the technical data sheet accompanying the abrasive. This value is easily checked and should be routinely monitored. An abrasive with an acid pH (less than 7.0) can cause premature corrosion of steel and coating failure.

A **soluble chloride test** is important, because chlorides may impart a detrimental residue. Most chemical laboratories can routinely analyze for soluble chlorides and field test kits are available for real-time determination of chloride levels. If the abrasive source is near seawater, routine checking for soluble chlorides is recommended.

The manufacturer generally provides an analysis for **free silica.** The level of free silica should comply with governmental regulations and customer requirements.

Trace toxic contaminants that may be present in slag abrasives should be reviewed prior to use, and suppliers should provide an analysis for potentially toxic substances.

Acknowledgements

The authors and SSPC gratefully acknowledge the participation of Joe Brandon and Hugh Roper in the peer review process for this chapter.

About the Authors

H. William Hitzrot
Bill Hitzrot, prior to his retirement, was an active member of SSPC for about 30 years, chair of the abrasives committee and member of the SSPC Board of Governors. He was also an active participant in the Chesapeake Chapter of SSPC. Bill retired as vice president of Chesapeake Specialty Products, a manufacturer of steel abrasives and iron oxides for industrial use. He remains active in SSPC assisting in updating publications and training programs in the areas of surface preparation and abrasives.

James D. Hansink
Jim Hansink has more than 30 years experience in the mining and mineral business. He holds technical degrees in geology and engineering from St. Louis University and an advanced degree in management from MIT. He has been responsible for development and marketing of sand, slag, and garnet properties, and he has held executive management positions with several international mineral companies. Jim is currently president of Garnet Services, Inc., a Seattle-based consulting and mineral brokerage firm.

Chapter 2.4
Metallic Abrasives

H. William Hitzrot

Introduction

This chapter discusses the primary metallic abrasives that are used for surface preparation, including the various types, sizes, and hardness ranges, and the effect of each in determining the most cost effective solution for various applications. Many combinations of materials and processes can be used to achieve the specific surface profile requirements of any specification.

Metallic abrasives are predominantly ferrous, such as iron, steel, and low-carbon steel. There are some brass, aluminum, zinc, nickel, stainless steel, and cut-wire abrasives, but these are used primarily for very specialized applications not related to paint and rust removal prior to coating. The use of metallic abrasives dates back to the early 1900s when chilled iron abrasives were first employed. The advent of wheel blast machines in the late 1930s and early 1940s created a need for a more durable abrasive than chilled iron, and resulted in the development of heat-treatable, cast-steel abrasives in the late 1940s. By the early 1950s, cast-steel abrasives had become the medium of choice for use in wheel blast machines for cleaning structural steel, plate, and fabricated assemblies prior to coating. Cast-steel abrasives have virtually replaced iron abrasives, and now account for all but a very small percentage of the more than 300,000 tons of metallic abrasives used in the United States each year. **Tables 1 and 2** show the gradations for cast shot and grit.[1]

Types of Abrasives and Methods of Manufacture

Cast-Steel Abrasives

Cast-steel abrasives are usually made by melting steel scrap in electric arc, or less commonly, in induction furnaces. After the chemical composition of the melt is adjusted to the desired range, the melt is superheated, deoxidized, and atomized.

Atomization, commonly referred to as "shotting," is generally accomplished by striking a controlled stream of the molten steel with a jet of water under a controlled pressure (12-18 psi). Shotting may also be completed centrifugally or by the gas process. The shotting process is really a controlled explosion, with the stream of molten steel disintegrating into droplets of a predictable range of sizes, depending on water pressure. These molten droplets generally solidify as spheroids, as surface tension tends to round the particles until a surface crust has formed. These formed, semi-molten particles then fall into a water-filled pit that quenches them into a solid. Some of these droplets collide and fuse. Some solidify into irregular shapes, due to contact with the surface of the water or other obstacles. The quenched particles are then removed from the shotting pit and dried before further processing.

Cast steel abrasives are produced in numerous hardness ranges to suit specific applications. Most are produced in the standard SAE hardness range of 40 to 50 HR_C. The average hardness is a nominal 45 for most manufacturers. Steel grit is usually produced in four hardness ranges: soft grit, 40 to 45 HR_C; low hardness grit, 45 to 52 HR_C; medium hardness grit, 50 to 57 HR_C; and hard grit, 60+ HR_C.

High-Carbon Cast Steel

Typically referred to simply as cast steel, high-carbon cast steel shot and grit are characterized by their 1% carbon content. With this carbon content, the particles approach a hardness of 65+ HR_C, and can be modified through further processing to achieve the desired hardness range. Since shot and grit particles fail because of the fatigue that results from repeated impact, the best quality cast-steel abrasives are austenized and requenched to form a finely tempered and durable martinsitic structure. After quenching, oversize and irregular particles are separated and crushed into grit. Both the shot and grit particles may be sold after screening to size, or tempered to meet the hardness requirements of customer specifications. Steel grit and steel shot are used extensively in the blast cleaning industry to remove paint, rust, mill scale,

Tables 1 and 2. Gradations for Cast Shot and Grit.

Screen No. ASTM E-11	Screen Opening, Inches	Shot Size										
		780	660	550	460	390	330	280	230	170	110	70
7	0.111	all pass										
8	0.0937		all pass									
10	0.0787	85%		all pass	all pass							
12	0.0661	97%	85%		5% max	all pass						
14	0.0555		97%	85%		5% max	all pass					
16	0.0469			97%	85% min		5% max	all pass				
18	0.0394				96% min	85%		5% max	all pass			
20	0.0331					96%	85% min		10% max	all pass		
25	0.0280						96% min	85% min		10% max		
30	0.0232							96% min	85% min		all pass	
35	0.0197								96% min		10% max	
40	0.0165									85% min		all pass
45	0.0138									97% min		10% max
50	0.0117										80% min	
80	0.0070										90% min	80% min
120	0.0049											90% min

Screen No. ASTM E-11	Screen Opening, Inches	Grit Size								
		G12	G14	G16	G18	G25	G40	G50	G80	G120
8	0.0937	all pass								
10	0.0787		all pass							
12	0.0661	80%		all pass						
14	0.0555	90%	80%		all pass					
16	0.0469		90%	75%		all pass				
18	0.0394			85%	75%		all pass			
25	0.0280				85%	70%		all pass		
40	0.0165					80%	70%		all pass	
50	0.0117						80%	65%		all pass
80	0.0070							75%	65%	
120	0.0049								75%	60%
200	0.0029									70%

and other surface contaminants from steel, concrete, and other surfaces prior to coating. Often shot used alone does not provide a suitable profile on steel when used without grit.

Low-Carbon Cast Steel

Low-carbon cast steel shot is characterized by a carbon content that is usually less than 0.2%. The shotted particles generally have a hardness in the range HR_C 35 to 42 as cast, and are not readily heat-treated at this low carbon content. After drying, the particles are screened to the desired size for sale. It cannot be crushed into grit due to its low hardness. Crushing produces flat, rounded "pancake-type" particles of steel that are referred to as nickels. Low-carbon steel shot is often used in foundry applications where it is undesirable to damage cast numbering or identification, and where efficiency, speed, and surface finish are not as important as cost. This type of steel shot is unusual in surface preparation applications because of its low hardness and slow cleaning rates in comparison to the harder higher carbon cast-steel abrasive.

Cast Stainless Steel Shot

Cast stainless steel shot, conforming in composition to 300 series stainless, is available for specialized applications where ferrous contamination might be a problem. The ferrous particles that steel abrasives leave on a surface can rust and stain it unless they are scrupulously removed.

Cut-Wire Abrasives

Cut-wire abrasives are manufactured by shearing wire in the desired composition and diameter into cylinders equal in length to the wire diameter. The cut particles are sold "as-cut," or conditioned. Conditioned particles are rounded by repeated, high-velocity impact against a hard target, and are available in three standard levels: rounded cylinders, near-spherical pellets, and spherical pellets.

Carbon Steel Cut-Wire. Carbon steel cut-wire abrasives are characterized by a carbon content of about 0.40-0.85%, size ranges from .020-.099 inches in diameter, and a range of hardness from HR_c 30 to HR_c 65. Because the particles have a uniform grain structure enhanced by drawing, with no casting defects, micro-porosity, or non-metallic voids, they have excellent resistance to fatigue damage, and may provide consumption figures low enough to offset their high initial cost of purchase. Cut-wire abrasives generally are not used for surface preparation for coatings. Fully conditioned pellets are used in high-tech peening of plates and castings for aircraft and space applications, primarily to improve fatigue resistance. In Europe, however, unconditioned cut-steel wire cylinders have been used for surface preparation under some specific conditions.

Stainless Steel Cut Wire. Stainless steel cut-wire abrasives are available in both 300 and 400 series compositions, and in hardness ranges of 35 to 55+ HR_c. The 300 series abrasives may experience significant work hardening, reaching values of HR_c 55 or higher. All are available in the complete range of sizes, from 0.3–1.6 mm. Stainless steel abrasives, cast and cut wire, are routinely used where ferrous contamination might be a problem.

Chilled Iron Abrasives

Chilled iron abrasives are characterized by carbon contents greater than 1.6%. The method of manufacture is similar to that of steel abrasives, except that the melting may be done in cupola furnaces. After shotting, chilled iron particles are quite hard, HR_C 55+, and are often sold as shot at this hardness. The shot may be crushed and sold as grit in the same hardness range. In the past, chilled iron abrasives were often given a malleabilizing heat treatment to provide particles in the hardness range 35 to 45 HR_C. They were also available partially decarburized, with surface hardness values of about 20 HR_C.

Ferrous Metallic Grit

Ferrous metallic grit is prepared by a different process than conventional cast-steel abrasives, and usually is supplied in one hardness range. It normally has a very wide range of particle shape, size, and hardness, and will produce a widely varying range of profile depth and surface roughness. Ferrous metallic grit can be used for removing paint, rust, mill scale, and other contaminants from surfaces prior to painting if a uniform surface is not a priority.

Reclaimed Abrasives

Reclaimed metallic abrasives, or remanufactured metallic abrasives, have been used,

salvaged, cleaned and screened to size, and packaged for sale. When the reclaimed abrasive is required to meet the remanufacturing requirements of SSPC AB 3, it may be comparable to some new abrasives in terms of cleaning but less durable because of fatigue from prior use. Since numerous batches of abrasive may be combined in the reclamation process, the possibility is high that a wide range of hardnesses may be found in the mix, which will result in a significant variation in the profile produced from container to container.

Abrasive Factors That Influence Productivity

There are five key factors that affect the productivity of any abrasive for any given job:

• **Particle shape—**Rounded abrasive particles produce a peened surface, whereas angular or irregular shaped abrasive particles produce an etched or angular surface profile. Selecting the right particle shape to produce the required profile and texture for the job at hand can impact productivity and the performance of the coating to be applied.

• **Particle weight—**Different metallic abrasives have different mass weights per unit volume and different impact values. For a given impact velocity and particle shape, the weight (mass) of the particle determines the shape and depth of the profile produced. Because steel abrasives have approximately 1-1/2 to 2-1/2 times the density of nonmetallic abrasives, steel abrasives create more impact for a given particle size. Smaller steel abrasive particles will produce the same impact value as nonmetallic particles 1-1/2 to 2-1/2 times larger. With the smaller steel abrasive there are more abrasive particles impacting the surface per unit time, which means faster cleaning rates.

• **Particle size—** Abrasive particle size influences two primary functions of blast cleaning: rate of cleaning and profile. Decreasing particle size may increase cleaning rate because more particles are impacting the surface per unit time. For example, a pound of G25 grit operating mix contains around 500,000 particles while a pound of G40 operating mix contains 2,500,000 particles. The finer G40 mix has 5 times more impacts per pound than the G25 abrasive mix. Increasing abrasive size may be necessary to increase profile and/or to remove heavy coatings. The general rule is always use the smallest size abrasive that will do the job.

• **Particle hardness—**It is generally believed that the harder an abrasive, the better it will perform on difficult to clean areas. However, very hard abrasives may shatter on impact, expending most of their energy in particle disintegration and dust generation rather than surface cleaning. As with selecting abrasive size, the general rule is to select the minimum abrasive hardness that will effectively do the job.

• **Particle velocity—**Particle velocity is the most significant variable affecting profile depth and cleaning speed. The kinetic energy equation illustrates this:

$$E = 1/2\ MV^2$$

Where:
e = Kinetic energy
m = Particle mass (weight)
v = Particle velocity

It can be seen that a small increase in velocity creates a significant increase in the energy level or impact value of the abrasive pellet. By increasing the velocity modestly, size 40 grit particles can provide the same impact energy level as size 25 grit particles, and will create the same depth of profile. Moreover, there is an added benefit in that there are many more uniform peaks, and a smoother overall surface that will consume less coating to achieve the desired film thickness. The total surface preparation job can be completed faster with G40 grit when applied properly.

Abrasive Selection

There are many options available to the user of metallic abrasives, such as shape, hardness, and size. This section is devoted to how these various options influence the performance and productivity of specific types of blast cleaning operations.

Shape

Round (steel shot) abrasive is often used in wheel blast machines to remove brittle scale and rust from steel plates, shapes, and fabricated parts. Steel shot produces a relatively low profile with a fairly smooth, peened surface. This surface can be coated

successfully when it is clean, however, such coatings are usually limited to pre-construction primers that will be removed during abrasive grit blasting after field erection prior to final coating. The use of shot in surface preparation prior to coating for repair or severe service applications is not recommended. Shot has a tendency to peen the surface and pound contaminants into it, producing a scalloped profile.

When the abrasive operating mix is properly controlled, steel grit (angular) produces a more uniform (higher peak density) surface for the same profile. This creates a larger, more consistent surface area. A surface prepared with the properly selected grit will provide a better base for any coating, resulting in improved adhesion factors. In any case, it is always best to select the abrasive shape (shot, grit, or shot/grit mix) that is compatible with the blast equipment, the surface to be cleaned (mill scale, rust, paint, etc.), and the coating to be applied.

Steel Shot/Grit Blends

Steel shot/grit blends are often used where both mill scale and rust are present, typically in centrifugal wheel machines. The ratio of shot-to-grit in the work mix is adjusted to meet the cleanliness and profile requirements of the job.

Hardness

Choosing the right abrasive hardness for any given job can increase productivity and lower overall operating costs. For most surface cleaning operations in a wheel machine where productivity is a factor, steel grit hardness in the range of 50 to 52 HR_C is recommended. Steel abrasives in this hardness range will maintain their irregular shape for a longer time, blend well naturally, and accomplish the uniform sharp profile required for the majority of coatings. They have good durability as well. When the abrasive hardness increases from 52 to 57 HR_C, the abrasive particles are more brittle and breakdown faster, except when the target material is soft. In air blast applications, it is most cost-effective, from the standpoints of productivity and clean up, to use the smallest, hardest abrasive available that will produce the required profile and surface finish required to complete the job at hand.

Size

Choosing the right size for a particular job will depend on but not be limited to the factors sited here:

• **Type of surface contaminant:** If the steel surface is covered with a thick (5-10 mil) coating that needs to be removed, then the abrasive mix should contain some coarser particles, such as G40 to G25 grit. If the steel surface has a lighter (1-5 mil) coating or light rust, then a G50 to G40 grit abrasive mix is suggested. When removing a thick, soft, rubbery coating, a larger granular abrasive works best. Smaller abrasives have a tendency to create heat and soften the coating, making it even more rubbery and harder to remove.

• **Nozzle pressure:** The nozzle pressure used influences abrasive-size selection. When nozzle pressures in the range of 120-150 psi are selected, finer abrasive sizes (G 50 and G 80) are recommended.

Table 3. Abrasive Size Needed to Achieve a Given Profile Height.

Abrasive Type	Profile Height in Mils				
	1 mil	1.5 mils	2 mils	2.5 mils	3-4 mils
Steel Grit	G80	G50	G40	G40	G25
Steel Shot	S110	S170	S280	S280	S330

These profile heights are typical when the nozzle pressure is between 90 and 100 psi.

• **Surface profile requirements:** Profile height is primarily a function of particle size, impact velocity, and hardness. Other factors, such as the angle of impingement, also affect profile. Iron abrasives are generally harder than steel abrasives, however, they are less durable, resulting in faster breakdown. Steel can be heat treated to be harder than iron, but this is not usually done for abrasives used in surface preparation for painting. All things being equal, harder abrasives produce higher profiles than softer abrasives. **Table 3** shows the abrasive size needed to achieve a given profile height. Make certain that the size of abrasive chosen for the job will provide an acceptable profile that meets the job requirements.

It is recommended that the abrasive selection be tested using the equipment available for the job on representative surfaces at the site, with parameters for its use established, and a written protocol followed.

Important Considerations When Using Metallic Abrasives

Abrasive Containment and Recycling

To effectively utilize the advantages of metallic

abrasives, containment and recycling systems must be in-place so that the material can be reused many times. The containment system keeps the blast media, dust, and debris in a confined area for easy recovery. The recycling system must quickly pick up and transport the abrasive and blast debris to the cleaning system, where all trash and contamination are removed before the abrasive is returned to the blast system. SSPC AB 2 defines the minimum cleanliness requirements for recycled ferrous metallic abrasives. A well-manufactured steel abrasive can be recycled 100 to 1,000 times before its useful life is expended.

Dust Generation

Metallic abrasives do not break down on impact like conventional nonmetallic abrasive products. Consequently, there is considerably less dust and waste generated during the blasting process. Low dust levels mean better visibility, faster cleaning, increased productivity, and shorter cleanups, saving time and labor and disposal costs.

Embedment

Because of their brittle nature, nonmetallic abrasives can leave particles embedded in the blasted surface. Hard steel grit may do the same. To avoid embedment, use a low angle brush blast technique. A low angle, when combined with a pulling action instead of a pushing action, allows the overspray of cleaning abrasive to slide along the surface behind the higher angle forward cutting edge. This action loosens the abrasive and removes particles that may have become embedded in the substrate. It will also remove most hackles or rogue peaks that may have been created on the surface by the cutting action of the blast process and help reduce the amount of micronic dust (pulverized contamination from scale, rust, paint, etc.) levels on the surface. The best blast angle (angle between the substrate surface and the nozzle) for steel grit is the lowest angle that will efficiently break and remove the contaminants from the surface being cleaned and profiled. It is not acceptable to exceed a 70° blast angle when using a recyclable abrasive. After blast cleaning an area, it is a good practice to quickly brush (or sweep) the area just cleaned to remove residual loose dust and abrasive.

Work Mix

As metallic abrasives are reused, the abrasive particles gradually wear down and become smaller. It is important to add regular amounts of new abrasive to maintain a consistent size range in the abrasive operating or work mix. Maintaining a consistent abrasive operating or work mix will give the blast operator the ability to create a uniform blast profile and surface texture. More detail on abrasive change with use appears in SSPC-AB 3.

The work mix in any blast cleaning operation must be clean and free of contamination prior to every use. When coating chips, dust, or other contamination are present in the blast stream, there is a good chance that this contamination will be embedded in the surface being cleaned or pulverized into ultra-fine dust, dramatically reducing a blaster's visibility. Statically charged ultra-fine particles that adhere to the surface are extremely hard to remove and will add significantly to clean-up costs.

In some areas of coating application, this phenomenon is referred to as "backside" contamination. Not readily detectable using visual methods, backside contamination levels in excess of 12-20% may have serious effects on the adhesion of any coating.

To establish the level of backside contamination apply a 5 or 6 inch strip of slightly milky looking paper repair tape with a thick, soft adhesive to the test area and press or rub it until it is clear or transparent. The tape must be uniformly rubbed until completely clear. Remove the tape quickly and then place it on a clean, bright white surface to evaluate the degree of coverage, in terms of gray color. It is necessary to establish the darkest shade of gray that is acceptable for coating that particular surface using the specified coating. Take several test readings, place them on the same surface, and record the location, date, and comments for future reference. This is a workable adaptation of ISO 8502-3:1992.[2]

Metallic Abrasives and Moisture

As with all blast cleaning abrasives, metallic abrasives must be kept dry and free of corrosive materials. If the abrasive becomes wet or contaminated with corrosive materials, the particles will rust, tend to stick together in lumps, and create major blast cleaning and recycling problems. Any metallic abrasive should be recovered and cleaned as soon after use as feasible. This is especially important if the abrasive comes into contact with any type of soluble salt.

Bulk Density Considerations

The bulk density of an abrasive is a measure of an abrasive's weight per unit volume, and is usually expressed in pounds per cubic foot. It is important to be aware of the large difference between the bulk density of metallic and nonmetallic abrasives when switching from one to the other. For example, a typical nonmetallic abrasive weighs approximately 100 lb/ft^3, whereas steel abrasives typically weigh 250 lb/ft^3. This becomes an important factor when moving large containers filled with steel that were formerly filled with nonmetallic abrasive. If the container that usually carries 5 tons of a nonmetallic abrasive is filled with a steel abrasive, the filled container will weigh over 12.5 tons. If the lifting equipment used to move this container has a maximum capacity of 5 tons, the container will now exceed the lift equipment's maximum capacity by 7.5 tons, creating a major problem and a potentially dangerous hazard if the crane operator is not aware of the weight of a blast pot full of steel.

Summary of Key Factors in Steel Abrasive Selection

Shape

• Steel shot—Best suited for removing brittle contaminants such as mill scale

• Steel grit—Best suited for removing soft, friable contaminants such as paint and rust

Size

• Large abrasives give deep profile and lower productivity

• Small abrasives give lower profile and higher productivity

Hardness

• High hardness—Deeper profile, faster cutting rates, and reduced durability

• Lower hardness—Less profile, slightly lower cutting rates, increased durability.

Nozzle

• Use the highest nozzle pressure available to get maximum productivity

• The blast angle affects the depth of profile, roughness, and cleaning rates

There are a number of specifications covering abrasives available from different technical organizations and they can be helpful guides in selecting an appropriate abrasive for any application. For further information, consult the bibliography at the conclusion of this chapter.

References

1. *USGS Mineral Industry Survey: Annual Review for Metallic Abrasives in the United States;* U.S. Geological Survey: Reston, VA, 2000.

2. ISO 8502-3: 1992. *Preparation of Steel Substrates Before Application of Paints and Related Products—Tests for the Assessment of Surface Cleanliness—Part 3. Assessment of Dust on Steel Surfaces Prepared for Painting (Pressure-Sensitive Tape Method).* ISO: Geneva, Switzerland, 1992.

Bibliography

SSPC-AB 2 *Specifications for Cleanliness of Recycled Ferrous Abrasives*; SSPC: Pittsburgh and NACE: Houston.

SSPC-AB 3 *Ferrous Metallic Abrasives;* SSPC: Pittsburgh and NACE: Houston.

SSPC-SP COM *Surface Preparation Commentary for Steel and Concrete;* SSPC: Pittsburgh.

SSPC-VIS 1 *Visual Standard for Abrasive Blast Cleaned Steel;* SSPC: Pittsburgh.

SSPC-VIS 2 *Standard Method for Evaluating Degree of Rusting on Painted Steel Surfaces;* SSPC: Pittsburgh.

SSPC SP 5/NACE 1 *White Metal Blast Cleaning;* SSPC: Pittsburgh and NACE: Houston.

SSPC SP 6/NACE 3 *Commercial Blast Cleaning;* SSPC: Pittsburgh and NACE: Houston.

SSPC SP 7/NACE 4 *Brush-Off Blast Cleaning;* SSPC: Pittsburgh and NACE: Houston.

SSPC SP 10/NACE 2 *Near-White Blast Cleaning;* SSPC: Pittsburgh and NACE: Houston.

SSPC SP 14/NACE 8 *Industrial Blast Cleaning;* SSPC: Pittsburgh and NACE: Houston.

SAE-J444 *Cast Shot And Grit Size Specifications For Peening And Cleaning;* SAE: Warrendale, PA.

SAE-J445 *Metallic Shot and Grit Mechanical Testing;* SAE: Warrendale, PA.

SAE-J827 *High Carbon Cast Steel Shot;* SAE: Warrendale, PA.

SAE-J1993 *High Carbon Cast Steel Grit;* SAE: Warrendale, PA.

SAE-J2175 *Low Carbon Cast Steel Shot;* SAE: Warrendale, PA.
ASTM B 215 *Method B Methods of Sampling Finished Lots of Metal Powders;* ASTM: Philadelphia.
ASTM E 384 *Test Methods for Micro Hardness of Materials;* ASTM: Philadelphia.
ISO 11124 *Preparation of Steel Substrates Before Application of Paints and Related Products—Specifications for Metallic Blast-Cleaning;* ISO: Geneva, Switzerland (available from ANSI: Washington, DC).
ISO 11124-1 *Preparation of Steel Substrates Before Application of Paints and Related Products—Specifications for Metallic Blast-Cleaning—Part 1: General Introduction and Classification;* ISO: Geneva, Switzerland (available from ANSI: Washington, DC).
ISO 11124-2 *Preparation of Steel Substrates Before Application of Paints and Related Products—Specifications for Metallic Blast-Cleaning—Part 2: Chilled-Iron Grit;* ISO: Geneva, Switzerland (available from ANSI: Washington, DC).
ISO 11124-3 *Preparation of Steel Substrates Before Application of Paints and Related Products – Specifications for Metallic Blast-Cleaning—Part 3: High-Carbon Cast-Steel Shot and Grit;* ISO: Geneva, Switzerland (available from ANSI: Washington, DC)
ISO 11124-4 *Preparation of Steel Substrates Before Application of Paints and Related Products – Specifications for Metallic Blast-Cleaning—Part 4: Low-Carbon Cast-Steel Shot;* ISO: Geneva, Switzerland (available from ANSI: Washington, DC).
ISO 11125 *Preparation of Steel Substrates Before Application of Paints and Related Products – Test Methods for Metallic Blast-Cleaning Abrasives;* ISO: Geneva, Switzerland (available from ANSI: Washington, DC)
ISO 11125-1 *Preparation of Steel Substrates Before Application of Paints and Related Products—Test Methods for Metallic Blast-Cleaning Abrasives—Part 1: Sampling;* ISO: Geneva, Switzerland (available from ANSI: Washington, DC).
ISO 11125-2 *Preparation of Steel Substrates Before Application of Paints and Related Products—Test Methods for Metallic Blast-Cleaning Abrasives—Part 2: Determination of Particle Size Distribution;* ISO: Geneva, Switzerland (available from ANSI: Washington, DC).
ISO 11125-3 *Preparation of Steel Substrates Before Application of Paints and Related Products—Test Methods for Metallic Blast-Cleaning Abrasives—Part 3: Determination of Hardness;* ISO: Geneva, Switzerland (available from ANSI: Washington, DC).
ISO 11125-4 *Preparation of Steel Substrates Before Application of Paints and Related Products—Test Methods for Metallic Blast-Cleaning Abrasives—Part 4: Determination of Apparent Density;* ISO: Geneva, Switzerland (available from ANSI: Washington, DC).
ISO 11125-5 *Preparation of Steel Substrates Before Application of Paints and Related Products—Test Methods for Metallic Blast-Cleaning Abrasives—Part 5: Determination of Percentage Defective Particles and of Microstructure;* ISO: Geneva, Switzerland (available from ANSI: Washington, DC).
ISO 11125-6 *Preparation of Steel Substrates Before Application of Paints and Related Products—Test Methods for Metallic Blast-Cleaning Abrasives—Part 6: Determination of Foreign Matter;* ISO: Geneva, Switzerland (available from ANSI: Washington, DC).
ISO 11125-7 *Preparation of Steel Substrates Before Application of Paints and Related Products—Test Methods for Metallic Blast-Cleaning Abrasives—Part 7: Determination of Moisture;* ISO: Geneva, Switzerland (available from ANSI: Washington, DC).

Acknowledgements

The author and SSPC gratefully acknowledge the participation of Joe Brandon, Carl Mantegna, Hugh Roper, Don Sanchez, and Ray Weaver in the review process for this chapter.

About the Author

H. William Hitzrot

Bill Hitzrot, prior to his retirement, was an active member of SSPC for about 30 years, chair of the abrasives committee and member of the SSPC Board of Governors. He was also an active participant in the Chesapeake Chapter of SSPC. Bill retired as vice president of Chesapeake Specialty Products, a manufacturer of steel abrasives and iron oxides for industrial use. He remains active in SSPC assisting in updating publications and training programs in the areas of surface preparation and abrasives.

Chapter 2.5
Abrasive Air Blast Cleaning

Scott Blackburn

The Process

Abrasive air blast cleaning is the process of propelling abrasive particles from a blast machine, using the power of compressed air. Converting abrasive particles and compressed air into an effective cleaning treatment takes skill, properly engineered equipment and good judgment. Each component contributes to the overall performance of the system **(Figure 1).**

Primary Elements of a Blasting System

- **Air compressor–**properly sized to produce sufficient volume and pressure
- **Moisture separator and air drying equipment –** to reduce or eliminate troublesome stoppages caused by water
- **Air supply line–**large, with unrestrictive fittings to maintain pressure
- **Blast machine–**with the capacity, valves, and piping for high production
- **Abrasive metering valve –** engineered for steady, uniform flow
- **Remote controls–**for safe, efficient operation
- **Blast hose and couplings–**sized to minimize friction loss
- **Blast nozzle–**matched to compressor output
- **Operator safety equipment–**NIOSH approved and available for all personnel
- **Abrasives–**high quality (clean, angular) and intended for blast cleaning
- **Blast Operator–**experienced and trained for the job

Air Compressor

A standard pressure blast system uses compressed air to pressurize the blast machine, convey abrasive to nozzles, provide breathing air, and

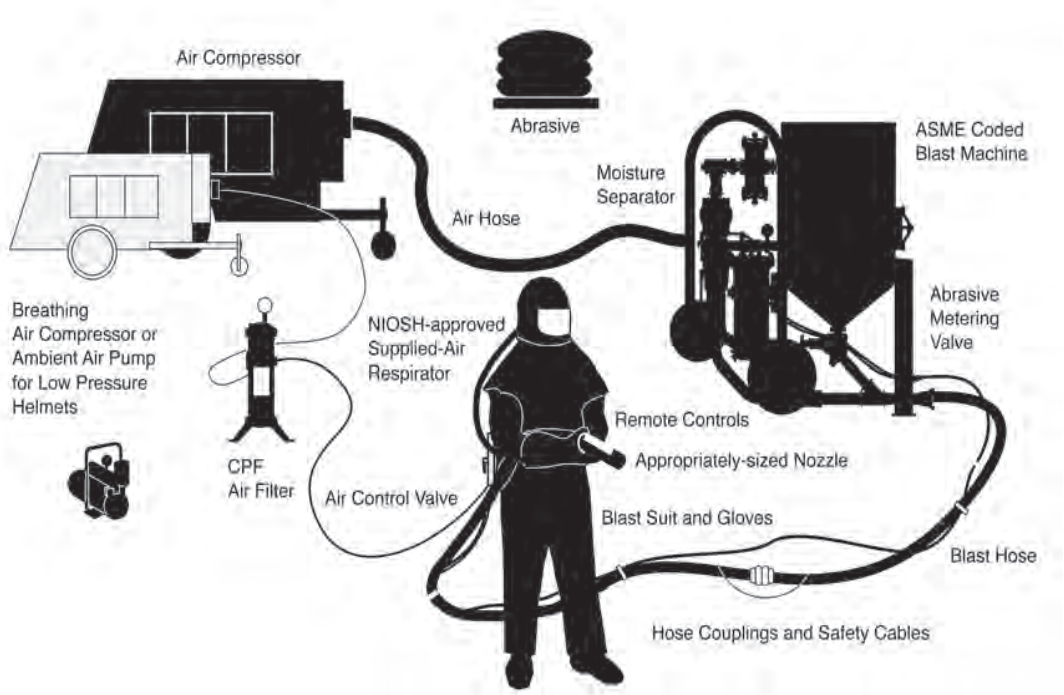


Figure 1. Blast cleaning system components.
Courtesy Clemco Industries Corp.

operate valves and accessories. A compressor's output is measured in pressure and volume. Pressure is expressed in pounds per square inch (psi) or pounds per square inch gauge (psig), volume in cubic feet per minute (cfm). Metric systems use cubic meters per hour or minute to express volume and bar to express pressure **(Figure 2).**



Figure 2. Air compressor. SSPC file photo.

Most air tools operate by using air-driven pistons or diaphragms, which consume the compressed air intermittently. Air supported abrasive blast cleaning equipment demands more from a compressor than any other air-powered tool. High air pressure is not enough – blasting requires a steady supply of high-pressure, high-volume air.

Choose an air compressor that will generate a steady flow of air at high pressure and high volume, built to withstand the environmental conditions found at blast sites, and position the compressor upwind of dust generated by blasting. Also, locate the compressor where vehicle exhaust will not enter the air inlets and ensure that the compressor's own exhaust is directed away from its air inlet.

Moisture Separators and Air Drying Equipment

Water and oil are the worst enemies of abrasive blast equipment. They cause clumps to form in the abrasive, which can clog metering valves, blast hoses, and nozzles. If moisture reaches a steel surface being cleaned, it will cause the steel to rust. If oil reaches a surface, it can cause coating failure **(Figure 3).**

The air around us contains moisture. In the process of getting air to the nozzle for abrasive blasting, the air is heated during compression and then allowed to cool in the line between the compressor and the nozzle. When this air is subjected to rapid expansion at the blast nozzle, the air can be cooled below the dew point, and condensation will form as a water mist. Depending on conditions, condensation can also form in the blast machine and in the blast hose.



Figure 3. Moisture separator. Courtesy Clemco Industries Corp.

Depending on the relative humidity in the ambient air, the tools used for removing oil and moisture from compressed air vary. Representatives from compressor manufacturers can recommend air drying equipment based on the application and the humidity normally encountered on a given job site.

Air Supply Lines

Air flows best through straight, hard air lines. On large-scale, long-term field applications, such as bridges, some contractors install rigid lines in fixed locations. Where hard piping is impractical, the contractor should invest in high-quality, fabric-reinforced rubber air hose. The inner tube of the hose should be of a material that resists swelling caused by moisture and oil. The outer casing should be of durable material, which will provide pressure strength and support the round shape of the inner tube to minimize pressure loss through the system.

Keep the hose length as short as possible and avoid erratic bends. Even correctly sized air hose loses two to three pounds of air pressure for every 50 feet (15 meters) of length. Just one 90 degree bend increases this loss to five or six pounds. Use only as much hose as required for the specific job.

Using the proper size air lines is critical for obtaining the best results from the compressor and the blast system. The inside diameters of the air line sizes must be consistent with the inner diameters of all fittings to allow smooth air flow. For air lines up to 100 feet in length (30 meters), the inner diameters should be at least four times the blast nozzle orifice size.

Refer to the *Minimum Compressor Air Line Sizes* chart to determine the absolute minimum inside diameters to use. Use air lines larger than the minimum recommended whenever possible. No air line is too large **(Figure 4).**

Minimum Compressor Air Line Sizes

Nozzle No.	Nozzle Orifice Size	Minimum Air Line ID
No. 3	3/16" (5.0mm)	1" (25.0mm)
No. 4	1/4" (6.5mm)	1" (25.0mm)
No. 5	5/16" (8.0mm)	1-1/4" (32.0mm)
No. 6	3/8" (9.5mm)	1-1/2" (38.0mm)
No. 7	7/16" (11.0mm)	2" (50.0mm)
No. 8	1/2" (12.5mm)	2" (50.0mm)
No. 10	5/8" (16.0mm)	2-1/2" (64.0mm)
No. 12	3/4" (19.0mm)	3" (76.0mm)

Figure 4. Minimum Compressor Air Line Sizes. Courtesy Clemco Industries Corp.

Choose air hose connectors that offer the least resistance and the greatest internal area. Do not confuse inside diameter (I.D.) with outside diameter (O.D.). An air hose connector's size refers to pipe thread size or to the I.D. of hose it fits. A 1-1/2 inch (38 mm) threaded air hose connector has an O.D. of 1-1/2 inches (38 mm) but only an I.D. of 1-1/4 inches (32 mm) or less, which limits the volume of air that is allowed to pass.

Be especially wary of quick disconnect connectors and threaded swivel air hose fittings. While these may seem to offer convenience and reduce kinking, the internal passageways can be too small and limit air volume.

Blast Machines

There are two basic types of blast machines–suction blast and pressure blast. Suction blasting is less aggressive than pressure blasting and is generally used for light-duty work, such as touch-up blasting. Pressure blasting is used to clean tough surfaces and large areas, indoors and out.



Figure 5. Suction blasting container. Courtesy Clemco Industries Corp.

Suction Blast. Suction blasting, sometimes referred to as venturi blasting, draws the abrasive from a non-pressurized container into a blast gun chamber, then propels the particles out a nozzle **(Figure 5).**

A typical suction system consists of an abrasive container, an air hose, an abrasive hose, and a blast gun and nozzle. Compressed air flows through an air jet located in the blast gun to create suction. This suction pulls abrasive from the container, through the abrasive hose and into the gun body where it is accelerated out the nozzle with the air.

This less-forceful blasting is appropriate for light to moderate cleaning and for spot applications and is useful where the air supply is very limited **(Figure 6).**

Pressure Blast. In pressure blasting, abrasive feeds into a moving stream of compressed air through a metering valve that is mounted beneath the blast machine to regulate the quantity of abrasive fed into the system. Blast machines are known by a variety of names–blast pots, pressure generators, pressure vessels, tanks, and so on **(Figure 7).**

Pressure blast systems are easily distinguishable from suction systems by the single hose that feeds the blast nozzle. Air and abrasive travel through this blast hose at high pressure and



Figure 6. Pressure blasting equipment. Courtesy Clemco Industries Corp.



Figure 7. Abrasive air blast machine. Courtesy Clemco Industries Corp.

high speed, exiting the nozzle at about four times the velocity produced by suction blasting. Pressure blast machines are used in structural steel blasting, for their high production rates, and in lightweight media blasting, for their precise regulation of media flow.

While it may appear to be little more than a steel tank, a blast machine has integral parts that make sizable differences in safety, efficiency, and convenience. Poorly designed blast machines can have restrictions that reduce air flow and air pressure, thereby reducing productivity.

In the United States, all pressure blast machines must be built to meet American Society of Mechanical Engineers (ASME) standards. ASME specifies the type of steel and welding methods used in the manufacture of blast machines, and an ASME-Authorized Inspector supervises the hydrostatic testing of each pressure vessel. A National Board certificate of approval is issued and a metal plate, which bears the board approval number is permanently affixed to the approved machine. Most countries have similar requirements, though the specifications may differ.

In the U.S., most pressure blast machines are manufactured with a rated working pressure of 125 psi (8.8 bar/880 kPa) or 150 psi (10.3 bar/1033 kPa). ASME requires all machines be built with a safety margin 30% greater than the working pressure. If a machine's working pressure is unknown, check the National Board approval plate. Never operate a pressure blast machine that does not have a National Board approval number stamped on a permanently affixed plate and never exceed the rated working pressure of the machine. Serious injury or death may occur if a blast machine explodes under air pressure.

Pay particular attention to a blast machine's external plumbing and valves. Air and abrasive flow through hoses, piping, couplings, valves, and blast nozzles that are all cylindrical. Any reduction in the diameters of these cylinders dramatically reduces the rate of flow. As an example, a 1 inch I.D. (25 mm) cylinder has an area of .80 square inches (49 cm^2). A 1/2 inch I.D. (12.5 mm) cylinder has an area of only .20 square inches (12.3 cm^2). Reducing the diameter of the cylinder by half, reduces its area by three-fourths.

Choose a blast machine that has the capacity, portability and convenience features that best fit the type of work to be performed. The blast nozzle orifice size determines the amount of work that can be done and the amount of air required to perform the work. The compressor must be able to supply sufficient air for the nozzle, plus any accessories, plus a reserve

amount to compensate for nozzle wear.

Based on the compressor and nozzle that will be used, choose a blast machine with an abrasive capacity to supply a minimum of 20 to 30 minutes of steady, non-stop blasting.

Abrasive Metering Valves

In the vast majority of pressure blast machines used for high-production work, a metering valve uses gravity to feed abrasive into a fast-flowing stream of compressed air. Too little abrasive can result in a wide-spread pattern, which slows production and leaves non-blasted surfaces.

Too much abrasive causes particles to collide with each other, which wastes energy and disperses particles unequally within the blast pattern. Exorbitant abrasive usage wastes material and labor **(Figure 8).**

Properly adjusted metering valves ensure the maximum in cleaning power from each abrasive particle. Begin by closing the valve completely. Engage the remote control handle to start air flowing from the nozzle, then slowly open the valve a little at a time. Observe the air and abrasive mixture exiting the nozzle.

A proper valve setting will show a slight coloration of abrasive in the air stream, and experienced operators can hear a steady abrasive flow. Too little abrasive causes a high-pitched sound; too much abrasive, an erratic, pulsating sound.

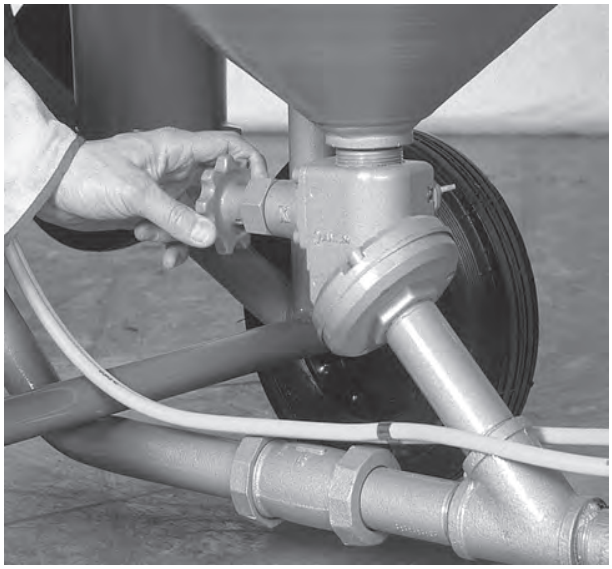
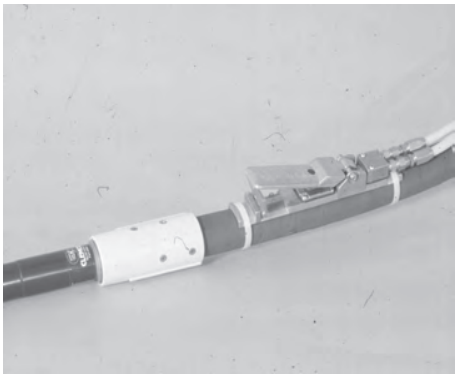
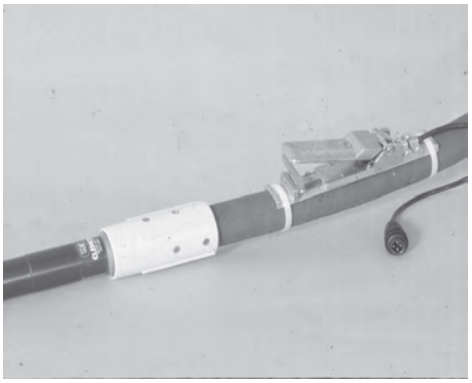


Figure 8. Abrasive metering valve. Courtesy Clemco Industries Corp.

Remote Controls

The Occupational Safety and Health Administration (OSHA) requires remote controls on all abrasive blast machines (Ref: OSHA 29 CFR 1910.244). Using a blast machine without remote controls, especially a “deadman” switch, is a dangerous practice that may result in serious injury or death to an operator or others who may be on the job site. In addition to their safety features, remote controls save substantial amounts of labor, compressed air, and abrasive. If a blast operator must wait for someone to turn off the machine, air and abrasive are squandered. Also, removing the need for a dedicated pot tender saves labor by allowing one person to load abrasive for several machines or do other work between refills **(Figures 9 and 10).**





Figures 9 and 10. Pneumatic and electric remote control handles. Courtesy Clemco Industries Corp.

Two basic remote control operating principles are used in abrasive air blasting. The most popular, pressure-release, allows the machine to depressurize each time the remote control handle is disengaged by the blast operator. This handle must always be located near the blast nozzle and must be used correctly by the operator. Pressing down on the remote control

handle causes the machine to pressurize and blasting to begin. Releasing the handle stops the air supply to the machine, which depressurizes. Abrasive that is held in the blast machine's concave head, or in an overhead storage hopper, automatically refills the machine.

Pressure-hold systems maintain air pressure in the machine even when blasting stops. On a multiple-operator machine, a pressure-hold system allows one operator to stop blasting without affecting the other operator(s). Also, pressure-hold systems can be installed if the blasting demands frequent on and off cycles that might waste too much time, and air, in pressurizing and depressurizing.

Most remote control systems work pneumatically and are well suited for distances up to 150 feet (45 meters). Electric remote control systems may be better suited for distances greater than that.

Different types of air hoses are used with different brands of remote controls. When replacing any control lines or valves, use only those replacement items specified by the manufacturer of the remote control system and install the replacements according to the instructions in the owners operator manual.

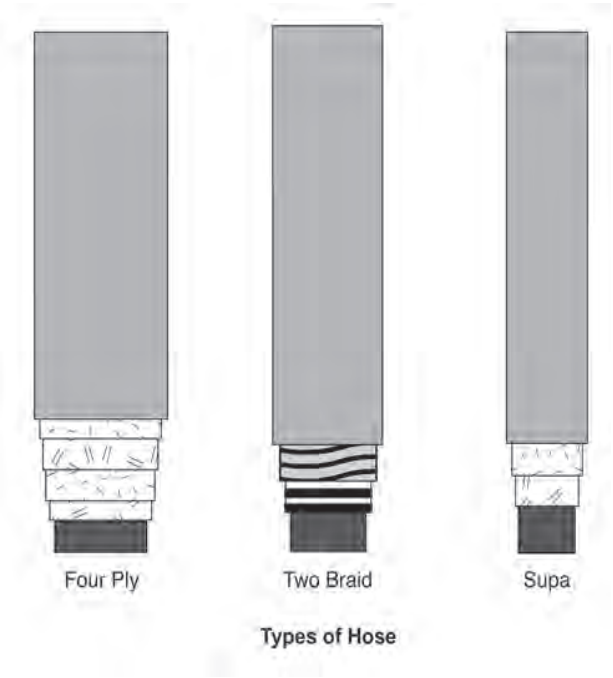


Figure 11. Types of hoses. Courtesy Clemco Industries Corp.

Blast Hose and Couplings

Blast Hose. Blast hose is subject to rapid wear and tear due to the eroding action of high-velocity abrasive on the inside and harsh treatment and weathering on the outside. While couplings rarely wear out they do break from rough handling or are crushed by vehicles.

The best way to help keep costs in line and production high is to use appropriately sized, top-quality blast hose, specifically manufactured for abrasive blasting and rated at the appropriate working pressure. Install only top-quality couplings, designed specifically for use with blast hose **(Figure 11).**

When installing couplings, take extra care to ensure that the blast hose end is cut squarely for a firm, uniform seal against the coupling shoulder. Abrasive that escapes around the end of a sloppily cut hose end will wear away the coupling wall in a matter of minutes.

Like all hose, blast hose is rated for a given working pressure and it should never be used beyond this rating. Its working pressure should be stamped along the length of the hose.

To efficiently convey air-driven abrasive from the blast machine to the nozzle, blast hose should have a sufficient inside diameter and the hose length should be kept as short as possible.

Using a blast hose with an inner diameter that is smaller than the blast machine outlet diameter greatly reduces the amount of air and abrasive flowing to the nozzle.

As an example, a high production blast machine with 1-1/4 inch (32 mm) I.D. piping feeding a 3/4 inch (19 mm) I.D. blast hose must overcome a 64% reduction in capacity. Air and abrasive are now being forced into an area that has one-third the capacity of the blast machine's external piping. This would not be a problem if the blast nozzle is sized for the smaller diameter blast hose. However, if the blast nozzle chosen is sized for a large diameter (1-1/4 inch I.D.) blast hose, the nozzle pressure will drop dramatically. The blast hose I.D. should be three to four times the size of the blast nozzle orifice.

Couplings. Blast hose couplings and nozzle holders are available in a wide variety of materials, sizes, and configurations. Some of the more common materials are aluminum, steel, brass alloy, and glass-filled nylon. Like blast hose, couplings and nozzle holders are

subject to wear from the inside as well as the outside **(Figure 12).**

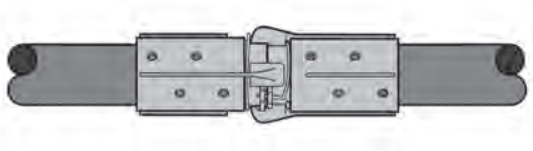


Figure 12. Couplings. Courtesy Clemco Industries Corp.

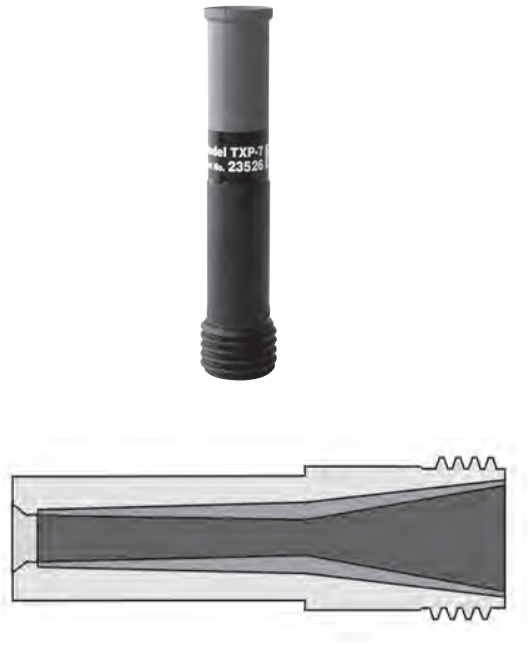
Operators should choose couplings and holders based on their safety and suitability for specific job site conditions—not on their cost. Couplings and holders can become a major replacement expense if the wrong types are chosen.

Couplings should have two locking lugs, identically formed to allow any two sizes of couplings to be firmly connected. These compatible locking lugs are typically found on couplings for blast hoses ranging from 1/2 inch to 1-1/2 inch I.D. (12.5 to 38 mm). When two couplings are placed together for connection, it is important to ensure that each coupling is fitted with a serviceable gasket and that when the couplings are twisted together, firm compression is maintained between the gaskets. Worn gaskets can cause serious air pressure loss and can be a threat to safety. Couplings can become worn to the point where the locking lugs no longer have the material and strength to hold together, destroying the coupling and accidentally disconnecting the blast hose while the hose is under pressure.

Blast Nozzles

Nozzles accelerate the air-driven abrasive into a highly effective abrading or cutting force to handle the toughest applications. The size, type, and shape of the nozzle help determine the production speed and the appearance of the end product. Using the most appropriate nozzle for the application yields a substantial payback in productivity. Additionally, performance of the nozzle reveals whether or not all of the previous requirements for air and abrasive flow have been correctly followed **(Figures 13 and 14).**

There are two basic styles of blast nozzles–straight bore and venturi. Most contractors prefer blast nozzles designed with wide, cone-shaped entrances and gradually tapered exits, which together, form a venturi. Abrasive enters the converging end of the nozzle, funnels through the orifice, and then rapidly expands into a high-powered stream through the diverging exit end. The venturi style nozzle offers greater cleaning capabilities than the straight bore style.



Figures 13 and 14. Blast nozzles. Courtesy Clemco Industries Corp.

However, as the nozzle wears beyond 1/16 inch (1.5 mm) over its original size, it loses its venturi shape and much of the accelerating force that shape provided.

The nozzle liner material primarily affects wear life, which is more than just how long a nozzle will last; it is critical to air consumption. As the nozzle orifice wears, it requires more air volume to maintain a given air pressure. A nozzle with a 3/8 inch (9.5 mm) orifice requires approximately 200 cfm (5.5 m^3/min) to maintain 100 psi (7 bar/689 kPa) working pressure. Through normal use, when this orifice enlarges by 1/16 inch (1.5 mm), the air requirement increases to more than 250 cfm (7.2 m^3/min) – a 25% increase. If the air compressor is unable to maintain nozzle pressure, due to increased demand as the nozzle wears, that pressure loss will decrease productivity. Each one-pound drop in nozzle pressure caused a 1-1/2% reduction in productivity.

It can not be overstressed that maintaining adequate nozzle pressure is essential to high-production blasting. The gauge on the air compressor indicates the air pressure at the compressor only. It does not indicate blasting pressure. Air and abrasive hoses, air filters and moisture separators, blast

machines, and other components between the compressor and the nozzle all contribute to friction and pressure loss.

To accurately determine nozzle pressure, the use of a hypodermic needle gauge is highly recommended for all air abrasive blast operations. This simple, inexpensive tool consists of a needle that is affixed to an air pressure gauge. In use, the needle is inserted into the self-sealing blast hose, just behind the entrance end of the nozzle. The gauge will indicate the actual pressure at the nozzle. The volume and pressure of air that is maintained at the nozzle directly affects the amount of work that can be completed properly.

The blast nozzle should be regularly inspected to ensure that it is not worn or cracked since either condition could lead, not only to a reduction in productivity, but to increased abrasive usage, a less effective blast pattern, and injury, should the liner fail.

Operator Safety Equipment

Air abrasive blasting can be dangerous for a poorly trained, poorly equipped operator. A blast machine produces a powerful stream of sharp particles that, in addition to cleaning a surface, creates clouds of potentially toxic dust. To prevent a variety of injuries and illnesses, personal safety equipment is mandatory for blast operators and other personnel in the work area.

Regulations. Throughout the world, laws govern air abrasive blasting safety. Most countries use safety standards similar to United States standards. In the U.S., the Occupational Safety and Health Administration (OSHA) enforces the regulations pertaining to the safe operation of abrasive blast equipment.

Respirators, such as air-fed helmets and hoods and pressure-demand full-face models, along with most of the other components of the breathing air system, must be tested and approved by the OSHA departments of the National Institute of Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA).

Contractors should always consult with local safety agencies for current regulations. Blast operators who are properly trained and fitted with the best safety and comfort equipment will be much more confident and efficient.

Air-Fed Helmets. OSHA defines an air-fed helmet for abrasive blasting as a continuous-flow, supplied-air respirator. These units are also commonly referred to as, simply, helmets **(Figure 15).**



Figure 15. Air-fed helmut. Courtesy Clemco Industries Corp.

The helmet should furnish the operator with breathing air, protect the face and head from rebounding abrasive and from impacts, muffle noise, and allow for an unobstructed field of view.

While OSHA regulations dictate that noise levels generated by the respirator at maximum airflow, and measured inside the helmet not exceed 80 dBA (decibels on the “A” scale), job site noise can many times exceed the permissible level. In those instances, operators must wear hearing protection appropriate to the surrounding noise environment.

Helmets are available in two basic types: high and low pressure. The high-pressure versions operate from a compressed air supply and the low-pressure units require an air pump. These pumps are commonly known as ambient air pumps or free-air pumps. Air pumps do not compress air; they merely draw in ambient air and push it through the breathing air hose to the helmet.

The helmet window lens system protects the operator’s face from rebounding abrasive. NIOSH requires a single lens of at least .040 inch (.01 mm) thick. Most helmets have frames designed to hold several thin, sacrificial lens covers, which protect the thicker inner lens. When these outer lenses become frosted, by use, the operator is able to tear away the outermost cover to expose another lens.

Breathing Air Filters. OSHA requires that breathing air

filters comply with the requirements for Grade D air (Ref: OSHA 29 CFR 1910.134). These filters are designed to remove oil mists, water vapor, and particles larger than 0.5 micron, which are commonly associated with most air compressors used for abrasive blasting. They should be high-capacity and super-efficient, especially designed for breathing air systems **(Figure 16).**



Figure 16. Breathing air filter. Courtesy Clemco Industries Corp.

The filter has to be able to handle sufficient air volume to supply all the respirators connected to it and it should have an easily replaceable cartridge. It must have a pressure regulator and gauge, not only to regulate the air pressure to the helmet, but also to indicate when the cartridge need replacement. The gauge will show declining pressure as the cartridge becomes saturated with liquid and solid matter that has been removed from the incoming air supply.

Breathing Air Hose. The breathing air hose, which carries air from the air filter to the helmet air control valve, must meet NIOSH specification size, strength, composition, and manufacturing techniques. As with all other regulated parts of this air supply system, the hose carries a NIOSH-approval stamp **(Figure 17).**



Figure 17. Breathing hose in place. Courtesy Clemco Industries Corp.

Never substitute other types of hose for breathing air hose. This special hose is manufactured with strict tolerance for I.D. to ensure unrestricted, steady airflow. Also, breathing air hose is produced without using toxic chemicals in the hose or in the release agents applied to molds and mandrels that are used in the manufacturing process.



Figure 18. Air temperature valve. Courtesy Clemco Industries Corp.

Air Temperature Valves. Two types of air control valves are available for use in place of the standard air control valve that is provided with helmets. One valve

cools the air directed to the helmet and the other valve can cool or heat that air **(Figure 18).**

When the outside air is warm and the compressed air is hot, a valve that provides cooling can reduce the temperature of the air entering the helmet by approximately 30˚F. On the other hand, when working in cold temperatures, a valve that can direct the warm air into the helmet could be very beneficial to the comfort of the operator.

Carbon Monoxide Alarms and Converters. Oil-lubricated air compressors sometimes produce carbon monoxide (CO), a colorless, odorless, deadly gas. Air compressors that are used to supply breathing air should be serviced at the manufacturer's recommended intervals and overheating, shut-off devices, and/or carbon monoxide alarms should be installed. If only an overheating device is used, OSHA regulations require that the air be frequently tested for CO (Ref: OSHA 29 CFR 1910.134) because even brief exposure to CO can kill **(Figure 19).**



Figure 19. Carbon monoxide system. Courtesy Clemco Industries Corp.

An alarm continuously tests air samples for CO. These systems measure the amount of carbon monoxide in the air line and trigger an alarm if the gas exceeds permissible levels. Carbon monoxide converters use chemicals to change CO to carbon dioxide (CO_2). The human respiratory system can tolerate much higher levels of CO_2 than CO.

Protective Clothing. High-velocity abrasive can inflict serious injury upon an unprotected operator. OSHA regulations 29 CFR 1910.94 and 1910.134 require that operators wear canvas or leather gloves and aprons or the equivalent. If the operator is on or around heavy materials, safety shoes are required as well **(Figure 20).**



Figure 20. Protective clothing. Courtesy Clemco Industries Corp.

High quality blast suits have leather, canvas, or equivalent fortification over the areas exposed to rebounding abrasive, usually including the sleeves and the front area of the garment, from the waist to the ankles. The helmet cape usually shields the operator's chest.

Communication Equipment. The age-old method of getting the blast operator's attention is to shut down the blast machine. The operator then has to remove the helmet in order to hear and to respond to what is being said—possibly becoming exposed to toxic dust **(Figure 21).**

A better method is to use battery-powered radio sets, specifically designed for blasting. These

sets allow a supervisor to communicate with several operators at distances as great as one mile (1.6 km).



Figure 21. Helmet communication system. Courtesy Clemco Industries Corp.

Helmet communication systems can speed training of new operators and increase productivity of experienced operators. Communication is more than a convenience, however. A communication system can provide an extra measure of a safety when blasters work outside visual range and blasters can alert their supervisor to any trouble they may encounter.

Abrasives

The air compressor powers it, the blast machine stores and meters it, the blast hose transports it, and the blast nozzle accelerates it. All are important, but the abrasive does the work.

Selecting the correct abrasive is crucial to producing the required finish, on time and within budget. Selecting the incorrect abrasive may produce an inferior, or out-of-spec finish, impede production, require expensive rework, or cause all of the above. Many coating failures can be traced to the use of the wrong abrasive. The best possible blast system cannot compensate for abrasive that is not designed for the work to be done. Use only high-quality abrasives intended for blasting.

There are three sources for abrasives that are used for air blasting–natural, manufactured, and by-products. Natural abrasives are minerals, such as flint and garnet, that are found in deposits. Manufactured abrasives are produced specifically for blasting and include steel, iron, glass, aluminum oxide, plastic, starch, and others. By-product abrasives result from other manufacturing processes. These include slag that is left from power generating stations, smelting operations, and agricultural media from food sources, such as corn cobs and rice hulls. For detailed information on abrasive materials, see separate chapters on metallic and nonmetallic abrasives.

Abrasives are usually classified according to size, shape, density, hardness, and friability, and each characteristic must be taken into account when selecting the abrasive for a specific job.

Blast Operator

Without question, the most important element of any manually operated, air abrasive blast system is the blast operator. The best available equipment will not perform to its potential without trained, knowledgeable, careful and safety minded operators. Investing time and money, up front, to train operators pays off quickly in productivity and reduces the risk and liability of accidents and injuries.

Air blast equipment operators must develop a thorough understanding of what the equipment will do and what will happen if the source of compressed air is altered. Once they comprehend the value of air pressure and volume, they will be better prepared to evaluate the entire blasting system.

Blast equipment manufacturers and professional organizations can be contacted to provide technical training programs on specific blasting equipment and techniques. Once an operator is completely familiar with the form, fit, function, and maintenance of everything from the air compressor to the blast nozzle, the potential hazards that are inherent to abrasive blasting will pose little danger, if the operators are properly attired and use safe work practices.

Equipment Set-Up Procedure

Job Site Conditions

Job sites can present their own set of potential work hazards. Many hazards are relatively easy to identify; however, some are inconspicuous. In either case, close attention must be paid to any chance of worker endangerment Owners, supervisors, safety engineers, and workers have a responsibility to identify safety threats and take necessary precautions prior to starting any work.

Prior to setting up the equipment, carefully survey the job site using a common-sense approach to locate potential problems. If there is any doubt about any particular situation, all necessary steps should be taken to eliminate the hazard.

While it is impossible to list all of the potential hazards that may exist on any job site, some of the most common are heat, electrical power lines, hazardous gases, work surface and noise hazards, and operator visibility.

Equipment Set-Up

After performing the job site inspection, the blast equipment may be set in position. For outdoor work, the air compressor should be placed upwind from the blasting area to help prevent dust from entering the compressor air intake. The pressure setting on the compressor must not exceed the working pressure of the blast machine(s). Conventional machines have a maximum working pressure of 125 psi (8.6 bar/860 kPa) while other machines have higher ratings. Check the metal identification plate that is permanently affixed to the blast machine to determine its working pressure. Refer to the air compressor manufacturer's manual for the proper start-up, operation, and maintenance information.

Install the components of the blasting system according to the instructions in the operator's manuals that are supplied with the blast equipment.

Lay the air hose and the blast hose in the most direct line to the blast machine and the work, with as few bends possible. Since there is less friction loss in an air hose without abrasaive than in a blast hose with abrasive, the blast machine should be located as close to the work as possible.

After laying out all the components required for the job, hook-up the air hose and the blast hose to run a test on the remote control system. Do not add abrasive to the blast machine at this time. Make sure the air hose and the blast hose are properly connected and that safety cables are in place at each hose connection. Also ensure that each blast hose coupling is in good working condition, includes a firm fitting gasket, and is equipped with safety locking pins. Check the blast nozzle and nozzle holder for wear, paying special attention for cracks in the nozzle liner and worn threads in the holder. Make sure the nozzle washer is in place and in good condition.

Carefully inspect the operator protective equipment to determine that each component is in perfect working order. Check air-fed helmets for any damaged or worn parts, being especially attentive to broken head bands, cracked helmet breathing air hoses, over-stretched inner collars, damaged outer capes, leaking window gaskets, broken window frames, and clogged air supply valves. Check the air filter cartridge for cleanliness, as described in the owner's manual. Carbon monoxide (CO) monitor and alarm systems should include field calibration equipment.

Remember that no dust, from any source, is safe to breathe. Blast operators may be well protected while using approved, filtered, air-fed helmets during the blasting process, but they need to safeguard their respiratory systems before and after the blasting process as well. A great danger is often posed by early removal of operator and bystander respirators in dust-laden abrasive blast areas.

Cycle the air on and off several times to ensure that the remote control system is functioning properly. Do not use the blast machine until the remote control system operates as designed and according to its instruction manual.

When all equipment is assembled and given a thorough check, the machine may be loaded with abrasive and work can begin.

Equipment Tear-Down

Once the job is completed, or at the end of the workday, follow the shut-down procedures described in the equipment owner's manuals. All personnel in the blasting area during shut-down and abrasive clean-up must wear NIOSH-approved, properly rated, supplied-air respirators. Clean-up can be more hazardous than blasting because of the high concentration of pulverized abrasive.

The blast machine should be emptied of all abrasive. Leaving abrasive in the machine overnight could cause moisture absorption. One effective method for emptying the machine is to uncouple the blast hose from the machine outlet, adjust the metering valve to its full open position, close the pusher line choke valve, reduce the air pressure to approximately 40 or 50 psi, and pressurize the blast machine until empty.

Upon completion of abrasive clean-up, the safety engineer should test the blasting zone atmosphere with a dust monitor for the presence of

dust. When the air is clear of dust, the blast operator and all personnel in the blasting zone should vacuum clean their clothing. After removing the vacuum-cleaned respiratory protection equipment, inspect it for wear or damage, immediately replacing worn parts as necessary using the owner's manual as a guide.

Turn off the air compressor and bleed-off the air receiver tank. Hearing protection should be worn during this process. Bleed accumulated water from moisture separators, air dryers, and after-coolers following the manufacturer's instructions. Continue to refer to the owner's manuals that the manufacturers have provided in order to keep the blast system components operating safely and efficiently.

Acknowledgements

The author and SSPC gratefully acknowledge the participation of Hugh Roper and Steve Dobrosielski in the peer review process for this chapter.

About the Author

Scott Blackburn

Scott Blackburn has worked in the abrasive blast and paint spray equipment industry for the past 34 years. Currently vice president of sales at Clemco Industries Corp., he has also served as a field sales and service representative in the Midwest and managing director of Clemco's Southeast Asia operations based in Singapore, during his 28 years with the company.

Chapter 2.6
Centrifugal Blast Cleaning

Hugh Roper and Allen Slater

Introduction

Cleaning surfaces by propelling abrasives at high velocities began in the late 1860s. Although wheel blast technology was not formally introduced until the 1920s, it is widely used today to prepare industrial surfaces for coating.

It was soon recognized that there was a real need to produce equipment designed to handle and dispose of large quantities of abrasive and to contain the dust generated in the cleaning operation. It was also necessary to find abrasives that produced the desired levels of cleanliness and profile, caused minimal damage to the equipment, and could be recycled.

Fortunately, industry was able to produce equipment and shot and grit abrasives to meet these requirements. A mix of shot and grit may be used for desired surface conditions and optimum cleaning rates. This chapter describes the use of modern centrifugal blast cleaning systems.

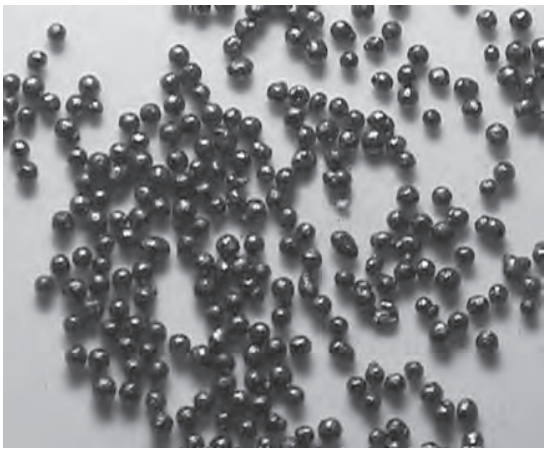


Figure 1. Steel shot.
Courtesy Wheelabrator Abrasives, Inc.

Relative Blast Cleaning Capabilities

Centrifugal blast cleaning rates for cleaning fabricated steel items to a near-white finish (SSPC-SP 10/NACE 2) may vary from 2,000 to 5,000 ft^2/hr,

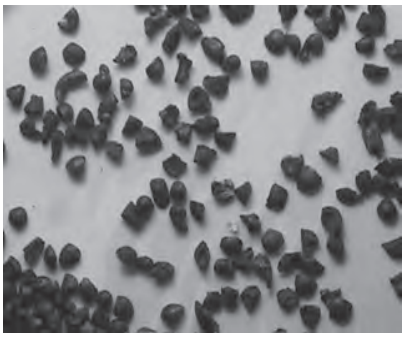


Figure 2. Grit.
Courtesy Wheelabrator Abrasives, Inc.

depending upon the materials and structural design. Steel plates have even higher cleaning rates. Typical rates for conventional air blast cleaning of steel at 100 psi using a no. 8 venturi nozzle orifice are 200 to 260 ft^2/hr. Also, centrifugal blast cleaning normally results in more uniform cleaning and profiling than does conventional air blast cleaning.

On the other hand, centrifugal blast cleaning does have some operational disadvantages in comparison to conventional air blast cleaning. Even though wheels can be located to clean items with complex configurations, complete cleaning is often difficult to achieve.

In many instances, it is necessary to complete the cleaning using conventional blasting equipment. Also, portable blasting equipment does not have close access to walls and other obstructions (e.g., ladders on exterior tank walls), so that conventional air blasting may be required to complete the work.

Centrifugal Blast Machines and Their Operating Principles

Automated centrifugal blast machines are used in shops to clean and profile coiled steel sheet, structural steel beams, rail cars, and other fabricated products. Portable wheel machines are used on ship decks and hulls, water storage tanks, and concrete floors and pavements.



Figure 3. Centrifugal blast equipment. Courtesy Wheelabrator Abrasives, Inc.

Blast wheels range in diameter from 10 to 38 inches and turn from at speeds of 1,200 to 3,600 rpm. Motors range in size from 1 to 150 horsepower. Speed and horsepower are selected to meet specific surface preparation needs. The abrasive is introduced at the center of the wheel onto the blades that propel it at a high velocity onto the substrate, as directed by the control cage setting. Impact force is based on the familiar equation:

$$F = MV^2/2$$

where:
m = mass
v = velocity (increasing the velocity greatly increases the impact force)

An abrasive velocity of 100 ft^2/sec. can be achieved using a 12-inch-diameter wheel running at 1,800 rpm; four times this velocity can be achieved using a 20-inch-diameter wheel running at 3,600 rpm. The smallest abrasive size that produces the desired cleaned condition and the greatest number of impacts results in the greatest cleaning rate. Thus, increasing the horsepower of motors or using multiple wheels can increase cleaning rates. Of course, multiple wheels are used to clean all surface areas of fabricated items. Size, shape, composition, and hardness of the item/substrate dictate the number and locations of wheels at optimum angles of impingement.

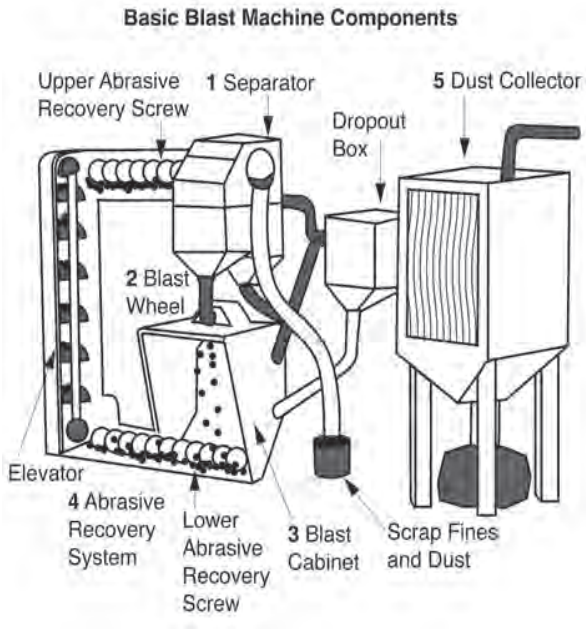


Figure 4. Basic blast system components. Courtesy Wheelabrator Abrasives, Inc.



Figure 5. Typical duct work with dampers. Courtesy Wheelabrator Abrasives, Inc.

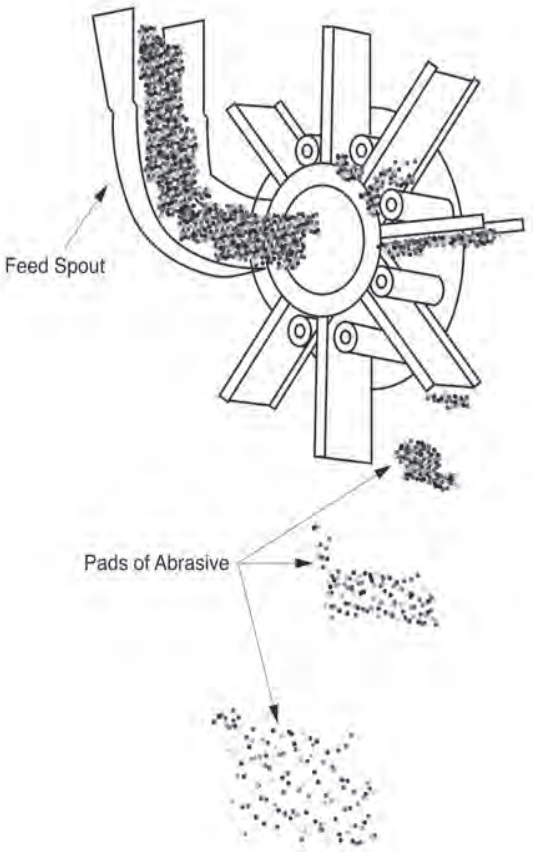


Figure 6. Typical wheel assembly throwing abrasive. Courtesy Wheelabrator Abrasives, Inc.

The three sections of a typical basic abrasive blast pattern are headings, hotspots, and tailings **(Figure 7).** The control cage can be used to control the hot spots for optimum cleaning rates.

An adequate dust collector and ducting system must be used to contain the spent abrasive and debris and prevent it from contaminating the work area. The spent abrasive is transferred to the separator for cleaning and mixing with new abrasive, as appropriate for reuse.

SSPC-AB 2 covers the requirements for cleanliness of recycled ferrous metallic blast cleaning abrasives used for the removing coatings, paints, scale, rust, and other foreign matter from steel or other surfaces. Steel abrasives can be recycled many times, as long as they are properly cleaned and returned to the abrasive storage hopper.

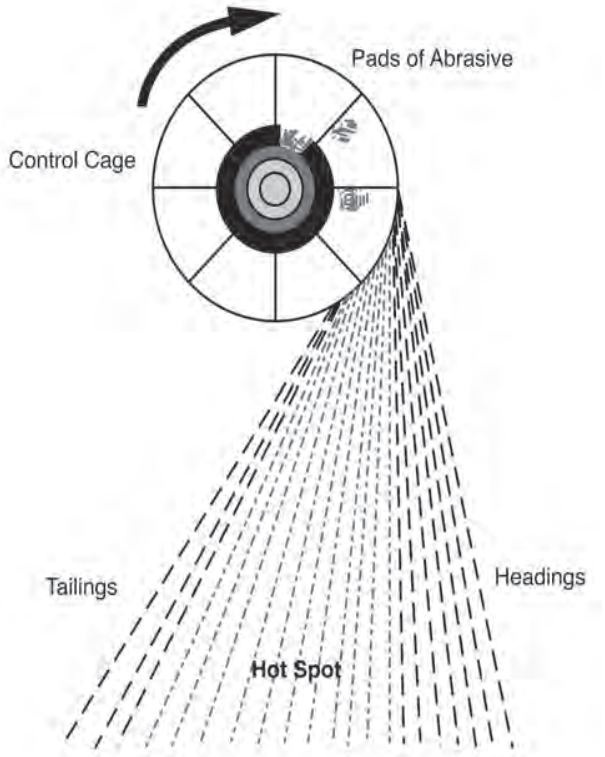


Figure 7. Control cage setting and typical blast pattern detailing headings, hot spots, and tailings. Courtesy Wheelabrator Abrasives, Inc.

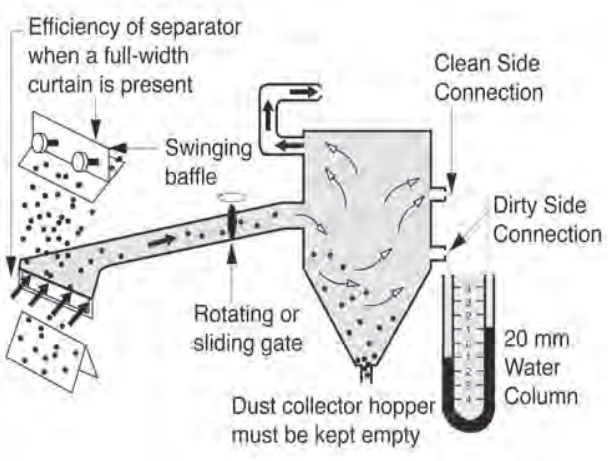


Figure 8. Basic air separator operating system with dust collector and necessary controls. Courtesy Wheelabrator Abrasives, Inc.

Shop Wheel Blast Cleaning

Centrifugal blast cleaning and profiling of steel for painting is most effectively used in production shops where standard items are routinely cleaned and primed or completely coated, as described in the chapter of this book on shop coating. Cleaning steel plates, structural members, and pipes prior to fabrication requires a loading conveyer, often equipped with other accessories. When specialized (non-standard) post-fabrication items are cleaned, it is necessary to reconfigure the wheels, which takes time and money.

Portable Wheel Blast Equipment

Over the past 40 years, the use of portable wheel blast equipment has steadily grown. All portable wheel blast machines consist of a throwing wheel encased in a lined and mobilized blast housing. Attached to the housing is a rebound collection plenum, an air-wash separator, and an abrasive storage tank. A flexible mouth seal and negative pressure is used for these systems to minimize contamination of surrounding areas. The advantages of portable wheel blast systems compared to conventional air abrasive blasting are economics, consistency in levels of cleaning and profile, and waste reduction.

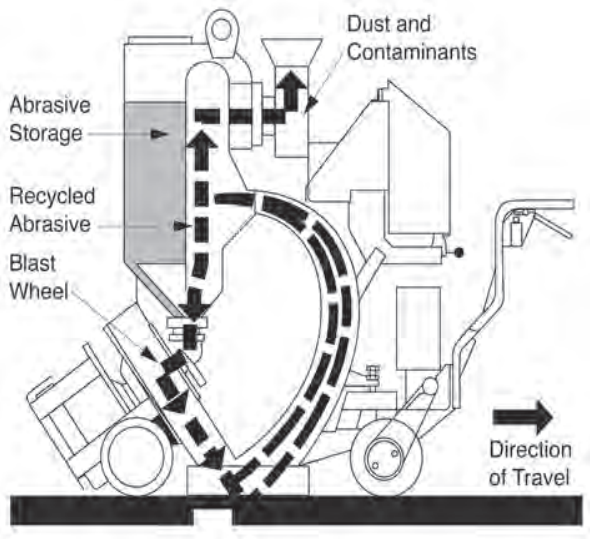


Figure 9. **Portable wheel blast schematic. Courtesy USF Surface Preparation Group.**

Steel Substrates

Initially, this equipment was developed to remove non-skid coatings from the steel decks of aircraft carriers **(Figure 10).** Other applications now include steel ship decks, storage tanks, and chemical process vessels.



Figure 10. Portable wheel blast equipment on an aircraft carrier deck. Courtesy USF Surface Preparation Group.

Horizontal machines are capable of cleaning new and previously painted steel decks and floors at rates of 200 to 1,100 ft^2/hr, depending upon machine size, structural configuration, and desired level of cleaning and profiling. Some units can be disassembled to fit through a 19 to 24 inch passageway and then reassembled for cleaning **(Figure 11)** in a tank or other enclosed space.



Figure 11. Steel surface preparation inside a storage tank. Courtesy USF Surface Preparation Group.

Vertical machines can be used to blast clean tank exterior walls and hulls of ships at rates of 250 to 3,000 ft^2/hr. Cranes or specially designed rigging systems support the machines during cleaning operations.

Special rigging systems are designed to

permit portable wheel systems to clean cone, dome-shaped, and flat roofs.



Figure 12. Vertical cleaning system. Courtesy USF Surface Preparation Group.

Concrete Substrates

Mobile equipment for blast cleaning and profiling concrete with steel shot can be powered by electricity, gasoline, diesel, or propane. Different shot sizes (e.g., S-170 to S-460) will produce different concrete profile heights, as described in International Concrete Repair Institute Guideline No. 03732, *Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays*.

These machines are used mostly to clean and roughen horizontal surfaces for the application of coating materials. It will remove some existing coatings, adhesives, and surface contaminants. They are not usually suitable for removing uncured resins, resilient coatings and adhesives, and tar materials. Vertical concrete walls are usually cleaned with hand-held equipment.

Production rates for machine cleaning concrete vary widely with the type and size of equipment used, the strength of the concrete, the type of material being removed, and operator skill. For small units, typical rates are 150 to 250 ft^2/hr; for larger units, they may be 2,000 to 4,500 ft^2/hr.



Figure 13. Self-contained wall cleaner. Courtesy USF Surface Preparation Group.

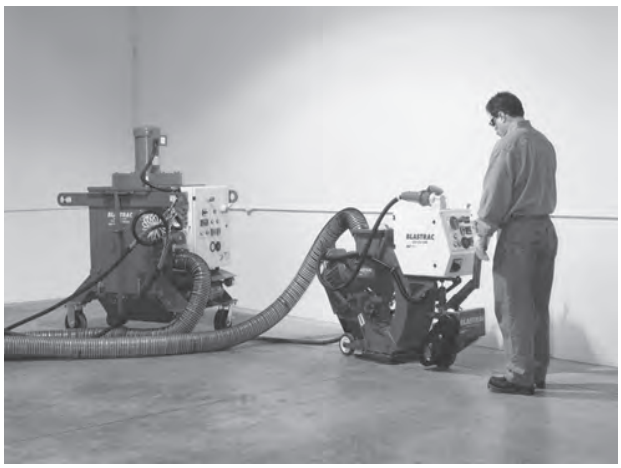


Figure 14. Small floor unit. Courtesy USF Surface Preparation Group.

Suggested Reading

Mallory, A.W. *Guidelines for Centrifugal Blast Cleaning;* SSPC: Pittsburgh,1984.
Mastering The Profiling Process With Wheel Blast Machines; Wheelabrator Abrasives: Atlanta,1998.
Fauntleroy, T; Kehr, J.A. *Fusion Bond Epoxy Application Manual;* 3M: Austin, TX, 1991.
Centrifugal Wheel Blast Cleaning of Steel Plate, Shapes, and Fabrications; NACE: Houston,1974.
Palaster, H. J. *Blast Cleaning and Allied Processes Volumes 1 and 2;* 1972.
Centrifugal Blast for Surface Preparation; SME Technical Paper MR 79–764.
Methods of Dust Free Abrasive Blast Cleaning Plant Equipment; PP 116–125; 1978.

Acknowledgements

The authors and SSPC gratefully acknowledge Joe Brandon, Charles Carlin, J. A. Kehr, Maurie McCally, and Gary Weil for their participation in the peer review process for this document.

About the Authors

Hugh J. Roper
Hugh J. Roper is a technical advisor with Wheelabrator Abrasives, Inc. He is active in SSPC's abrasives and surface preparation group committees and is also a member of the SSPC committee on soluble salt contamination.

Allen Slater
Allen Slater is a regional sales manager for Blastrac®, a part of the USF Surface Preparation Group. He provides factory support to the distribution group and technical support to the marketing department on issues relating to surface preparation of steel and concrete. Allen serves on the board of directors for the International Concrete Repair Institute (ICRI) and is a member of several SSPC and NACE committees. He has been in the industry for 24 years and has spoken to industry groups both in the U.S. and in Australia about the benefits of surface preparation.

Chapter 2.7
Wet Abrasive Blast and Pressurized Water Cleaning (Waterjetting)

Lydia M. Frenzel, Ph.D.

Introduction

In the past ten years, wet abrasive blasting (WAB) and waterjetting (WJ) have evolved as surface preparation methods. This attitude and cultural change is driven by environmental regulations, safety and health concerns, economics, and enhanced performance. Since 1994, SSPC has issued these documents about WAB and WJ:

- SSPC SP 12/NACE 5. *Surface Preparation and Cleaning of Steel and Other Hard Materials*
- SSPC-TR 2/NACE 6G198. *Wet Abrasive Blast Cleaning*
- SSPC-VIS 4/NACE VIS 7. *Guide and Reference Photographs for Steel Cleaned by Waterjetting*
- SSPC-VIS 5/NACE VIS 9. *Guide and Reference Photographs for Steel Cleaned by Wet Abrasive Blast Cleaning*

Wet abrasive blast cleaning encompasses several different methods in which water, air, and abrasives are used to clean the substrate. The processes range from injecting water into abrasive streams propelled by air (air/water/abrasive blast cleaning) to adding abrasive into a pressurized water stream (water/abrasive blast cleaning). Wet abrasive blasting has been found to be an increasingly popular application where dust cannot be tolerated in new and maintenance projects.

Waterjetting or water cleaning (WC) is the use of water alone to clean the substrate; in other words, to remove unwanted materials such as rust, dust, grime, paint, scale, grease, oil, or salt to expose the existing profile. The coatings industry uses WJ primarily for recoating or relining projects where there is an adequate preexisting profile.

Wet Abrasive Blast Cleaning

There are a large variety of systems for WAB ranging from almost all abrasive with a little water to mostly water with a little abrasive. Generic terms to describe specific air/water/abrasive blast cleaning methods are “water shroud” or “wet-head” blasting, wet blasting, low-volume water abrasive blasting, and slurry blasting. Generic terms to describe specific water/abrasive blast cleaning methods are slurry blasting, abrasive waterjetting (AWJ), or abrasive injected waterjetting/blasting (AIWJ or AIWB).

SSPC-TR 2/NACE 6G198 describes processes and equipment but does not redefine the cleaning standards previously defined for dry abrasive blasting: SSPC SP 5/NACE 1, SSPC SP 10/NACE 2, SSPC SP 6/NACE 3, SSPC SP 7/NACE 4, and SSPC SP 14/NACE 8.

Surfaces cleaned by WAB typically appear darker and duller than surfaces cleaned by the same abrasive in dry blasting. When the surface is examined in a wet condition, it appears darker with defects and variations in shading magnified. Thus, it is advised that a small area be examined in a dry condition to determine the level of cleanliness. As the surfaces dry, streaks may form. Whether or not these streaks are acceptable should be addressed by the contracting parties.

The variety of water/abrasive combinations allows WAB to be used in cleaning sensitive substrates, cutting steel and concrete, dismantling and demolishing tanks and concrete, and removing coatings. Abrasive waterjet cutting systems are used in areas where hot work is not allowed.[1] The water helps wet the abrasive and reduce dispersion of respirable particles. When substantial amounts of water are used, the flow can assist in dissolving soluble contaminants. Conventional dry blast equipment can be fitted with a head to introduce pressurized or tap water. Specialized equipment combines air/abrasive streams with pressurized water from 5,000 up to 40,000 psig.

Pressurized water equipment is modified so that the abrasive can be added under pressure or via a suction head. There are systems where the mixed water and abrasive steam is pressurized through the

water pump, but they are not commonly found in the paint removal industry. **Figure 1** illustrates an abrasive pot and induction head for use on a pressure washer.



Figure 1. Wet abrasive blast cleaning. Induction head, two-stack blast pot, soft soluble abrasive for LP W. Cleaning graffiti from concrete. Courtesy Universal Minerals.

Any type of abrasive commonly used with dry blast cleaning can be used with WAB with limitations on the duration of wetting and solubility. Some of the abrasives used in WAB or AWJ cutting are sand, magnetite, ilmenite, hematite, natural iron oxides, aluminum oxide, garnet, copper, slag, coal slag, sodium bicarbonate, and Kieserite. Use of expensive abrasives is generally limited because the abrasive is wetted and normally not recycled. In recent years, equipment to collect the wetted abrasive, hydrocyclones to separate the water and solids, filter presses to dewater the solids, and filters and pressure pumps to recycle the water are becoming more popular. Complete recycling systems are more commonplace.

Production rates for WAB are similar to dry blasting. All traces of wetted abrasive should be removed from the surface before painting. This is typically accomplished with a power wash that might contain inhibitors. The removal step and subsequent time for the water to dry can reduce the overall production rate. Contractors experienced with WAB can increase the overall production rate by employing waste minimization and pollution prevention techniques.

Table 1. Air/Water Abrasive Parameters.

	Compressed Air	Water	Water Rate
External Ring	100 psig	0-4500 psig	5-8 gpm *
Internal Ring	100 psig	0-150 psig	3-5 gpm *
Internal/Air Assist	100 psig	25-60 psig	0.25 gpm *
Hybrid	100 psig	5,000-36,000 psig	2 gpm **
Slurry Blaster	100 psig	0-150 psig	0.5 to 3.0 gpm
Integrated Slurry	100 psig	25 psig	0.2 to 0.4 gpm ***

gpm = gallons per minute

* The abrasive feed and consumption rate is the same as normally for dry abrasive blast systems.

** Water is pressurized: a compressed air stream carries the abrasive. The two streams are mixed proprietary head. Typical feed rate is 2 to 3 pounds abrasive per minute.

*** Water and abrasive are mixed 1:4 parts in a pot and propelled by compressed air.

In systems where water is added to the air/abrasive stream, the safety precautions of dry blasting prevail. The largest waste stream in dry blasting is the abrasive. WAB offers the potential to reduce the size of the abrasive waste stream. The advantages include the ability to be able to work close together and to decrease the amount of ricochet and the amount of respirable dust. The disadvantages include having to wash off the wetted abrasive and to collect the water and wet abrasive.

Water Cleaning or Waterjetting

SSPC SP 12/NACE 5 defines low-pressure (LP) (<5,000 psig), high-pressure (HP) (>5,000 psig), ultra high-pressure (UHP) (>30,000 psig) water cleaning and waterjetting (>10,000 psig). Water blasting is a generic term originating from the trade name Water Blaster. SSPC limits the terms “blasting” or “blast cleaning” to describe activities where abrasives are present.

Table 2. Abrasive Injected Waterjetting.

	Water	Water Rate
Abrasive Injected Waterjet	3,000-40,000 psig	2 to 10 gpm

The abrasive rate can vary from 0.5 pound per minutes to 6-10 pounds per minute.

When water is used alone, the water stream does not create the primary profile for paint systems. However, WJ opens the profile under the existing paint or rust and removes the detritus. Just as in abrasive

blasting, the key to cleaning by water is to get the energy of the pressurized water transferred to the substrate efficiently. When moving from low-pressure water cleaning to UHP WJ, the energy density increases.

SSPC SP 12/NACE 5 defines four levels of visible cleanliness (WJ-1, WJ-2, WJ-3, and WJ-4) to correlate to the four levels of cleanliness defined for abrasive blast cleaning (SP 5/NACE 1, SP 10/NACE 2, SP 6/NACE 3, and SP 7/NACE 4). The WJ levels of cleanliness are not exactly the same, especially for the WJ-2 and WJ-3 as tightly adhering foreign matter, including welding residues, coating, rust, or mill scale are allowed to remain on the surface. WJ-2 and WJ-3 are closer in concept to SP 14. Experienced jetters can remove coatings one layer at a time, create surface roughness in the intermediate coatings, or clean to bare metal.

WJ can remove all materials to the bare substrate. However, as it is used in refurbishment, coatings manufacturers prefer removing coating that has minimal adherence or cohesion while maintaining the material that is still good. WJ can reveal many defects in the surface—from scratches to heat spots to differences in the steel composition and prior corrosion under the existing paint system. This can challenge someone trained in traditional dry blast techniques who is seeing WJ for the first time, especially when general education and training material is limited.

SSPC-VIS 4 illustrates a series of of unpainted and painted surfaces. The Advisory Council also provides educational and training modules for contractors, engineers, and inspectors. Consult these sources to learn more.

At levels below 10,000 psig, the cleaning action of the water is determined predominately by the hydraulic characteristic (gal./min.); above 30,000 psig, the action of the water is determined predominately by the velocity (pressure). Both low and high-pressure systems use engines, pumps, hoses, and guns. Clean, filtered water is driven through a pump and the pressurized water conveyed through hoses to guns with small diameter orifice(s) in a nozzle **(Figure 2).** In addition, WAB systems have some means of mixing abrasive into the water stream or water into an abrasive stream as shown earlier in Figure 1.

The size of the cleaning job dictates the equipment required. The volume of the water and the pressure influences the cleaning rate. The quality of

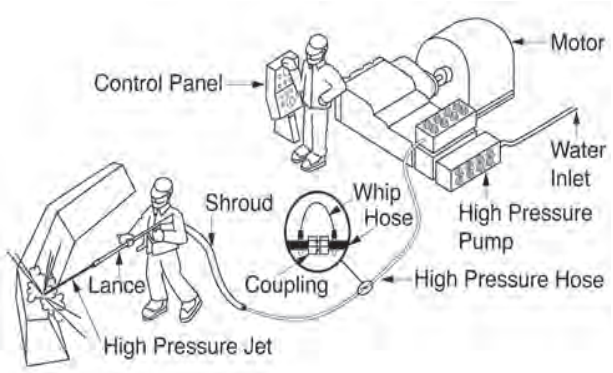


Figure 2. Waterjet cleaning operations showing system components. Courtesy Waterjet Technology Association.

the potable water can affect the pump life, as well as the final cleaned substrate. UHP WJ systems are more sensitive to general water quality than the LP WC or HP WJ systems.

Pressure and flow are varied within LP WC, HP WC, HP WJ, and UHP WJ to provide comfort for the user while maximizing production. The back thrust should be no more than 1/3 the body weight. **Figure 3** illustrates that the back thrust for UHP WJ does not appear tiring. Details concerning flow rates, pressures, and energy intensity are found in SSPC SP 12/NACE 5.



Figure 3. UHP WJ with manually held gun. Illustrates lack of back thrust and the water mist the rewets the steel. Courtesy Flow International.

Pressurized water systems are also used in mining, food preparation, sculpture, quarrying, restoration, graffiti cleanup, concrete demolition, sewage and environmental cleaning, internal and external pipeline

rehabilitation, and airport maintenance. Specialized equipment and heads are available from a number of sources.

Low-Pressure Water Cleaning

LP WC, also called pressure or power washing, is usually below 3,500 psig. It is used to remove loosely adhered materials such as chalk, dirt, dust, weak concrete laitance, marine growth, and light scale. Pressure washers are used in conjunction with chemicals or detergents to remove oil and grease accumulations. LP WC is prevelant in sidewalk cleaning, car washes, wood restoration, shipyards, and bridge cleaning. Typically LP WC utilizes a fixed orifice, or a rotating nozzle with fixed orifices. Thus, the production rate is generally increased by increasing the flow. Abrasives of all sorts may be injected into low-pressure water cleaning or pressure washing in order to increase the effectiveness of removing materials.

High-Pressure Water Cleaning and High-Pressure Waterjetting

Pressurized water pumps are available in ranges from 5,000 psig up to about 24,000 psig. At 10,000 psig, the velocity of the water is close to 1,100 ft./sec., or a fluid jet. The velocity then starts to change the amount of cutting or cleaning from a hydraulic action to an erosion action.

Table 3. Water Cleaning and Jetting at High Pressures.

High-Pressure	>5,000 psig to < 30,000 psig
High-Pressure Water Cleaning	>5,000 psig (34 MPa)
High-Pressure Waterjetting	>10,000 psig (68 MPa)

High-pressure water cleaning (HP WC) and high-pressure waterjetting (HP WJ) are used to remove or clean all types of substrates. Nominally filtered potable water as well as filtered river, lake, or salt (sea) water are used in these pumps.

Typical cleaning applications for at various pressures include:

- **4,000 psig:** weak concrete, medium marine growth, sandstone and mudstone, loose scale, loose rust and paint, product accumulation on floors, and clear pipes
- **6,000 psig:** concrete in pipes, severe marine fouling, runway rubber, lime scale, burnt oil deposits, petrochemicals, exposed aggregate, stains, building restoration, vegetation, tar, cement, asphalt on vehicles, sewers, and drain pipes
- **10,000-24,000 psig:** concrete cutting, most paints, mill scale, burnt carbon deposits, tube bundles, clinkers, expansion joints or paint stripes on highways, concrete demolition, tube cleaning, decontamination of tools and equipment

Flow, pressure, and tip combinations are selected to suit the job. Pressure and volume must provide maximum removal rates while limiting back thrust and fatigue. If the gun is to be held manually, then the combination of pressure and flow are selected so that the back thrust is around 25 to 30 pounds, or less than 1/3 the body mass of the jetter.

There are several different types of pumps and guns available. The length of the gun barrels range from 15 inches to 3 ft. The head may consist of a single orifice with a diffusion pattern or a multiple orifice nozzle rotating up to 3,000 rpm. Pumps are available in a range of horsepower. In HP WC, HP WJ, or UHP WJ, the production rate is generally enhanced by increasing the pressure but not necessarily the flow.



Figure 4. UHP WJ. Remote-controlled crawler with full vacuum recovery. Welding in the same vicinity. Courtesy Flow International.

Ultra High-Pressure Waterjetting

UHP WJ has been used for cutting or abrasive waterjet cutting since the 1970s. The small diameter orifice transforms the water into a high-energy stream that erodes the material. Since 1990, development of longer lasting seals and rotating heads with multiple orifices to diffuse the pattern has opened UHP WJ cleaning applications.

Equipment is now available to remove up to

2,000 ft^2/hr of thick non-skid coatings. As **Figure 4** shows, welding and other trades can work in close proximity with WJ applications. Manually held equipment at 40,000 psig (270 MPa) is operated around 2.5 gallons/min. (gpm) with a total back thrust 25 pounds compared to 6 gpm total for remote heads in crawlers and mower configurations. At SSPC 2001, field equipment operating at 55,000 psig was exhibited.



Figure 5. HP and UHP WJ. 78-inch wide path for fast removal of heavy coatings and concrete repair. Courtesy NLB Corp.



Figure 6. HP and UHP WJ. Cleaning concrete with typical mower. Operates from 7,000 to 35,000 psig. Courtesy of NLB Corp.

WJ equipment and accessories are changing rapidly in much the same manner as the computer industry has changed. By the time equipment is purchased and integrated, it seems obsolete. Production rates continue to increase each year. The overall production rate does not appear to be limited by the equipment capability but rather by mechanical considerations: how fast the jetter can move the guns or push the mower; how much time is spent in inspecting the cleaned area; or movement of scaffolding or the anchor points of heads hung on the side of structures. **Figure 5** is a head that cleans 78-inch wide swaths. **Figure 6** shows removing coatings from concrete prior to repainting. **Figure 7** illustrates a hand-held tool with a 6-inch nozzle and a “shop vac” or simple Venturi head vaccum source mounted on a 55-gallon drum.

The move to higher and higher pressures is driven by the use of less and less water (less back thrust), higher production rates, and cleaner surfaces. The higher the pressure, the more critical the water quality becomes.



Figure 7. Six-inch diameter hand-held head with small vacuum source attached. Courtesy Advisory Council and Aqua-Dyne, Inc.

Flash Rust

Flash rust, or water bloom, is oxidation that occurs on steel within minutes as water dries (defined in SSPC SP 12). Steel naturally oxidizes when water is present. Flash rust quickly changes appearance to a rust bloom over a large surface area. The color of the flash rust may vary depending on the age and composition of the steel and how long the substrate was wet prior to drying. Drying with hot air blowers or the vacuum systems can reduce or eliminate flash rust. The problem can become a major obstacle inside

confined spaces where it is difficult to reduce the humidity or remove the standing water. Figure 4 illustrates water mist that rewets the substrate to create flash rust.

If light-to-moderate flash rust is relatively free of soluble salts, many coatings manufacturers will allow paint to be applied over it. Heavy flash rust is a loose powder or dust that should not be painted over. Selecting coatings with good wetting characteristics can encapsulate the loose dust. When flash rust is too heavy for coating application, it may be reduced or be removed with clean hand-held wire brushes or by pressure washing with fresh water.

Some questions to ask when rusting appears are:

- What is the source and accelerant of the rust?
- Is the surface clean and the iron oxides relatively pure?
- Does the rust contain salt, acid, chloride, sulfate, or other contaminants?

Corrosion is accelerated by temperature, and the presence of dissolved oxygen or conductive species. Osmotic blistering is made more severe by leaving conductive, water-soluble species on the substrate under the coating.

Inhibitors and Salt Removers

Inhibitors and salt removers are used extensively in industrial cleaning operations to reduce or prevent rusting on wetted steel. Some additives possess both inhibitor and salt remover properties. If water-soluble ionic materials are reduced, then the problem of osmotic blistering as water is transported through the coating is also decreased.

Originally, inhibitors were a permanent part of the coating used to protect against the presence of invisible contaminants. Currently, the philosophy is that inhibitors should not remain on the surface because the long-term effects of any residual contaminants on the coating system are not known. There are presumably no invisible contaminants left on the surface if the WJ job is done correctly; therefore inhibitors, salt removers, and detergents are transitory.

Overall, chemical additives are should reduce flash rust, leave no detectible residue, be environmentally safe, and be effective at a low concentration. To avoid “pooling” of chemical-treated water on flat surface, the excess should be blown away with oil-free compressed air or thoroughly washed off with freshwater.

There is no clear consensus concerning inhibitors and salt removers. In 2001, coatings manufacturers typically recommend painting over light-to-moderate tight flash rust rather than risk incompatibility additive and paint or the possibility of leaving water-soluble materials on the surface. It is strongly recommended that the coatings manufacturer be contacted to assure that the rust inhibitor or salt remover is compatible with the specific coating system being applied.

Salts

One of the greatest benefits of water is to remove invisible soluble contaminants. Waterjetting can be effective in removing water-soluble surface contaminants that may not be removed by dry abrasive blasting alone; specifically, those contaminants found at the bottom of pits and craters on severely corroded metallic substrates. Waterjetting, with and without detergents, also helps to remove surface grease and oil.

Three levels of “non-visible” contaminants are described in SSPC SP 12. There is no consensus on what levels of salt cause premature failure in the field. When a coating is placed in laboratory testing where vapor-phase transmission is the driving force, a given formulation from the same manufacturer at the same thickness exhibits less blistering when there is less salt on the substrate. The amount of blistering can vary for the same formulation from different manufacturers.

In a comparison on the USS Paul Foster in 1995, the Navy reported the following results for 13 salt species:

- **Hand-held grit blasting unit:** 120.71 µg/cm^2 left on surface
- **Hand-held waterjetting unit:** 2.61 µg/cm^2 left on surface

Select a process appropriate for the task: use pressure washing to wash down painted surfaces that have been contaminated with salt spray; use HP or UHP WJ to remove salt at the bottom of deep pits.

Recycling—Environmental

Just as respirable dust must be contained and collected in abrasive blasting, the water must be collected and contained in WJ and WC. Droplets of water and wetted abrasive fall to the ground within a

short space of the actual blasting. Typically, the containment walls are made of breathable cloth or plastic; the ground is bermed with impervious plastic sheets; and the water/solid mixture is collected in a low spot and moved to the treatment process by diaphragm trash pumps.

Since 1995, equipment for collection, solid separation, oil removal, and recycling water has become prominent. For WJ, mechanical separation of solids from the water is handled by filters or settling tanks. Removing solids and sending water to a publicly owned treatment facility after a single use oftentimes is more economically than recycling. Depending on the specific project, water is recycled routinely in the <25,000 psig range. Equipment is available for recycling water in the >30,000 psig range.

WAB generates wetted abrasives that generally cannot be reused nor recycled. Fluid hydrocyclones, simple chemicals, or electrical techniques are used to "drop out" or flocculate the solids and de-watering filter presses are employed where the effluent water is of "drinking-water" quality. The abrasive-paint mixture becomes a solid cake or is dried for reclamation.

The waste streams are divided into the solids associated with the coatings and dirt; the paint solids/solvents; and the water. With vacuum collection techniques the water does not enter the environment but can recycled throughout the entire project, so that only water lost to evaporation must be replaced. As an example, in 1994, a pump system operating at 10 gpm and 40,000 psi with a closed-cycle recovery system was demonstrated at Puget Sound Naval Shipyard. Over time, it was established that the consumption rate was only 50 gallons (200 liters) per day.

Production Rates

Production rates, which vary tremendously with the experience of the jetter, can range from 30 $ft.^2$/hr to 2,000 $ft.^2$/hr. Cleaning speed is dependent on the highest manageable working pressure, volume of water, and abrasive injection. Heads range from a single orifice to rotating 2-inch nozzles to wide paths. As with other processes, WJ has been successful in removing some mill scale while other mill scale does not come off as readily.

The size of the work crew and how many different tasks can be completed within the same area will further impact the production rate. Figure 4 illustrates welding in close proximity to WJ. The problem of linear task sequencing becomes non-linear in this process. When turnaround time is important, it is possible for a contractor to have one WJ crew cleaning complex shapes, one crew applying the stripe coat, one crew using a crawler on the flat surfaces (with optional vaccuum), one crew painting the flat surface, and welding or engine repair going on in the same vicinity. Published WJ production rates also factor in the time required to set-up and build the containment and collect spent abrasive/water as well as ease of disposal and clean-up time.

Production rates for WAB compare favorably with dry blasting. Wet abrasive blasting requires an additional step of rinsing the surface to remove the wetted abrasive. However, the requirements for engineering controls may be less than for dry blasting, particularly where paint with toxic materials are being removed.

Cost Comparison

There are two obstacles to adopting WJ: the cost to replace capital equipment (i.e., moving from blast pots and abrasive blasting hoses/lines to HP WJ pumps and lines and nozzles), and training required for efficient equipment use. New equipment costs are approximately the same and production rates vary.

Contractors who perform both dry blasting and WJ confirm that whether or not WJ and WAB are more economical than traditional blasting depends on the specific project. Sometimes the cost differences are close; sometimes there is clear advantage to either. Historically, only part of the surface preparation and repainting costs were included in any comparisons since set-up and disposal costs were left to the owner. When the cost of the entire project is considered—containment, mobilization, engineering controls, inhibitors/rinsing, workers/activities occurring in close proximity, turn-around time, waste minimization, cleanup, and disposal—WAB and WJ may have an edge.[2]

Health and Safety

Companies working with WJ cite these positive safety aspects:

- Workers can see better
- Site is clean
- Respirable particulates are agglomerated in the water mist and are no longer breathable

• Drift of the wetted particles is limited so they fall to the ground within a short distance
• Incidence of personal accidents down

It is not easy to verify that personal accidents have decreased. The information was gleaned from panel safety discussions at WJTA meetings and talks with contractors. Those accidents that do occur are quite disastrous, making manufacturer training of operators in the correct use and maintenance of equipment essential at the time of purchase. Only persons who have completed a proper training program and have demonstrated knowledge, skill, and experience should perform assigned tasks.

Injuries to hands and feet are the most common reported problems. Operators should treat the high-velocity fluid jet just as carefully as a high-pressure grease or airless spray gun. As stated in WJTA's *Recommended Practices for the Use of Manually Operated High-Pressure Waterjetting Equipment:* "A person injured by being hit with a waterjet will not necessarily see the full extent of the injury, particularly the internal damage and depth of penetration. Even though the surface wound may be small and may not even bleed, it is quite possible that large quantities of water may have punctured the skin, flesh, and internal organs through a very small hole."[3]

Safety for WAB incorporates the same considerations important during dry abrasive blasting and in the use of fluid jets. It also varies with specific processes and ranges. In areas where sparks are a hazard, abrasive waterjet (AWJ) cutting is used; UHP WJ cutting of high explosive materials has been tested up to 143,000 psig (1,000 MPa).[1]

Some safety tips include:
• Never point the equipment at anyone.
• Never put hands in front of the gun.
• Depressurize equipment not in use.
• The blast gun should have an automatic controlled-release pressure and the operator should always be in control of the pressure.
• Use clean, filtered water.
• The area around the work site should have controlled access and proper signage.
• The higher the pressure, the smaller the orifice, the shorter the effective distance.

Acknowledgements

The author and SSPC are grateful for editorial assistance from Nancy Shaver of *Cleaner Times* magazine, peer reviews by Ken Trimber and Joe Brandon, and for these companies that have provided input and support: Aqua-Dyne, Inc; Flow International; NLB Corp.; Ingersoll-Rand Corp.; HoldTight Solutions; Hydrochem Industrial Services; UHP Projects, Inc.; Ameron Protective Coatings; International Paint; Carolina Equipment and Supply; Aulson Co.; Atlantic Marine, Inc.; A-1 Able Services, Inc.; Nozl-Tech LLC; Freemyer Industrial Pressure; Hammelmann Corp.; Hartman-Walsh Painting Co.; Nor-Vac Industrial Services; John Odwazny; Acquablast Tratamento De Superficies Ltda.; Bridgecote Feroguard Technology Inc.; and Universal Minerals.

References

1. Miller, Paul L. Fluid Jet Ignition Hazards Safety Analysis. In *Proceedings of 1999 American Waterjet Conference;* pp 873-893; Impact Initiation Mechanisms of High Explosive Materials During Waterjet Demilitarization. In *Proceedings of 2001 American Waterjet Conference;* pp 425-438.
2. Lever, Guy. Hydroblasting Permits Safe, Cost-Effective Dam Rehabilitation. *Materials Performance,* April 1996, pp 38-41; Lever, Guy. WaterJetting Cuts Hazardous Waste at Dam. *Journal of Protective Coatings and Linings*, April, 1996, pp 37-41; Johnson, Mark L. Get the Lead Out! Removing Lead-Based Paint on Hydro Plant Structures. *Hydro-Review,* May 1996, pp 54-57.
3. WaterJet Technology Association. *Recommended Practices for The Use of Manually Operated High Pressure Waterjetting Equipment;* WJTA: St. Louis, 2000.

About the Author

Dr. Lydia Frenzel
Dr. Lydia Frenzel has been chair of the SSPC and NACE water blasting committees almost every year since 1985. She received the 1996 Technical Achievement Award, has been vice president of the Waterjet Technology Association, written over 55 papers and presented over 45 talks. She is passionate about promoting emerging technology in continuous improvement initiatives and is a professional speaker.

Chapter 2.8
The Effect of Soluble Salts on Protective Coatings

Bernard R. Appleman

Introduction

It has been well documented that soluble salts are widely present in marine, industrial, and urban environments. Sodium chloride is obviously present in marine atmospheres. As a result of de-icing of highways, salt is deposited on bridges and vehicles.

Research sponsored by the Federal Highway Administration demonstrated that test panels exposed in industrial and marine sites accumulated substantial surface deposits of sulfates and chlorides, respectively, in less than 6 months.[1]

Gross showed that bridge steel exposed to the atmosphere accumulated numerous types of salts, often in significant quantities.[2] Theoretical and experimental studies have demonstrated that salts, particularly chlorides, nitrates, and sulfates, initiate and accelerate corrosion of steel.[3, 4] They are also capable of causing coating breakdown through osmotic blistering. The critical question by users and applicators is the influence of these salts on the performance and economics of corrosion-protective coatings systems.

This chapter examines the following:

- What is the evidence of the effects and impact of soluble salts on coating performance? Are they a significant factor in the corrosion of steel?
- What techniques are available for detecting and identifying these contaminants?
- What techniques are available to remove them or negate their effects?
- What levels of soluble salts are permissible on steel to be coated?

Degradation Caused By Soluble Salts

Soluble salts can affect the performance of coatings systems on steel in several different manners: by accelerating the corrosion of the steel and by promoting blistering and loss of coating adhesion.

Influence Of Soluble Salts On Osmotic Blistering

Soluble salts under coatings have been shown to promote blistering in various theoretical and experimental studies.[5, 6] Osmotic blistering occurs because the salt on the substrate in the presence of moisture forms a highly concentrated solution. The water on the exterior of the film is at a much lower concentration. The water is more energetically stable if the concentrations are equal. The paint film behaves like a semi-permeable membrane, allowing water but not salt to penetrate the film and concentrate on the metal coating interface. The accumulation of water and salt under the coating results in a pressure (osmotic), which can cause a blister. The osmotic pressure is approximately proportional to the difference in the molar concentrations between the steel surface and the exterior of the film. Numerous studies have shown that the growth of blisters is directly related to the concentration of salt at the steel/coating surface.[7, 8]

For example sodium chloride has a molecular weight of about 58 atomic mass units (amu). Therefore 10 microgram (µg) of sodium chloride dissolved in 1 microliter of water would result in a concentration of 1700 millimoles/liter. Using an approximate conversion of 360 psi/mole; this solution could exert an osmotic pressure of 60 psi.

The effect of sodium chloride can be compared to that of sodium sulfate, which has a molecular weight of about 150 amu. Thus 10 µg of sodium sulfate would yield a concentration of only 65 millimoles/liter. Based on a weight of salt per unit area, sodium chloride would produce a higher differential in concentration between the steel surface and the exterior coating surface and a potentially higher osmotic pressure. Another important factor is solubility, which determines the maximum osmotic pressure that can be produced by a particular salt. Osmotic blistering can produce pressures of several thousand psi, which is enough to disbond the coating.[9]

The molecular weights, solubilities, and maximum osmotic pressures of several common salts are shown in **Table 1.**

The size and rate of growth of blisters depends not only on the salt concentration difference

Table 1. Molecular Weights, Solubilities, and Maximum Osmotic Pressures of Several Common Salts.

Compound	Solubility [i] G/100g water (1)	Maximum Osmotic Pressure*
Calcium nitrate	56.4 (20°C)	2500
Potassium nitrate	31.6 (20°C)	1100
Ammonium nitrate	192 (20°C)	8700
Sodium nitrate	88 (20°C)	3800
Sodium chloride	36 (20°C)	2200
Sodium sulfate	48.8 (40°C)	2500
Ammonium chloride	37.2 (20°C)	2500
Ammonium sulfate	75.4 (20°C)	4200
Potassium chloride	34.0 (20°C)	1700
Ferrous nitrate $6H_2O$	45.6 (20°C)	1200
Ferrous chloride $4H_2O$	42.2 (30°C)	1500
Ferrous sulfate $7H_2O$	26.5 (20°C)	690
Ferric chloride	91.8 (20°C)	6200

* Estimated using formula: P(osmotic[psi]) = concentration(moles/liter) * 365[ii]
i Handbook of Chemistry & Physics, 40th Edition, Chemical Rubber Publishing Co., 1959, pp 1694-1705

between the underside and topside of the coating, but also on the thickness, adhesion, and other properties. For a specific salt concentration and other factors being equal, osmotic blistering is more severe in fresh water than in salt water. Also osmotic blistering is only rarely encountered in atmospheric exposures unless the coating is subjected to frequent condensation or is partially immersed. **Figure 1** illustrates osmotic blistering.

Acceleration Of Corrosion In The Presence Of Salts

Salts, particularly chlorides, nitrates, or sulfates, can increase the rate of metal corrosion. These salts act as catalysts, accelerating the anodic reaction. Numerous studies have shown the pronounced effect of sulfur dioxide pollution and chlorides on corrosion rates of steel.[10, 11] One study showed that

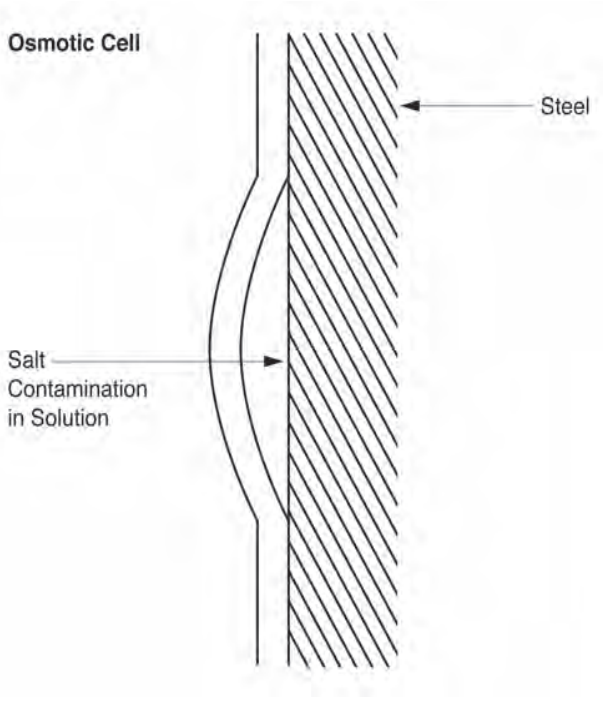


Figure 1. Osmotic blistering.

the presence of both chlorides and sulfates caused increased weight loss of steel, which was proportional to the amount of chloride or sulfate present.[12] Further studies have demonstrated that sulfate and chloride participate directly in the corrosion reactions of steel.

Alblas and van Londen have summarized the reactions of chloride with steel as follows:[13]

First the chloride (e.g., from sodium chloride) reacts with the iron at the anode to form ferric chloride ($FeCl_3$).

$$2Fe + 6Cl^- == 2(FeCl_3) + 6\ e^-$$

Ferric chloride can react with water to form ferric hydroxide and hydrochloric acid.

$$FeCl_3 + 3H_2O == Fe\ (OH)_2 + 3\ HCl$$

The hydrochloric acid attacks the steel to form ferrous chloride.

$$Fe + 2HCl == FeCl_2 + H^2$$

In the presence of oxygen and HCl the ferrous chloride

is oxidized to re-form ferric chloride.

$$4FeCl_2 + 4HCl + O_2 === 4FeCl_3 + 2H_2O.$$

The sum of the last 3 reactions therefore results in corrosion of iron (to ferric hydroxide) with the chloride serving as a true catalyst and not being consumed.

$$4Fe + 10\ H_2O + O_2 == 4Fe(OH)_3 + 4\ H^2$$

Morcillo, et. al., noted similar effects from nitrates in the influence on the corrosion rates on steel.[4, 15] The authors noted that the corrosion of steel depends on the presence of oxygen and water. The susceptibility of a coating film to under-film corrosion depends on its permeability to these two species. As expected, the permeation and hence corrosion was greater for thinner films. This study examined the influence of various salts in stimulating corrosion under vinyl and polyurethane varnishes (un-pigmented resins) at two coating thicknesses. The authors concluded that chloride ion contamination is more corrosive than nitrate ion contamination with sulfate having the least influence on corrosion. The authors explain these trends based on conductivity and solubility of the salts and the solubility of their corrosion products.

Lowering of Vapor Pressure by Soluble Salts

Soluble salts can also affect the propensity of water to condense on the surface of a coating or steel. Condensation occurs when the pressure of the water vapor in the atmosphere is equal to or greater than the vapor pressure of the water film on the surface. Any salt on the surface of the steel will reduce the vapor pressure of the water/solution and thereby increase the tendency for condensation from the water vapor. For example, at 68°F (20°C) water saturated with sodium chloride has a vapor pressure of about 14 mm, compared to a vapor pressure of 22 mm for pure water. As a result the saturated solutionwill absorb moisture up to 11°F (6°C) above the dew point. (The dew point is the temperature of the surface at which water from the atmosphere will condense.) Thus when the wet bulb (of a dew point determination) is 80°F (27°C), the surface covered with sodium chloride needs to be 11°F (6°C) warmer, or 91°F (33°C), to avoid condensation.[9]

Here it is clearly established that soluble salts can affect the protective ability of coatings by promoting osmotic blistering of coatings and increasing the corrosion rates of steel by catalyzing the corrosion reaction. The next aspect to consider is the capability of determining the type and quantity of the salts deposited.

Extraction Of Salts From Steel Substrates

Determining the type and quantity of soluble salts on the surface requires two steps: extraction and analysis. A few of the techniques accomplish these in one procedure, but typically two separate operations are required.

Extraction Methods

The field methods utilized for extracting the soluble salt are:

- Swabbing
- Adhesive patch cell
- Adhesive sleeve
- Wet filter paper extraction method

This section also describes a laboratory method for total extraction.

Swabbing. In this technique, the operator rubs or swabs cotton cloth saturated with deionized water across a measured surface (typically about 4x4 inches [100 x 100 mm]). The method is described in SSPC TU-4.[16]

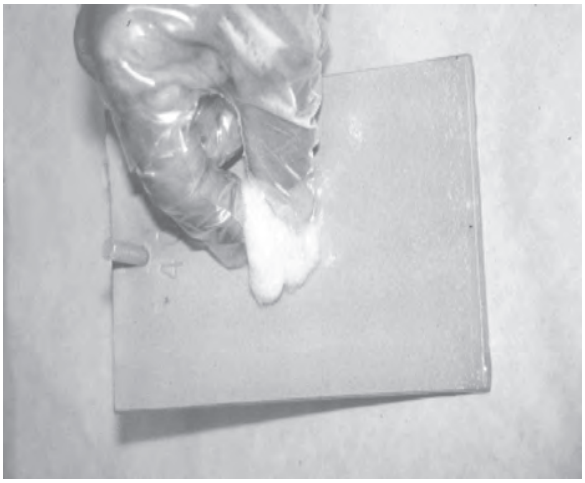


Figure 2. Swabbing steel surface.

Adhesive Patch Cells (Bresle Cell). The Bresle Cell consists of a small adhesive patch covered with a latex

film that attaches to the substrate forming a cell cavity. Deionized water or other extraction fluid is injected using a syringe to extract the soluble salt. This method is described in SSPC TU-4 and in ISO 8502-6.[17]



Figure 3. Adhesive patch cell (Bresle).

Adhesive Sleeve (Chlor-Test). In the Chlor-Test method, the extracted liquid is added to a sleeve before attaching it to the surface. Also a proprietary acidic solution is used instead of water. This method is included in the proposed revision of SSPC TU-4.[18]

Wet Filter Paper Extraction Method. A pre-wetted absorbent filter paper is placed on the surface to be extracted. The paper wets the surface and extracts soluble salt. This method is included in the proposed revision of SSPC TU-4.[18, 19]

For each of the first three methods, the liquid is then analyzed for soluble salts as described here. For the wet filter method, the filter paper is placed over the electrodes of a resistivity meter to measure conductivity.

Boiling Extraction Method. In this method, the substrate is immersed in boiling deionized water for 30 minutes or more. The method is used as a reference method to compare the salt retrieval rates (extraction efficiencies) of other methods. It is also referred to as the "Mayne" method. This method is also described in SSPC TU-4.[19]

Efficiency of Extraction

A critical factor in this process is the capability of the above methods to quantitatively extract the salts from the surface. The efficiency is defined as the percent of salt extracted divided by the total salt on the substrate. Numerous experiments have been undertaken to determine this quantity. One approach is to add a known quantity of specific salts (typically sodium chloride) and compare the quantities extracted with different techniques under different conditions. This technique is normally applied to relatively pristine (uncontaminated) blast-cleaned steel. Accordingly, it does not provide direct data on the extraction efficiency on rusted and pitted steel, which are often the locations of greatest concern.

An alternative technique is to measure the total concentration of soluble salts on sections of steel comparable to the specimens measured using field extraction methods. The "total" concentration can be measured by the boiling water method as described previously. Yet because it requires immersion, the method can only be used on small panels or on pieces of steel cut from a structure.

A review of recent literature indicates a wide spectrum of extraction efficiencies of the various methods **(Table 2).** The extraction efficiency apparently depends on the nature of the substrate and the concentration of the salt as well as on the specific technique and the operator's proficiency. Efficiencies greater than 100% can occur due to inaccuracies in the doping of the surfaces or errors in the boiling method used as a reference or operator error.

Neal, et. al., evaluated numerous properties of chloride-contaminated line pipe, including efficiency and accuracy of extractions.[19] They used two extraction procedures, a specially designed extraction cell and the swab method. The cell, measuring 6 inches (152 mm) in diameter, was adhered to a surface, filled with 6.8 oz. (200 ml) of distilled water, left to soak overnight, and withdrawn and analyzed for chloride using ASTM D 512, Method A (titration). Multiple sections of a chloride-contaminated pipe were extracted with each of the methods. The swab was done in triplicate for each section and the extraction cell in duplicate. The researcher observed that for chloride levels of up to (4.5 µg/cm^2) [using the cell method as a reference] the swab method was unable to detect any chloride in over 80% of the cases. In the other instance, the swab method extracted a maximum of 20% of the quantity extracted by the cell.

Steinsmo noted that the amount extracted with the Bresle cell varied with the time of contact (extraction time), with his data based on 5 minutes.[23]

Table 2. Extraction Efficiencies.

Method	Surface/ condition	Salt/ concentration	Efficiency*	Source/ Comment
Swabbing	SP 5/doped/ 12 hrs @75%RH A36 steel [1]	Cl: 20, 200, 250 & 500 µg/cm^2	43% to 78% avg.. 56%	Appleman et al., (1992) [1]
	SP 5/doped/ 12 hrs @75%RH	SO4: 20 & 200 µg/cm^2	27% to 42% avg.. 34%	Appleman et al., (1992) [1]
	SP 5/doped/ 12 hrs @75%RH	NH4: 10 & 100 µg/cm^2	24% to 86% avg.. 55%	Appleman et al., (1992) [1]
Magnetic cell	SP 5/doped/ 12 hrs @75%RH	Cl: 20 & 200 µg/cm^2	63% to 87% avg.. 75%	Appleman et al., (1992) [1]
	SP 5/doped/ 12 hrs @75%RH	SO4: 20 & 200 µg/cm^2	30% to 38% avg.. 34%	Appleman et al., (1992) [1]
	SP 5/doped/ 12 hrs @75%RH	NH4: 10 & 100 µg/cm^2	25% to 32% avg.. 29%	Appleman et al., (1992) [1]
Boiling	SP 5/doped/ 12 hrs @75%RH	Cl: 20 & 200 µg/cm^2	95% to 103% avg.: 99%	Appleman et al., (1992) [1]
	SP 5/doped/ 12 hrs @75%RH	SO4: 20 & 200 µg/cm^2	40% to 94% avg.: 67%	Appleman et al., (1992) [1]
	SP 5/doped/ 12 hrs @75%RH	NH4: 10 & 100 µg/cm2	62% to 77% avg.: 69%	Appleman et al., (1992) [1]
Swabbing	Degreased Cold rolled steel (CRS)/doped	Cl: 5, 15, 50, 100 µg/cm2	82% to 120% avg.. 100%	Flores Selective ion electrode (SIE) [iii]
	CRS doped	SO4: 100, 150, 200 µg/cm^2	80% to 86% avg.: 83%	Flores-94 turbidity [iii]
Bresle	CRS doped	Cl: 15, 50 µg/cm^2	133% to 166% avg.: 150%	Flores-94 SIE [iii]
	CRS doped	SO4: 100, 150, µg/cm^2	57% to 126% avg.: 92%	Flores-94 turbidity [iii]
Boiling	CRS doped	Cl: 5, 15, 50, 100 µg/cm^2	99% to 125% avg.: 113%	Flores-94 SIE [iii]
	CRS doped	SO4: 100, 150, 200 µg/cm^2	110% to 114% avg.: 112%	Flores-94 turbidity [iii]
	SP 5/doped	Cl: 10, 25, 50 µg/cm^2	63% to 95% avg.. 77%	Boocock [iv]
Bresle	SP 5/doped	Cl: 10, 25, 50 µg/cm^2	42% to 90% avg.. 62%	Boocock [20]
Boiling	SP 5/doped/ 10 days @ 80%RH	Cl: 10, 25, 50 µg/cm^2	69% to 78% avg.. 74%	Boocock [20]
Bresle	SP 5/doped/ 10 days @ 80%RH	Cl: 10, 25, 50 µg/cm^2	17% to 28% avg.: 22%	Boocock [20]
	SP 5/doped/ 10 days @ 80% RH/SP-10	Cl: 10, 25, 50 µg/cm^2	26% to 53% avg.: 35%*	Boocock [20]
	SP 5/doped	Cl: 1.5, 3.0, 6.0, 18 µg/cm^2	20% to 80% avg.. ~60%*	Steinamo [v] 1.2-3.0 µg/cm^2 remained #

* Compared to boiling (assumed to yield 100%)
Constant level of chloride after Bresle extraction
iii Flores, S., Simancas, J., Morcillo, M. "Methods for Sampling and Analyzing Soulble Salts on Steel Surfaces: A Comparative Study." JPCL, March 1994, pp. 76-83.

Mitschke also observed this trend.[20] He attempted to maximize the extraction efficiency by allowing a contact time of 24 hours in the laboratory. This variation of the technique is not practical for most field applications.

Steinsmo also observed that an early version of the Bresle patch itself contributes to the concentration of sodium chloride detected. The level is estimated at 1.0-1.5 µg/cm^2 of chloride, which is considered excessive as the maximum permitted may be as low as 3 µg/cm^2. Boocock investigated the use of 1 molar nitric acid as an alternative to de-ionized water as an extraction fluid. The acid increased the retrieval efficiency by 4%-40%.[21]

The chloride extraction kit by Chlor*Rid uses proprietary fluid in the sleeve instead of water. No independent data were available on the extraction efficiency of this sleeve with water or with the proprietary fluid. Similarly, there are no independent data on the extraction efficiency of the wet filter extraction method.

Repeatability of Extraction Procedures

Very little work has been published on the precision of salt extraction procedures. Precision is a measure of the degree to which two measurements taken by the same operator (repeatability) or by two different operators (reproducibility) differ. In the laboratory, tests plates are contaminated by doping (spreading a known quantity of salt over a measured area) or by exposing the plates to an environment of high salt concentration (e.g., salt spray cabinet). The latter method seems likely to produce a higher variation of salt concentration across the surface than the former.

Neal, et. al., performed a large number of measurements of chloride on pipe. Based on over 200 measurements, they derived an average difference of duplicate measurements of 0.58 µg/cm^2. These data had an approximately normal distribution with a standard deviation of 0.58. This suggests that, for this method, two replicate measurements would be adequate to detect chloride at 2 µg/cm^2, which is the authors' recommended maximum level to be allowed on pipes to be coated. The study also provided data showing good reproducibility among different operators.

Mitschke compared the variation in extractions for steel plates contaminated by doping and by exposing for several weeks in a 5% salt spray cabinet.[25] Each plate was cut into 25 sections and each section extracted and analyzed for chloride. The standard deviation was lower for the doped panels as expected.

These measurements demonstrated that with careful technique, a reasonable degree of precision could be attained. In this experiment, the sources of the variation included the non-uniformity of the chloride distribution, the error in the extraction procedure, and the error in the analysis. From the data available it was not possible to determine the relative contributions of these or other sources of error.

Tator, et, al., examined chloride-doped surfaces with a scanning electron microscope.[22] They found that the surface included "hot spots" of high, very localized chloride concentration. Therefore the precision (as well as the accuracy) of the extraction procedure depends on the area extracted compared to the frequency of "hot spots."

Each of these previous studies measured laboratory-contaminated substrates produced under uniform conditions. When these procedures are used in field analysis of surface salt concentrations, the variability of the concentration is undoubtedly much greater. These variations may arise due to differences in exposures, structural configurations, and degrees of coating breakdown. Multiple extractions and analyses from a small area on a structure would therefore tend to yield a higher standard deviation than similar extractions on a laboratory specimen, even if the operator technique and other factors were equal.

Unfortunately, the current practice among specifiers is to take only one measurement in each location on a structure where salt contamination is suspected. The rationale is that the goal is to identify the most severely contaminated areas (worst cases) and that additional measurements would be better done on different locations. This argument neglects the serious risk of erroneous information from a single measurement. A contractor may be required to rework an area, which gives an elevated salt level based on one measurement, yet because of an error the area may well be in conformance with the specification. Similarly, the inspector may approve a section of a tank based on an erroneous low measurement.

Analysis Of Solutions Extracted From Substrates

It is possible to analyze the salt solutions for specific ions or for the total quantity of dissolved salts.

The species normally of greatest interest is chloride. Other ions which have been analyzed include sulfate, nitrate, ammonium, and ferrous.

For each of these salt species, there are well-established analytical laboratory test methods with high levels of accuracy and precision. For practical use in assessing soluble salt concentration under field conditions (e.g., inside ship ballast tanks or on bridge beams), the critical requirements are:

- Sensitivity (ability to detect low concentrations of salt)
- Accuracy (1-2% is often sufficient)
- Precision (5% or less for different operators)
- Ease of use and interpretation
- Safety and ruggedness of equipment
- Cost effectiveness

Chloride Ion Analysis

The industry has developed three widely used, generally acceptable methods for field analysis of chloride, the ion detection tube (Kitagawa tube), the paper chromatography strip (Quantab), and the field titration. All are based on proprietary materials. Other methods using other field titration kits are also available, but there is little published data on their use on steel structures.



Figure 4. Ion detection tube.

Ion Detection Tubes (Kitagawa). This method uses a sealed vacuum tube containing a silver compound. When the tube is immersed in the solution to be analyzed, the water wicks up the tube. Any chloride combines with the silver to form a white insoluble silver chloride. The line at which the white color ends is a measure of the chloride concentration in the solution. Tubes are available with ranges from 1–50 PPM or 5–200 PPM with a precision of approximately +/- 5%. Each measurement requires a disposable tube. The tubes have a shelf life of 3 years from the date of manufacture. They must be handled carefully to avoid breakage. This method is described in SSPC TU-4 and in ISO 8502-5.[19, 23]



Figure 5. Paper chromatography.

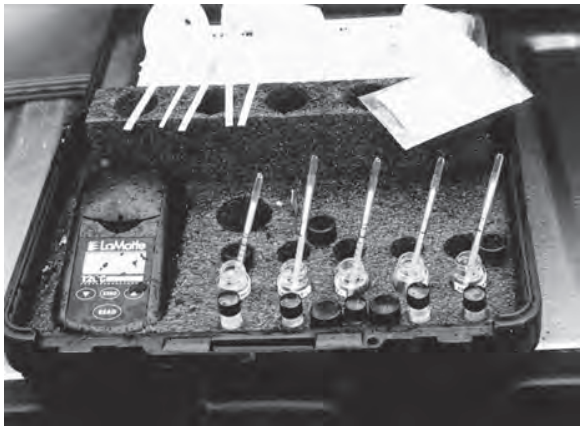


Figure 6. Field titration.

Paper Chromatography Strips (Quantab). This method is based on a reaction of the chloride with silver chemicals impregnated in a small paper strip. The strip is placed in the extraction solution, which is allowed to wick up and saturate the strip. The scale number where the white wicking stops is compared to the chart furnished with the kit to give a chloride concentration in PPM. The method detects chloride from 30 to 600+ PPM with a precision of +/- 5 PPM.

The strips are available in bottles of 60. They have a shelf life of about 120 days from the date of

manufacture. This method is further described in SSPC TU-4.[19]

Field titration. This method uses a titration (sometimes referred to as "drop titration") based on a reaction of the extract with mercuric nitrate from insoluble mercuric chloride. The reaction turns the solution from yellow to blue. The titration is performed on a small sample (0.067 oz. or 2-3 mL) from the solution extracted from the surface using a commercially available test kit. The kit includes four solutions contained in reagent bottles. The precision depend on the surface area. For an area of 10 cm^2, the precision is about 2 $\mu g/cm^2$.

Sulfate Ion Analysis

The standard method for analysis of sulfate ion is turbidity (cloudiness). This is based on the reaction of sulfate with barium to form insoluble barium sulfate. In the field procedure, barium chloride powder is added to the extract solutions and the degree of turbidity (cloudiness) is measured with a colorimeter. This reading is then compared to standards derived from known concentrations of sulfate. A supplier has recently introduced a field kit for this method, in which sulfate concentrations are read directly. The field turbidity method can detect sulfate down to 1 PPM with a precision of +/- 1 PPM, according to the supplier. The procedure is described in the revision of SSPC TU-4. The relevant ISO standard is ISO 8502-11.[24]

Nitrate Ion Analysis

This method, which also uses paper chromatography, is based on a reaction of the chemicals impregnated in a small paper strip with nitrate ion. The strip is placed in the extraction solution, which is allowed to wick up and saturate it. The scale reading can be converted to PPM nitrate ion and to $\mu g/cm^2$.

Ferrous Ion Analysis

Test strips are available for semi-quantitative determination of ferrous ions. The method is based on a reaction between the ferrous ion and a chemical reagent (2,2'-bipyridine). The intensity of the red color, which is proportional to the concentration of the ferrous ion, is compared to a standard color chart. The detection limit is approximately 3 PPM.

A qualitative spot test using potassium ferricyanide paper is also available for field detection of ferrous ion. The paper changes color when exposed to soluble ferrous ion. According to Neal, et., al. (1995)[24] and others, these strips are not very reliable. They can indicate ferrous ion when none is present (false positive) and can fail to detect existing ferrous ion (false negative). The ISO standards are ISO 8502-1 and ISO 8502-12.[25, 26]

Conductivity Analysis

The conductivity of a solution is to a first approximation directly related to the total dissolved salts. Several instruments are available for measuring conductivity.

Although this quantity measures the total salt in solution, it is possible to convert this to equivalent concentrations of a specific salt, typically sodium chloride. (See Appendix.) This conversion assumes that all the soluble salt is from one specific salt, e.g., sodium chloride. It can be used as a worst-case analysis, as chloride is normally considered the most detrimental soluble salt in terms of coating performance and steel corrosion.

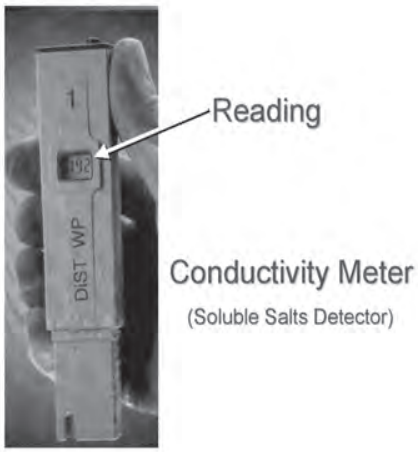


Figure 7. Conductivity.

Pocket Size Conductivity Meter For Total Soluble Salt. Several companies manufacture small (4 x 1 x .05 inch [100x25x13mm]) meters for measuring total soluble salts. The tester inserts the probe end of a calibrated meter into a blank solution (usually deionized water) and into the solution to be analyzed.

The difference between the two readings is a measure of the total soluble salts in micro-siemen per centimeter (µS/cm) or milli-siemen per meter (mS/m). These quantities can be converted to PPM and

ultimately to surface concentration (e.g. µg/cm^2) if the extracted area is known. (See Appendix.)

Cup-Type Conductivity Meter. An alternative is a conductivity meter with a cup for placing the solution and control to be analyzed. The procedure needs a larger quantity of extraction liquid.

Resistivity Meter For Filter Paper. The filter paper is placed in the resistivity meter and, after a programmed time, the meter displays the conductivity in µS/cm.

Other Conductivity and Resistivity Meters. At least one other manufacturer has developed a commercially available conductivity/resistivity meter that is integral to a magnetically attached cell. In this device, the surface is extracted with a small volume of water inside the cavity of the cell. The meter automatically measures the conductivity. Preliminary evaluations of this device have indicated problems with reliability due to the tendency of the cell to leak.[27]

Operation and Validity Of Results. The conductivity meters are capable of measuring conductivity down to several µS/cm with an estimated precision of +/- 2%. The conductivity recorded is dependent on the time interval from the extraction to the measurement. Typically, conductivity increases with time, as attributed to the absorption of CO_2 from the atmosphere forming a soluble carbonate ion. It is important therefore to include a standard time for the measurement, e.g., within 2-3 minutes. The conductivity methods are described in SSPC TU-4 and in ISO 8502-6 and ISO 8502-13.[19, 28, 29]

Steinsmo analyzed solutions extracted from sodium chloride-contaminated laboratory panels with two different analytical methods: atomic absorption analysis of sodium and conductivity.[23] Upon converting the conductivity to sodium chloride using the standard equation, he found a very good correlation between the two methods. He points out however that in the field other ions would likely be present, invalidating the correlation.

Removing Soluble Salts

Comparing Wet and Dry Abrasive Blasting For Chloride Removal

Fosgren prepared panels by blast cleaning with copper slag abrasives and exposing them outdoors for five months with daily spraying of 3% sodium chloride.[30] A set of control panels was washed with an alkali detergent and rinsed with de-ionized water. Other sets were cleaned with various surface preparation methods. The level of chloride was determined directly by the Bresle method and indirectly by conductivity. In the Bresle method, the researchers used 5 ml of de-ionized water and a 10-minute contact period. The chloride was analyzed by a titration method with a detection limit of 1 PPM. The conductivity was measured with a proprietary surface salt meter (TOA Electronics Model SSM-14P), which uses a cell held to the surface with a magnet to measure conductivity after various intervals.

The results are summarized in **Table 3.** The wet abrasive blasting (4,400 psi [300 bar] water with injected aluminum silicate abrasive) and the ultrahigh pressure waterjetting (32,000-36,000 psi [2,200-2,500 bar] gave by far the greatest chloride reduction (about 95%). The dry blasting (with copper slag to SSPC SP 1) was slightly less effective (80-85%) but greatly superior to power tool cleaning (ISO 8501 grade St3[31] [equivalent to SSPC-SP 3]) and hand tool cleaning (approximating SSPC SP 2).

Allen examined the capability of a similar set of surface preparation methods to reduce chloride levels.[35] He started with corroded, pitted steel panels cut from submarine tanks. The preparation methods included: wire brushing to St 3[34] (SSPC-SP 2); needle gunning to St 3 (SSPC-SP 3); waterjetting to 2 levels of cleanliness (DW2 and DW3 [approximately similar to WJ2 and WJ3 of SSPC-SP 12/NACE 5]); and dry abrasive blasting to Sa 2.5 (SSPC-SP 10/NACE 2). The results are very similar to those of Fosgren. The chloride reduction achieved by waterjetting was greater than 90%, by dry blasting about 85%, and by hand and power tool methods under 10%. The author did not describe the method for extracting and analyzing chloride.

SSPC evaluated various surface preparation methods for chloride-contaminated weathering steel in a project for FHWA.[32] The regimen for contaminating the panels was to expose them to 100 cycles of alternating salt fog exposure (3 hours) and dry-out (4+ hours) after blast cleaning to remove the mill scale. The panels were cleaned as follows: dry blast with medium and fine abrasives; repeated dry blasting; dry blast followed by low pressure water wash or by steam

Table 3. Comparison of Removing Salts Via Wet and Dry Abrasive Blast Cleaning.

Method	Remaining Salt (µg/cm²)	% Extracted	Source
Wet blasting	0 to 3.2	Avg.: 96.2%	Fosgren [26]
Waterjetting (35ksi)	0 to 2.4	Avg.:* 95.9%	Fosgren [26]
Hand tool (SP 2)	160 to 288	Avg.:* 43.8%	Fosgren [26]
Power tool (SP 3)	212 to 298	Avg.:* 35.4%	Fosgren [26]
Blast (SP 6)	44 to 68	Avg.:* 83.0%	Fosgren [26]
UHP waterjet	1.6 to 1.8	Avg.: 93.5%	Allen [vi]
Blast (SP 10)	3.3	84%	Allen [35]
Needle gun (SP 3)	11.4	3%	Allen [35]
Wire brush (SP 2)	15.2	9%	Allen [35]
Blast (SP 5)	<3.2 to 3.4	Avg.: 90.2%	Trimber [vii]
Power tool (SP 3)	16.2 to 24.1	Avg.: 43.5%	Trimber [vii]
SP 3 + steam	8.6 to 12.9	Avg.: 69.9%	Trimber [vii]
Power tool (SP 11)	7.0 to 13.9	Avg.: 72.1%	Trimber [vii]
SP 11 + steam	3.9 to 7.7	Avg.: 84.5%	Trimber [vii]
Power tool (SP 3)	22 to 97	Avg.: 45.4%	Peart [viii]
Power tool (SP 11)	41 to 124	Avg.: 17.2%	Peart [viii]

a. Salts extracted by Bresle and analyzed by conductivity.
b. Methods not included in paper.
c. Salts extracted by boiling and analyzed by selective ion electrode.
d. Salts extracted by swabbing and analyzed by conductivity.

cleaning; high pressure waterjetting with and without abrasives; ultrahigh pressure waterjetting; air-abrasive wet blast, chemical stripper; and rotary peening (SSPC-SP 11) followed by low pressure water wash. The salts were extracted by swabbing and analyzed by chloride selective ion electrode. The salts were also analyzed for conductivity. For a few of the removal processes, the test specimens were extracted using the boiling water method. The results are shown in **Table 4.** These data indicate that overall weathering steel is more difficult to clean than carbon steel. This difficulty is attributed to the inherently rougher surface and deeper pits that occur in weathering steel exposed to chloride.

Alblas and Van Londen summarized the findings of several papers recently published in Europe, which compared the effectiveness of wet and

Table 4. FHWA Study Test Results.

Method	Cl remaining (µg/cm²)	Percent removed*
Dry blast	100	75.1%
Dry blast +water wash	96	80.5%
Air abr. Wet blast	55	87.9%
Hi-press. Water w/ abrasive	46	89.2%
Hi-press. Waterjet	174	58.6%
Ultra waterjet (35ksi)	14	96.7%
Rotopeen+water wash	134	68.1%

* Based on estimate of 420 µg/cm² for boiling of hand-tool cleaned steel

dry blasting in reducing soluble chloride levels.[15] Data (shown in **Table 5**) support the previous studies on the superiority of wet blasting. The data also suggest that recycling abrasive can result in higher salt levels on the surface.

In an earlier project for FHWA, Frondistou-Yannas evaluated the quantities of chloride and sulfate removed from an exposed surface by various surface preparations methods.[33] (At this time, the technology for measuring the soluble salts on the surface had not been widely disseminated). The panels were blast cleaned to SSPC-SP 5/NACE 1 (white metal) and exposed to sheltered and exposed marine and industrial environments for 1–5 months By far, the most effective technique of those evaluated was pressurized waterjetting at 10,000 psi (700 bar). Steam cleaning was only 10-20% as effective as waterjetting, while hand-tool cleaning and solvent wiping were only about one third as effective as steam cleaning.

Comparing Power Tool, Hand Tool and Abrasive Blasting

The following studies specifically examined the published standard SSPC-SP 11, which includes definitions of the degree of cleaning and the surface profile. Trimber evaluated an alkyd and an epoxy mastic coating system over three initial substrates with six surface preparation methods.[vii] The initial substrates included:

- blast cleaned steel contaminated with 25 µg/cm² of chloride
- blast cleaned steel contaminated with 50 µg/cm² of chloride
- rusted and pitted lacing bars from a bridge

Table 5. European Comparisons of Wet and Dry Blasting Methods.

Method A	Cl Remaining*	Method B	Cl Remaining*	Method B vs. Method A	Source
Dry blast	5.0 to 20.0	Wet Blast	2.5 to 5.0	About 60% reduction	Sigma/1991
Dry blast	3.0 to 3.5	Wet Blast	1.0 to 2.0	About 50% reduction	TNO/1994
Recycled coal slag	3.8 to 5.8	New coal slag	2.4	About 50% reduction	AKZO/1989

* Units of $\mu g/cm^2$

The surface preparation methods included:

- SSPC-SP 3 with and without steam
- SSPC-SP 11 with and without steam (SP 11 consisted of needle gun and non-woven disc)
- SSPC-SP 5 with and without steam

The surface chloride levels were measured after cleaning prior to application of the coating. The results were as follows:

- Efficiency in removing chloride: SP 5 > SP 11 > SP 3
- The use of steam cleaning prior to mechanical cleaning (SP 1) improved the efficiency of salt removal

Plates coated with the alkyd and epoxy mastic were exposed in a condensation cabinet for four months. Interestingly, the panels cleaned by SP 3 gave superior performance to those cleaned by SP 11.

Overall Comparison of Standard Removal Methods

Based on the review of the literature, the relative abilities of the surface preparation methods are estimated as shown in **Table 6.**

Salt Removal with Conventional Solvent Cleaning

Solvent cleaning also encompasses emulsion and steam cleaners. Each includes water as one of the cleansing agents, and therefore is capable of removing substantial quantities of the water-soluble salt. In order to dissolve the salt, the water or steam must penetrate and wet the surface containing these salts. Otherwise, the procedure will simply remove the soluble salts on the surface of the rust layer and not the salts embedded in the rust. There may well be some benefits from this surface rinsing, but the long-term properties have not yet been determined.

Specialty Materials For Removing Soluble Salt

The industry has developed several other methods specifically for removing soluble salt or paint. These include polyurethane sponges, chemical strippers, and proprietary additives.

Salt removal with polyurethane sponges. Very resilient polyurethane sponges are widely used to remove grease and oil from process areas (SSPC TU-X). As the sponge impacts the surface it deforms, allowing the abrasive to gain more intimate contact with the surface and any contaminants. According to the manufacturer, this results in more thorough scouring of the surface and more effective removal of soluble contaminants. These sponges can also be embedded with abrasives for more aggressive cleaning.

Salt removal with chemical strippers. Chemical strippers dissolve or soften the existing paint so it can be vacuumed, scraped, or rinsed off with water. The major types are caustic (e.g., potassium hydroxide) or organic solvents (e.g., methylene chloride, methanol, or N-methyl pyrrolidine. The caustics require special handling because of the reactivity. No data were identified on the level of salt after chemical stripping.

Salt removal with proprietary additives. Several manufactures have developed products specifically to remove chlorides and other soluble salts. One amine-based alkaline solution is added to water at concentrations of 5-10% by weight and sprayed at low pressure (300-1,500 psi [21-103 bar]).[34] Another supplier claims that their acid-based product can react with chlorides that are complexed to the steel because of the unique chemistry, although no documents are known to have been published. The company ran trials on a series of bridges owned by The Illinois DOT.[35] These results, show that this material is more effective than water without the additive.

Table 6. Relative Abilities of Various Surface Preparation Methods.

Preparation Method	Relative Salt Removal Rate	Percent of Salts Extracted
Dry abrasive blasting (SP 6 or SP 10)	0.8	75-90%
Power tool cleaning (SP 3)	0.25	3%-45%
Power tool cleaning (SP 11)	0.30	17%-72%
Hand tool cleaning (SP 2)	0.2	9-35%
Steam cleaning (SP 1)	0.35	N/A
Wet abrasive blasting (SSPC TR 2) or high pressure water with abrasives	0.9	88-96%
High pressure waterjetting (SP 12)	0.85	59-96%
Ultrahigh pressure waterjetting (SP 12)	0.95	93-97%
Ultrahigh pressure waterjetting (SP 12) with abrasives	1.0	N/A
Urethane sponges with abrasives	0.80	N/A

N/A: no direct data available, based on qualitative observations

Influence Of Soluble Salts On Coating Lifetimes

A major goal of specifiers, owners, and coating manufacturers is to determine the effect that a specific level of soluble salt has on the coating's lifetime. Many organizations have conducted or sponsored evaluations to determine this information from accelerated or field tests and evaluations.

This section briefly summarizes some of the most relevant and recent studies and reviews relating to the effects of salts on performance.

Immersion Studies

A NAVSEA-sponsored project evaluated seven immersion grade coatings in several laboratory-accelerated tests over several chloride levels.[36] The coatings included several types and thicknesses of an epoxy-polyamide (DOD-P-24441) and two newer technology materials, a polysiloxane and a siloxirane. After 52 weeks in a condensing humidity cabinet, five of the seven coatings failed by blistering at a chloride level of 5 µg/cm^2 with the other two failing at 10 µg/cm^2. The failures, with one exception, were evident at 18 weeks. Following immersion at 180°F (82°C) for up to 10 weeks, all the systems failed when applied over chloride levels of 5 µg/cm^2. All but two of the systems failed at zero chloride level, indicating that this condition exceeded their ability to withstand immersion at that temperature. The researchers observed similar results after two weeks in immersion at 200°F (93°C).

Soltz evaluated clear and pigmented coatings: epoxy-polyamides and coal-tar epoxy over chloride and sulfate-contaminated steel panels in a pressurized salt-water immersion cabinet.[37] The clear epoxy showed evidence of visible under-film corrosion at chloride levels as low as 0.5 µg/cm^2. At 8 µg/cm^2, micro-blisters started forming beneath the coating, which eventually erupted through the coating. Coal-tar epoxy also exhibited blister formation at 8 µg/cm^2, but the coatings did not fail until chloride levels reached 16 µg/cm^2 or greater. Failure was defined as a composite blister rating of 7 or less (based on SSPC blister-rating chart). For the epoxy polyamide, initiation of blistering and failure due to blistering were observed at chloride levels of 20–32 µg/cm^2 and 40–64 µg/cm^2, respectively. For the epoxy and coal tar epoxy coatings, blistering over sulfate-contaminated panels did not occur until levels of sulfate reached 125–250 µg/cm^2.

Mitschke evaluated a series of nine epoxy, epoxy Novolac, and epoxy phenolic tank linings over different levels of chloride immersed in tap water at different temperatures.[25] He examined the panels periodically, defining failure when 20% of the surface was blistered. At 75°F (24°C) after 13 months, the threshold chloride levels (concentrations that could be tolerated) ranged from 4–20 µg/cm^2. As the temperature was raised, the threshold levels decreased. At 190°F (88°C), an epoxy phenolic and an epoxy Novolac exhibited thresholds of 17.5 µg/cm^2 and 7.4 µg/cm^2, respectively. All the other coatings failed even with zero chloride on the surface. The author concluded that even very small quantities of chloride on the surface reduced the service life of these coatings.

Atmospheric Studies

Morcillo evaluated a series of conventional coatings over three to four levels of sodium chloride and ferrous sulfate.[38] He exposed the coatings for 4.5 years in a marine atmosphere and up to 14 years in industrial, rural, and urban atmospheres. For industrial and urban environments, the author concluded that at chloride levels of 10–30 µg/cm^2 most paints were at risk of failure. Some paints were at risk from chloride levels as low as 1 µg/cm^2. Zinc rich coatings, however,

Table 7. Recommended Soluble Salts Levels on Bridges—Specific Coatings and Conditions.

	Coating System	DFT: mils (micrometers)	Safe Level [a]
Condition A [b]	1. Ethyl silicate zinc/epoxy or epoxy/urethane	6-8 (150-200)	50
	2. Ethyl silicate zinc/vinyl	5-6 (125-150)	30
	3. Epoxy zinc/epoxy or epoxy/urethane	6-8 (150-200)	30
	4. High solids, high-build epoxy (mastic)/epoxy or urethane	6-9 (150-225)	30
	5. Alkali silicate zinc/ waterborne acrylic	5-7 (125-175)	16
	6. Oil alkyd (2-coat/alkyd or silicone alkyd)	5-7 (125-175)	7
	7. Acrylic waterborne (3 coats)	6-9 (150-225)	7
Condition B [c]	1. Ethyl silicate zinc/epoxy or epoxy/urethane	6-8 (150-200)	50
	2. Epoxy polyamide (2 coats)/urethane (optional)	6-8 (150-200)	10

a. Levels given in µg/cm^2 based on chloride. If sulfates are determined to be the major contamination species, multiply these levels by two.
b. Aggressive atmospheric: moderate to high industrial fallout (acid rain), intermittent exposure to deicing salts, no accumulation.
c. Immersion-like: heavy deicing salt usage, frequent splash, high time of wetness, ponding (e.g., top flange near leaking joints), and intermittent immersion.[b]

could tolerate chloride levels of 30 µg/cm^2 or greater. The author also noted that the same coatings could tolerate much higher levels of sulfate, up to 100-250 µg/cm^2. In a marine atmosphere, alkyd and acrylic coatings exhibited failure in 4.5 years at 10 µg/cm^2, but the chlorinated rubber and vinyl/alkyd systems showed no degradation.

SSPC evaluated typical bridge coating systems in accelerated laboratory tests and on test bridges over chloride and sulfate contaminated steel.[1] Based on these results and data from previous studies, the authors prepared a table of recommended maximum levels for soluble salts on bridges for specific coatings **(Table 7).** The authors identified two exposure conditions—A: aggressive atmospheric and B: immersion-like. These data are consistent with those of Morcillo in demonstrating that ethyl silicate inorganic zinc-rich systems have a very high tolerance to chlorides and sulfates.

Compilations

Alblas and van Londen reviewed the literature for studies on the effect upon coating performance by chloride contamination.[15] They identified 12 independent studies with experimental data on the performance of coatings applied over measured levels of chloride. Most of the studies recommend a level between 2 and 10 µg/cm^2. The two higher levels included an atmospheric evaluation of zinc rich coatings and an evaluation over very localized contamination. The authors conclude that " from available data, it is not possible to establish a definitive allowable level of chloride contamination," but nevertheless, they suggest a maximum of 1-5 µg/cm^2, "depending on the use and exposure guidelines."

A working group of the ISO Technical Committee on surface preparation of coatings also reviewed data from the published literature as well as guidelines from coating manufacturers on recommended levels of soluble salts for subsequently applied coatings.[39] For each of 10 primary published articles the group described the test conditions and recommendations of the author for levels considered "safe" and "failure." **Table 8** summarizes the data for epoxies in immersion or condensing humidity conditions. This report reviewed many of the same studies as the one by Alblas and van Londen,[14] although in greater detail. The results support the latter authors' conclusion that the majority of epoxy coatings can tolerate chloride levels of 3–10 µg/cm^2.

The ISO group surveyed major manufacturers of marine and industrial coatings for recommendations on acceptable levels of salts for different conditions. **Table 9** summarizes the results. The manufacturers are mostly consistent, with median levels of 5 and 7 µg/cm^2 for freshwater and seawater immersion, respectively. Freshwater immersion is considered more aggressive because of the greater osmotic pressure difference. It is also noteworthy that a majority of the manufacturers determine chloride from the conductivity. This result indicates the strong influence of the ISO standards on the major coating manufacturers, many of which are headquartered in Europe.

Norwegian and other ship classification societies and several major ship-owners have endorsed chloride levels on the low end of the above range. Det Norske Veritas (DNV) recommends a maximum chloride level of 2 µg/cm^2 to achieve a 15-year coating life in a ballast tank.[40] Representatives of

Table 8. "Safe" and "Failure" Levels for Epoxies in Immersion or Condensing Humidity Conditions.

Coating System (no of coats, thickness)	"Safe" level of Cl[a]	"Failure" level of Cl[a]	Test exposure	Source/ Comment
Epoxy phenolic (1)	1	3	100% humidity, 122°F [40°C]	Dekker et al. [ix]
Epoxy phenolic (2 & 3)	3	>3	100% humidity, 122°F [40°C]	Dekker et al. [ix]
Epoxy (1, 2 & 3)	<1	1	100% humidity, 122°F [40°C]	Dekker et al. [ix]
Epoxy polyamide (3)	5	10	Condensing humidity	Weldon et al. [8]
Coal tar epoxy (10 mils)	50	>250	500 hrs immersion, deionized water	West [7]
Fusion bonded epoxy	<3	3	48 hr immersion, 15°F [65°C] water, 1.5 volts cathodic disbondment	Midwest Research Inst.
Tank lining epoxy	20	40	Pressure immersion (90°F, 50 psi) [b]	Soltz [36]
Navy epoxy (DOD-P24441)	10	20	Pressure immersion (90°F, 50 psi) [b]	Soltz [36]
Coal tar epoxy	5	16	Pressure immersion (90°F, 50 psi) [b]	Soltz [36]
Epoxy mastic (2)	7	50	Pressure immersion, (90°F, 50 psi) [b]	Appleman et al., (1992) [1]

a. units of micrograms per square centimeter
50 psi = 3.4 bar, 90°F = 32°C

a group of ship-owners, the Tanker Structure Cooperative Forum, have recommended a level of 3 µg/cm^2. These authors, however, have not cited any specific data as a basis for these criteria.

Consensus on Acceptable Salt Levels

Chloride. A general industry consensus exists on the maximum level of chloride allowed prior to application of marine coatings. For salt-water immersion, the range is from 3–10 micrograms per square centimeter (µg/cm^2) with a median of about 5 µg/cm^2. This level is slightly higher than that used by the U.S. Navy—3 µg/cm^2. For atmospheric exposure, the data suggest that much higher levels of soluble salt may be tolerated, perhaps 20–30 µg/cm^2 of chloride. As with the immersion data, there are no definitive studies that have examined all the major variables (coating type, thickness, exposure conditions, salt level, and origin) and only a handful that have conclusive or statistically based results.

Conductivity. Several agencies including the U.S. Navy have adopted maximum levels for conductivity based on their equivalent chloride level. This conversion is based on the assumption that the salt is entirely composed of sodium chloride. From the measured conductivity of the extracted solution, the volume of extract liquid, and the surface area extracted it is possible to compute the conductivity equivalent.

Other salts. The joint standard SSPC-SP 12 /NACE 5 included three surface contaminant (SC) levels for sulfates and chlorides and ferrous ion as shown in **Table 10.** The sulfate levels were 0 (SC 1), maximum of 17 micrograms/cm^2 (SC 2), and maximum of 50 µg/cm^2 (SC 3). This standard does not give any specific recommendations for where these levels are to be used, but rather provids a means to specify the levels.

Conclusion

This chapter has shown that strong evidence exists for the negative impacts of salts on coated steel. Certain soluble salts can result in accelerated degradation of the steel by participating in the corrosion reaction. In addition, nearly all-soluble salts can induce osmotic blistering in coated steel under partial or total immersion in water.

The industry has developed a substantial body of technology to quantify the presence of salts on steel

Table 9. Manufacturer Recommendations on Acceptable Levels of Salts for Different Conditions

Mfcr.	Fresh water immersion*	Salt water immersion*	Marine atmosphere*	Method
A	6.9	6.9	19.5	Based on conductivity (from Bresle)
B	5	10	—	Based on conductivity (from Bresle)
C	6	8	—	Based on conductivity (from Bresle)
D	10	10	—	Chloride titration (Bresle)
E	1	5	—	Based on conductivity (from Bresle)
F	3	3	—	Based on US Navy standard
G	5	10	25	Based on conductivity (from Bresle)
H	5	5	5	Based on German standard
I	5	5	5	Based on German standard
J	3	3	5	Based on conductivity (from Bresle)
K	7	7	7	No data
L		10	—	Bresle
Median	5	7	Insufficient data	

* Maximum chloride level (in $\mu g/cm^2$) tolerated

surfaces. The first requirement, quantitative removal of the salt from the surface, has proven to be a major challenge. The most common methods involve swabbing the surface or solubilizing the salt in a fluid contained in a cavity or sleeve.

Table 10. SSPC SP 12/NACE 5 Surface Contaminant Levels.

Surface contaminant level	Chloride ion (Micrograms/ cm^2)	Sulfate ion (Micrograms/ cm^2)	Ferrous ion (Micrograms/ cm^2)
SC 1	0 (non-detectable)	0	0
SC 2	7	17	10
SC 3	50	50	No value given

The efficiency of extraction varies considerably dependent on the particular method, the condition of the surface, the specific salt, and the operator proficiency. Also, the industry has not developed sampling techniques to determine the number and locations of surfaces to be extracted. Consequently, little statistical reliability can be assigned to the results of the extractions. Decisions made on the basis of these procedures must take these limitations into consideration.

Relatively reliable field methods of analysis are available for each of the most common species, chloride, nitrate, sulfate, and total dissolved salts, with the latter based on solution conductivity.

Numerous empirical studies have been completed to determine the specific impact of the various soluble salts on the performance of coatings. The majority of these have been undertaken using chloride as the salt and water or seawater as the exposure medium. Based on these studies, industry has established a preliminary consensus of an acceptable level of chloride for immersion of coated steel. By extension and analogy, similar tabulations have been constructed for soluble salts in atmospheric service.

The industry has evaluated current techniques and devised new ones for removing salts prior to the application of coatings. The most successful methods are those that employ pressurized water in conjunction with conventional and specialty abrasives, or other proprietary chemicals.

The technology of mitigating salts has seen numerous incremental advances in the last 10–15 years. There is a much greater and wider appreciation

for the need to address this issue in specifications, procurement documents, and field procedures. It is also more widely recognized as an explanation for past problems. The emerging consensus on acceptance levels is viewed more as a necessary starting point than as a firmly held conviction. Substantially more practical experience and focused research, testing, and evaluation are needed before these numbers can be accepted with a high level of confidence.

References

1. Appleman, B.R.; Boocock, S.K.; Weaver R.E.F.; Soltz, G.C. *Effect of Surface Contaminants on Coating Life.* SSPC: Pittsburgh, 1992.
2. Gross, H. Examination of Salt Deposits Found Under German Painted Steel Bridge Decks. *Materials Performance,* October 1993, pp 28-33.
3. Appleman, B.R. Painting Over Soluble Salts: Perspective. *Journal of Protective Coatings and Linings*, October 1987, p 68.
4. Morcillo, et. al. The Influence of Chlorides, Sulfates, and Nitrates at the Coating-Steel Interface on Under-Film Corrosion. *Progress in Organic Coatings # 31,* 1997, pp 245-253.
5. Van der Meer-Lerk, L.A.; Heertjes, P.M. Blistering of Varnish Films on Substrates Induced by Salts. *J. Oil and Colour Chem. Assoc. #58,* 1975, pp 79-84.
6. Weldon, D.G., et al. The Effect of Oil, Grease, and Salts on Coating Performance. *Journal of Protective Coatings and Linings*, June 1987, pp 46-58.
7. West, J. The Relationship Between Coating Thickness and Salt Contamination on Blistering of Coatings. Presented at *UK Corrosion/85,* Harrogate, 4-6 November, 1985.
8. Soltz, Gerald C. Understanding How Substrate Contaminants Affect the Performance of Epoxy Coatings and How to Minimize Contamination. In *Proceedings of SSPC '98,* pp 208-219.
9. Johnson, W.C. ASTM STP 841. *Detrimental Materials at the Steel/Paint Interface;* ASTM: West Conshohocken, PA; 1984, pp 28-43.
10. Townsend, et. al. Breakdown of Oxide Films on Steel Exposed to Chloride Solution. *Corrosion 37,* July 1981, p 384.
11. Martin, K., et. al. The Spreading of Sulfate Nests on Steel in Atmospheric Corrosion. *Corrosion Science 11*, 1971, pp 937-942.
12. Chandler, K.A. The Influence of Salts in Rusts on the Corrosion of the Underlying Steel. *British Corrosion Journal,* July 1966, pp 264-266.
13. Alblas, B.P.; Van Londen, A.M. The Effect of Chloride Contamination on the Corrosion of Steel Surfaces: A Literature Review. *Protective Coating Europe*, February 1997.
14. Bastidas, J.M.; Morcillo, M. Mild Steel Corrosion in the Saline Solutions: Comparison Between Bulk Solutions and Steel – Coating Interfacial Solutions. *Journal of Coatings Technology,* July 1998, pp 61-66.
15. SSPC Technology Update No. 4. *Field Methods for Retrieval and Analysis of Soluble Salts on Substrates;* SSPC: Pittsburgh, 1998.
16. ISO 8502-6:1995. *Preparation of Steel Substrates Before Application of Paints and Related Products—Tests for the Assessment of Surface Cleanliness—Part 6: Extraction of Soluble Contaminants for Analysis—The Bresle Method;* ISO, 1995.
17. *SSPC Guide to Field Retrieval and Analysis of Soluble Salts on Steel and Other Smooth Surfaces.* (Forthcoming)
18. Neal, D.; Whitehurst, T. Chloride Contamination of Line Pipe: Its Effect on FBE Coating Performance. *Materials Performance*, February 1995, pp 47-52.
19. Mitschke, Howard. Effects of Chloride Contamination on Performance of Tanks.
20. Boocock, Simon K. Detection and Significance of Surface Contamination. In *Proceedings of SSPC '96;* pp 15-32.
21. Tator, Kenneth B. Water-Soluble Salts Beneath Paint–Quantities and Consequences. *In Proceedings of PCE '98;* pp. 197-215.
22. ISO 8502-5:1998. *Part 5: Measurement of Chloride on Steel Surfaces Prepared for Painting (Ion Detection Tube Method);* ISO, 1998.
23. ISO 8502-11: 1998. *Part 11: Field Method for the Turbidimetric Determination of Sulfate;* ISO, 1998.
24. ISO/TR 8502-1:1991. *Part 1: Field Test for Soluble Iron Corrosion Products;* ISO, 1991.
25. ISO/DIS 8502-12. *Part 12: Field Method for the Titrimetric Determination of Water-Soluble Ferrous Ions;* ISO, 1998.
26. Fosgren, A.; Appelgren, C. Comparison of Chloride Levels Remaining on the Steel Surface After Various Pretreatments. In *Proceedings of PCE '00.*
27. ISO 8502-9:1998. *Part 9: Field Method for the Conductometric Determination of Water-Soluble Salts;* ISO, 1998.
28. ISO/WD 8502-13. *Part 13: Field Method for the*

Determination of Soluble Salts by Conductometric Measurement; ISO, 1998.
29. SSPC-SP 12/NACE 5. *WaterJetting;* SSPC: Pittsburgh and NACE: Houston.
30. ISO 8501-1:1988. *Visual Assessment of Surface Cleanliness—St3;* ISO, 1988.
31. Appleman, B.R.; Bruno, J.A., Jr.; Weaver R.E.F. FHWA-RD-91-087. *Maintenance Coating of Weathering Steel: Interim Report;* Federal Highway Administration: Washington, DC, 1992.
32. Frondistou-Yannas, S. Effectiveness of Nonabrasive Cleaning Methods for Steel Surfaces. *Materials Performance,* July 1986.
33. SSPC/NACE Joint Technical Report. *Specialty Abrasive Media.* (Forthcoming)
34. Chlor*Rid International, Inc. Chandler, Arizona.
35. Ellor, P.E.; Allen, J. OCRC Job: GEO-3. *The Effects of Surface Contamination on Paint Performance: A Report for Naval Sea Systems Command;* April 1996.
36. Soltz, G.C. NSRP 0329. *The Effect of Substrate Contaminates on the Life of Epoxy Coating Submerged in Sea Water;* U.S. Department of Transportation: Washington, D.C., June 1991.
37. Morcillo, Manuel; Simncas, Joanquin. Water-Soluble Contaminants at the Steel/Paint Interface: Their Effect in Atmospheric and Marine Services. In *Proceedings of PCE '97.*
38. ISO/PDTR 15235. *Preparation of Steel Substrates Before Application of Paint and Related Products–Collected Information on the Effect of Levels of Water-Soluble Salt Contamination Before Application of Paints and Related Products;* ISO TC35/SC12 Working Group 5, 1999.
39. Askheim, E. Ballast Tank and Cargo Holds in DNV's Guidelines for Corrosion Protection of Ships. In *PCE Guide to Marine Coatings,* Technology Publishing Co.: Pittsburgh, 2000, pp 332-341.
40. Osborne, M.; Eliasson, J. Guidelines for Ballast Tank Coating Systems and Surface Preparation. In *Proceedings of PCE '00,* p 38.

Special Table References

[i] *Handbook of Chemistry and Physics, 40th Edition;* Chemical Rubber Publishing Co.: New York, 1959, pp 1694-1705.
[ii] Moore, W.J. *Physical Chemistry, 3rd Edition;* Prentice Hall: New York, 1964, pp 135-138.
[iii] Flores, S.; Simancas, J.; Morcillo, M. Methods for Sampling and Analyzing Soluble Salts on Steel Surfaces: A Comparative Study. *Journal of Protective Coatings and Linings*, March 1994, pp 76-83.
[iv] Boocock, Simon K. Research News: SSPC Research and Performance Testing of Abrasive and Salt Retrieval Techniques. *Journal of Protective Coatings and Linings*, March 1994, p 28 (1A,B).
[v] Steinsmo, Unni; Axelsen, Sten B. Assessment of Salt Contamination and Determination of Its Effect on Coating Performance. In *Proceedings of PCE 1998,* pp 71-85.
[vi] Allen, Bill. Evaluating UHP Waterjetting for Ballast Tank Coating Systems. *Protective Coating Europe*, October 1997, p. 38. (2A, 3A)
[vii] Trimber, Kenneth A. An Investigation into the Removal of Soluble Salts Using Power Tools and Steam Cleaning. In *Proceedings of the 7th SSPC Technical Symposium (1998),* pp. 56-67.
[viii] Peart, J.W. *Evaluation of Coatings Applied on Less Than Ideal Surfaces;* Technical Report No. NSRP 0451; National Shipbuilding Research Program, September 1995.
[ix] Dekker, T.T. High Pressure Water Blasting, the Method of the Future? *News from the World of Industrial High Pressure Cleaning,* No. 3, 1990, pp 1-2 (in Dutch).

Acknowledgements

The author and SSPC gratefully acknowledge Jerry Colahan's peer reviewer of this document.

About the Author

Bernard R. Appleman

Dr. Bernard R. Appleman has been active in the protective coatings industry since 1974. He served as executive director of SSPC from 1984-1999, prior to his current position as vice president and technical director of KTA-Tator, Inc. He has also worked at the Federal Highway Administration on research and testing of bridge coatings, at Exxon Corporation on coatings and corrosion for the petrochemical industry, and for the U.S. Navy on corrosion and fouling-resistant ship coatings. He is an SSPC protective coatings specialist (PCS) and has published over 100 technical publications.

APPENDIX
UNITS AND CONVERSIONS FOR SOLUBLE SALTS

The ability to perform the measurements and make the comparisons and correlations requires a thorough understanding of the units of measurements and the assumptions in their use and interpretation.

Units for Soluble Salts

There are three basic concentration units that measure the quantity of salts: surface concentration, solution concentration, and solution conductivity.

• **Surface concentration:** This is the parameter normally of greatest interest as it has a direct influence on the performance of a coating. The most common unit is micrograms per square centimeter (µg/cm^2) (mass per unit area). An alternate unit used in Europe is milligrams per square meter (mg/m^2). The conversion is:

$$1\ \mu g/cm^2 = 10\ mg/m^2$$

• Solution concentration: This quantity is a measure of the amount of salt dissolved in a unit volume of solution. It is important because the standard procedure to determine surface concentration requires that the salt be extracted into a solution. The standard unit is mass per volume, e.g., grams or milligrams per liter or micrograms per milliliter (µg/mL). In a dilute aqueous solution, µg/mL is equivalent to parts per million (PPM), shown as follows:

$$1\ \mu g/mL = 1\ \mu g/g\ (of\ water) = 1\ PPM$$

• **Solution conductivity:** This quantity is a measure of the ability of the solution (assumed aqueous) to conduct an electric current. The conductivity is based on the total amount of dissolved ions and is not specific for any particular ion. In some instances, equivalent concentration of a specific ion (e.g., chloride) can be computed, assuming that this ion is the only soluble salt present. For low concentrations, the conductivity is directly proportional to the concentration of dissolved ions. Yet since different ions have differing abilities to conduct a current, a different conversion factor would be necessary depending on the actual or assumed ionic species present.

The standard unit for conductivity is micro-siemen per centimeter (µS/cm). Micro-siemen is equivalent to micro-mho. An alternate unit is milli-siemen per meter (mS/m). The conversion is:

$$1\ \mu S/cm = 0.1\ mS/m$$

Conversions

Determining Solution Concentration from Surface Concentration and Vice Versa

Basic Equation

$$E = (C \times V)/A \quad (Eq.\ 1)$$

E = surface concentration in micrograms/cm^2 (µg/cm^2)
C= solution concentration in PPM (microgram/cc)
V= volume in cc
A= area in square centimeters

Example 1

Surface area of 12.5 square centimeters is extracted with 2 cc of water. Using a titration strip, the solution concentration is 42 ppm. What is the soluble salt contamination concentration from the surface?

C = 42 PPM
A= 12.5 cm^2
V= 2 cc

$$E = 42 \times 2 / 12.5 = 6.7\ \mu g/cm^2$$

Determining Surface Concentration of Salts from Conductivity

Basic Equation**

$$E = S \times (V/A) \times k \quad (Eq.\ 2)^*$$

E = surface concentration in micrograms/cm^2
S= conductivity in micro-siemen/cm

V= volume in cc
A= area in square centimeters
K= constant that depends on the solute

For sodium chloride at dilute concentrations, k = 0.493

(Derived as follows: k = 1/c, where c is the conductivity measured for 1 g of solute in 1 liter of deionized water, c (NaCl) = 2.028)

Example 2

Two ccs of water are used to extract salt from a surface area of 12.5 cm^2, resulting in a conductivity of 70 µg/cm. What is the sodium chloride salt contamination equivalency on the surface? What is the chloride ion equivalency of the salt contamination?

S= 70 micro-siemen/cm
V= 2 cc
A= 12.5 cm^2
K= 0.493

E= 70 x 2x 0.493/12.5 = 5.5 micrograms/cm^2 of NaCl

For chloride, the surface concentration will be the ratio of the gram equivalent wt (GEW) of chlorine to that of NaCl.

GEW of Cl = 35.5; GEW of NaCl = 58.5 ratio = 0.605

In above example, the surface concentration of chloride would be 5.5 x 0.606 = 3.3 micrograms/cm^2.

Using same analogy, the constant for Cl in Equation 3 is 0.493 x 0.605 = 0.298

Determining Solution Concentration (C) from Conductivity (S)

Combine equations 1 and 2
E= C x V/A (Eq. 1)
E = S x (V/A) x k (Eq. 2)*

Note that k for Cl is 0.298

C x V/A = S x (V/A) x k (Eq. 3)*

This reduces to
C= S x k = 0.298 S = 0.3 S

Concentration (C[PPM]) = 0.3 x conductivity (S[µS/cm])
Or S = 3.3 x C

Example 3

If the conductivity of an extract solution is measured at 50 µg/cm, what is the chloride ion equivalency of the solution?

Conductivity = 50 µS/cm
Concentration = 3.3 x 50 = 165 PPM

*These equations are only valid where sodium chloride is the only soluble salt and at low concentrations.

** ISO/PDTR 15235. *Preparation of Steel Substrates Before Application of Paint and Related Product—Collected Information of the Effect of Levels of Water-Soluble Salt Concentration Before Application of Paints and Related Products.*

Note: Similar equation (slightly different form) published in ISO 8502-9. *Part 9: Field Method for The Conductometric Determination of Water-Soluble Salts.*

Chapter 2.9
Other Methods of Surface Preparation

For most industrial painting jobs, abrasive blast cleaning is the method of choice to prepare the surface for painting. The next most popular methods of surface preparation are wet abrasive blast cleaning and waterjetting. There are situations, however, where problems exist with the more conventional methods. This chapter consists of short summaries of a few alternative methods of surface preparation, some of which may be applicable in certain situations.

Chapter 2.9.1
Pickling

Dr. Thomas J. Langill and John W. Krzywicki

Introduction

Pickling in the metal finishing industry is a process in which iron or steel is immersed in acidic solutions to remove oxides or scale. Normally, all ferrous metals have a surface oxide from atmospheric exposure or scale from high temperature rolling and annealing. Various acids can be used in commercial pickling including sulfuric, hydrochloric, muriatic, nitric, hydroflouric, phosphoric, or mixtures of acids. For efficient pickling, these acids should be active enough to remove only oxides and scale from the iron or steel while minimizing the metal wasted through base metal dissolution. Inhibitors added to the acid solution are used to reduce the amount of acid attack on the base metal.

Metal finishers typically encounter two types of scale. The first type, high-temperature scale, is a composition of three layers of iron oxide, FeO, Fe_3O_4, and Fe_2O_3, and develops after rolling operations at temperatures above 1070°F (577°C).[1] The second type, low-temperature scale, consists of two iron oxide layers, Fe_3O_4 and Fe_2O_3, and develops when steel is heated in an annealing or finishing operation at temperatures below 1070°F (577°C). Since the steel and the iron oxides contract at different rates, the iron oxide layers develop cracks from the outer surface down to the interface between the iron oxide layer and the base steel as it cools.

The many cracks in the scale permit the pickling acid to penetrate to the inner layers of the scale and to the metal itself. The inner layer, being more soluble in some acids, dissolves more rapidly, allowing the bulk of the scale to fall off in the form of iron oxide flakes. As part of the acid chemical reaction, hydrogen gas is evolved, thereby helping to blow off the upper layers of oxygen-rich scale.

If all the scale were blown off at one time and the metal immediately removed from the pickling solution, there would be minimal acid attack on the base metal and little need for an inhibitor. This, however, does not occur. Scale exists in varying degrees of thickness on an individual piece of steel, and the light scale is removed very quickly, exposing the bare, clean steel. Additionally, all the mill scale may be blown off prior to a thorough cleaning of any localized rust areas. Uninhibited acid attacks and pits light scale areas before the remainder of the scale can be removed.

Rust, or iron oxides, are more soluble in sulfuric, muriatic, and phosphoric acids than are mill scales. Rust is removed by dissolution rather than being blown off. Rust, unlike scale, continues to develop cyclically, and if it were not removed along with the chemicals that caused it, it would continue to form, even under coatings of paint, oil, etc., when exposed to oxygen.

Sand or shot blasting is more economical for rust and scale removal from large assembled structures such as ship hulls, bridge plates, gas holders, etc., that are too large and, often, too thickly encrusted with pitted rust to be pickled in acid. On smaller assemblies, weldments should be abrasive blast or mechanically cleaned to remove welding slag prior to pickling.

In the United States, sulfuric acid, because of its low cost, high boiling point, availability, and regeneration in the plant, has been used extensively in pickling low carbon steels. Plant operations not employing acid regeneration and reclamation are being curtailed due to the high cost of disposing of waste pickle liquors. Disposal costs are closely related to increasingly strict environmental regulations.

Hydrochloric acid is becoming more popular for pickling steels. Unlike sulfuric acid, hydrochloric acid pickles efficiently at ambient temperatures, which decreases energy costs. This, in combination with new technology being developed in regeneration, will increase its use over the forthcoming years. In-plant regeneration of hydrochloric acid is expected to be available by 2005. The pickling process is divided into three steps:

- Cleaning and preparing metal
- Pickling
- Treating the pickled metal

Cleaning and Preparing Metal

Cleaning is necessary to remove any material from steel or iron that would prevent pickling acid from attacking the oxides and removing scale. The material most frequently encountered is oil. There are a number of methods that can be used to remove oil. Oil can be removed with oil solvents, most of which are volatile and leave a thin film on the surface. Solvents can be applied by any convenient means and wiped off with clean rags. The steel or iron can be degreased by immersion in solvents or solvent vapors. The latter method leaves metal free of oil but not from particles or smut held on the surface by oil film.

Alkali cleaning is relatively inexpensive and should be done when cleaning prior to pickling is necessary. This is employed regularly to remove oils, greases, cutting or forming compounds, etc. Other contaminants that should be removed prior to pickling are heavy rust and paint, which, on new steel, mainly involves shop and mill marks.

Scraping, wire brushing, or abrasive blast cleaning can remove heavy rust that might prolong pickling times. Paint and other types of marking can normally be removed mechanically or with solvents.

Pickling

Sulfuric and hydrochloric acid are commonly used for steel pickling. Almost identical pickling rates can be obtained from sulfuric and hydrochloric acids by suitable selection of bath temperature and pickling bath strength. Hot, dilute solutions of sulfuric acid are generally used for pickling, while hydrochloric acid is mostly used at ambient temperature to avoid undesirable fuming.

Typical sulfuric acid pickling for low carbon structural steels may not be suitable for some high-strength constructional alloy and heat-treated alloy steels. Some higher carbon and alloy steels burn in acid very easily, making surface smut more problematic. Test work sampling should occur before pickling large quantities of fabricated special steels, for which prior experience or test data is not available. Steel composition affects the time required for pickling.

Hydrochloric acid is highly volatile and generates fumes, even at room temperature. Fuming becomes worse with increasing solution temperatures. Fumes can cause severe corrosion of equipment and building structures in the vicinity of the pickle tank. Therefore, hydrochloric acid solutions are not heated unless ventilation is available.

Since sulfuric acid pickling solutions are heated, the process consumes more energy than hydrochloric acid pickling tanks. Pickling in sulfuric acid will produce a rougher steel surface than hydrochloric acid. However, either acid in combination with an inhibitor in the pickling bath can yield a smooth surface finish.

Tanks constructed of mild steel plate, wood, or polypropylene can be used for both cold and hot rinse, but ordinary steel, unlined, cannot be used to contain any of the acid solutions used in pickling. Wood tanks can be used temporarily to contain sulfuric, muriatic, hydrofluoric or phosphoric acids, but more permanent equipment, steel tanks lined with materials that resist the acids or propylene tanks, should be used to contain them.

A pickle tank suitably lined and constructed should be equipped with a large bottom drain for rapid emptying and easy cleaning, heating coils or another source of heat, water for diluting acid and for washing the empty tank, and provisions for adding concentrated acid to the bath.

Water should never be added to strong acids. Even when properly adding concentrated sulfuric acid to water, enough heat generates to boil and disperse the acid about. Workers should stay a safe distance from acid while it mixes with water. In small installa-

tions, steel chutes or pipes should be provided to aid in the addition of acid. In large installations, the acid should be pumped through a steel or lead pipe from the storage or measuring tank to the pickle tank.

It is advisable to have a separate tank for monitoring the amount of acid added to each pickle tank. For concentrated sulfuric acid, the storage tank may be safely constructed of mild steel, since concentrated sulfuric acid does not attack mild steel. However, other acids in concentrated form will attack mild steel. The acid storage tanks must use material or linings suitable for the acid being stored.

It is desirable to provide adequate ventilation around the pickling tanks. Warm air and exhaust ducts located over or near the tanks are helpful in ridding the atmosphere of fumes and acid mists. Also, structural steel within an enclosed pickling area should be properly coated with an acid-resistant corrosion protection system.

The rate of steel pickling is affected by the type of acid used for scale removal, the acid concentration, temperature, inhibitor concentration, and amount of agitation. **Figure 1** shows the effect of hydrochloric acid concentration on pickling time at various temperatures. **Figure 2** shows the same plot for sulfuric acid.

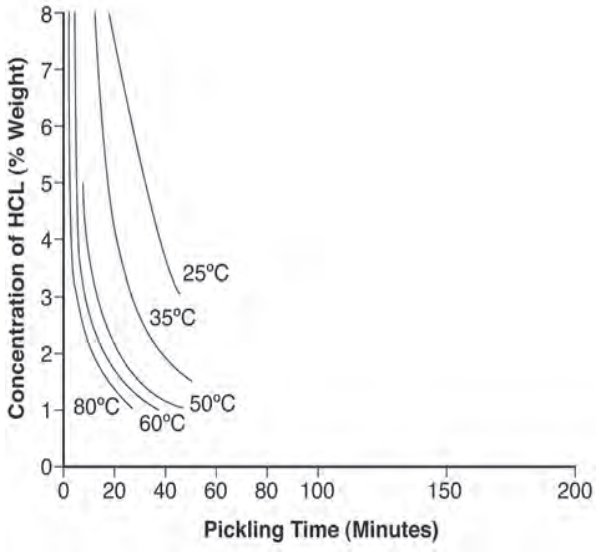


Figure 1. Effect of hydrochloric acid concentration on pickling time at various temperatures.

Sulfuric acid pickling takes place very slowly at room temperature, whereas hydrochloric acid pickles effectively at that temperature. The reaction rates for

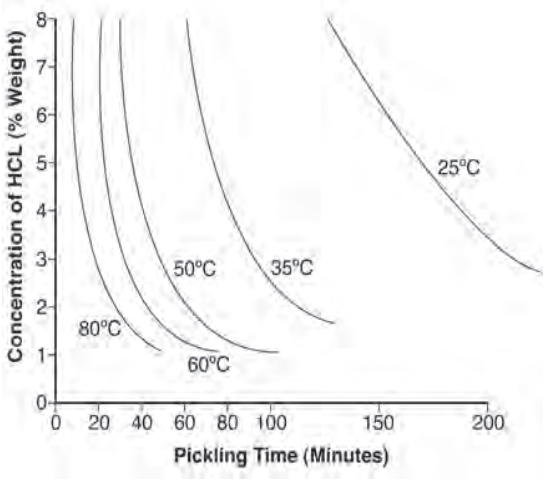


Figure 2. Effect of sulfuric acid concentration on pickling time at various temperatures.

both acids increase as the temperature is increased. Faster pickling rates can be obtained with hot sulfuric acid than with ambient temperature hydrochloric acid. Sulfuric acid baths are usually maintained at a temperature between 150 and 185°F (66 and 85°C), while hydrochloric baths are kept at ambient temperatures between 50 and 100°F (10 and 38°C).[1]

Figures 1 and 2 also show the effect of acid concentration. Hydrochloric acid is commercially available in concentrations up to 35% of 22 Baumé.[1] The rate of attack of hydrochloric acid is somewhat influenced by temperature, but the concentration of the acid plays a more important role. Hydrochloric acid becomes increasingly more corrosive with increasing acid concentration. For sulfuric acid pickling, a concentration of approximately 40% by volume of 66 Baumé acid is most corrosive to mild steel. However, for sulfuric acid pickling, the best economics are usually obtained by operating within a range of 2 to 20% by volume of 66 Baumé acid. Although the rate of scale removal and of attack on steel by sulfuric acid is somewhat dependent upon acid concentration, bath temperature rather than acid concentration primarily controls pickling times under normal pickling conditions.

When using hydrochloric acid for pickling, the desired pickling time obtained by using a particular acid concentration with the amount of fume produced by that concentration must be balanced. Lower acid concentration produces fewer fumes but also produces longer pickling times. Occasionally, the hydrochloric

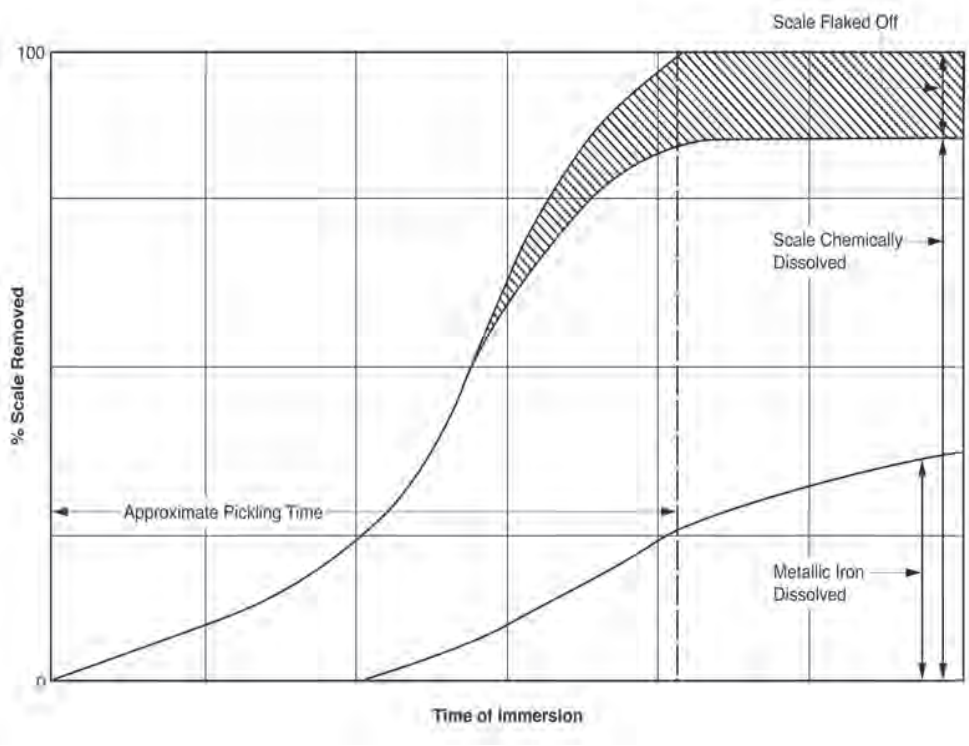


Figure 3. Time in the pickling bath is related to the amount of scale removed.

acid baths are slightly heated in order to use even lower concentrations of acid and reduce fuming. The tradeoff is, of course, higher energy bills to heat the acid.

Figure 3 illustrates how the effect of time in the pickling bath is related to the amount of scale removed. The shaded region is the ideal region for scale removal and suggests a longer immersion time.

The effect of dissolved iron on the pickling rate of steel also depends on the choice of acid. The corrosion rate of uninhibited hydrochloric acid increases dramatically as acid and iron concentrations increase. Corrosion rates of uninhibited sulfuric acid solutions fluctuate very little over wide acid and iron concentrations. Increasing amounts of dissolved iron in sulfuric acid eventually have a significant effect on pickling by delaying scale removal.

Scale removal can be increased with bath agitation. A stationary film of acid next to the scale surface decreases in free acid concentration while it increases in dissolved iron concentration. Both changes decrease the pickling rate. Faster pickling will result if fresh acid is brought to the steel surface and the weak acid contaminated with dissolved iron is circulated throughout the bath and away from the metal. Agitation may be obtained by mechanical means or by blowing air or steam up through the bath.

It is necessary on a periodic basis to monitor the pickling solution to determine the free acid content and the iron content. These checks should indicate when acid additions are needed and when the acid should be discarded or regenerated because excess iron is found in the bath. Iron content of the acid can adversely affect the efficiency of the pickling solutions when it becomes too high. Although hydrochloric acid pickling solutions are less affected by iron content than sulfuric pickling solutions, the upper limit can be anywhere from 85 g/liter to above 20% by weight, depending on the type of pickling solution.

Over-pickling can occur when the pickling solution attacks and dissolves the base metal after scale removal. It usually results because the scale layers are not uniform. Thicker or more deeply embedded materials require more time for removal. Proper selection and use of an inhibitor will minimize over-pickling.

A piece of metal is rarely uniformly covered with scale. The bare metal areas or areas with very light scale are attacked at once during acid pickling while no attack takes place on the heavily scaled areas. As a result, more metal is removed from the areas that are bare or are lightly covered with scale

without an inhibitor.

While adequate pickling is necessary, it is undesirable to over-pickle. This will cause a roughening or pitting of the base metal. Over-pickling also causes unnecessary consumption of the pickling acid. Inhibitors minimize the loss of iron, protect the metal against over-pitting, reduce acid fumes resulting from excessive reaction between the acid and the base metal, and reduce acid consumption.

Both natural and synthetic organic compounds are used as inhibitors. Natural compounds include low-grade bran, flour, gelatin, glue, sludge from petroleum, sulfonated coal-tar products, asphaltum, and wood tars. The synthetic materials are nitrogen-based materials such as pyridines, quinidines, aldehydes, and other compounds containing sulfur.[1]

Inhibitors are added to isolate the base metal once the oxides and other contaminants have been stripped away, preventing the attack on the base metal. Some inhibitors accomplish this by laying down a thin film, isolating the acid away from the metal. Other inhibitors stop the passage of galvanic cell current and the corrosion process by an action known as cathodic polarization, essentially preventing the release of hydrogen at the cathode and stopping the metal attack at the anode.

The use of an inhibitor with a wetting agent will provide better drainage of the pickling solution. This not only will conserve pickling acid but also will minimize the possibility of carrying acid and dissolved iron into any following processes. Wetting agents can actually increase the speed of oxide removal. Acid inhibitors must be stable at all possible operating temperatures and conditions and must not decompose in solution, stain, or contaminate the steel. An adequate inhibitor keeps maintenance costs down and does not emit offensive odors.

Over-pickling causes a roughening of the whole surface, discoloration of the steel and a decrease in size and weight of the part. Over-pickling can be avoided by removing the material from the bath promptly when complete removal of scale has been accomplished. Inhibitors aid in preventing over-pickling, but do not provide a sure guarantee.

Hydrogen embrittlement can occur when high-strength steels with very small steel grains are pickled. Steels in excess of 150,000 psi (1035 MPa) tensile strength should be cleaned using shot or grit blasting followed by a very quick immersion in a pickling bath. The proper choice of inhibitor can minimize acid attack on the bare steel and thus reduce the amount of absorbed hydrogen gas.

Spent acid is the name given to a pickling solution that has a chemical content of iron and scale that renders the acid ineffective. At this point, the iron starts to crystallize in the bath or the pickling is too slow. The spent acid must be responsibly discarded or recycled.

Neutralization is the most common and simplest way to treat spent acid. The spent acid, or pickle liquor, is treated with an alkaline chemical such as caustic soda or lime. An economical neutralizer would be residual chemicals in alkaline cleaning solutions. Neutralization of the spent solutions forms iron hydroxide, which is gelatinous and slow to settle out. After the spent pickle solution is neutralized, some method of disposal is required.

Hauling to a disposal site entails contracting a company to pump out spent liquor into a special tank carrier for transportation to a site. This site can either be an authorized disposal facility for this material, a central recycling plant, or another company able to utilize the spent pickle solution. Whatever the end destination, the user is legally liable to ensure that the material is not disposed of in violation to environmental laws.

Discharging spent pickle solution in deep wells is one means of off-site disposal; however, local and state authorities must permit this.

The alternative to neutralization or disposal would be an acid recovery by crystallization of the spent acid solution. Several methods of regenerating hydrochloric and sulfuric acid are commercially available for use in plants where the volume and cost make them viable.

Treating the Pickled Material

When steel or iron are removed from the pickle bath they are coated with a thin film of pickling acid and salts, resulting from reaction of acid with iron. The acid and salts, with the exception of some salts produced from phosphoric acid, actually stimulate rust formation and must be completely removed before they dry on the steel. An ample supply of clean water must be available for rinsing. Steel, wood, polypropylene, or concrete tanks provided with a skimming trough to take care of an ample overflow of water are generally used, although water can be applied liberally

with a hose.

Pickled work should be rinsed promptly, particularly if the acid is hot. If the film dries, it is difficult to rinse away and may cause difficulty in many subsequent operations.

When pickling acid and iron salts are removed or diluted, metal must be suitably treated in preparation for the operations that follow. Treatment prevents steel from rusting and prepares it for painting or other coating operations such as hot-dip galvanizing. When pickled steel parts are to be stored, weak alkali solutions, such as 1/4 to 1/2 ounce per gallon (1.9-3.7 g/L) of sodium carbonate or trisodium phosphate, are used in a boiling rinse following a cold rinse. The alkaline surface does not rust rapidly, but if the pickled steel part is to be stored indefinitely or exposed to weather it should be passivated in some manner. Alkali cleaning solutions after pickling are suitable for the subsequent application of oil but are not suited for the subsequent application of paint. There are other treatments that can be used to prevent rusting after pickling.

Most paints do not adhere well and form blisters in a humid atmosphere if applied to an alkaline or neutral surface. For best painting results, the surface pH should be slightly acidic. When using special paints, such as inorganic zinc, the best results occur when paint is applied to a neutral surface. In pickling processes for inorganic zinc applications, no further treatment is normally used after the hot water rinse.

For most paints, other than inorganic zinc, it is important that the proper acid be used to produce the correct pH. Phosphoric or chromic acids produce the best results. Muriatic or sulfuric acids should not be used because their residues stimulate steel surface rust under paint.

It is desirable to further clean and treat pickled and rinsed steel in a phosphoric acid solution prior to painting. Good results can be obtained by adding approximately 0.25% by weight of concentrated phosphoric acid to the hot rinse bath contained in a steel tank, and maintaining this rinse at a pH of 3 to 5 by addition of acid as small quantities are needed.

The cleanliness of the boiling rinse is important, since it is here that a satisfactorily cleaned surface can be spoiled for painting. For best results the bath should be discarded daily and the tank cleaned before making a new bath. This is not practical for large-scale structural pickling operations and good painting results can be obtained by merely maintaining a water rinse temperature at 140ºF (60ºC) or higher and painting promptly while the steel is warm and dry.

References

1. *Hydrochloric Acid Pickling;* American Galvanizers Association: Technical Services Committee, 1979.
2. Anderson, J. D. Pickling: *An Art or a Science;* Amchem Products, Inc.

Suggested Reading

The Galvanizing Handbook; Zaclon, Inc., 1996.

Metals Handbook—Volume 5: Surface Cleaning, Finishing, and Coating, 9th Edition; American Society for Metals, 1994.

Viljoen, C.L. et al. *A Comparative Study of the Use of HCl and H_2SO_4 in Acid Pickling in the South African Hot Dip Galvanizing Industry;* Galvanizers Party Ltd., 1991.

Hudson, R.M.; Warning, C.J. Factors Influencing the Pickling Rate of Hot-Rolled Low Carbon Steel in Sulfuric and Hydrochloric Acids. In *Metal Finishing;* U.S. Steel Corporation, 1980.

Kleingarn, J.P. Pickling in Hydrochloric Acid. *Intergalva* '88; VDF, Germany FR., 1988.

About the Authors

Dr. Thomas L. Langill

Thomas J. Langill is technical director of the American Galvanizers Association (AGA), 6881 South Holly Circle, Suite 108, Englewood, CO 80112. He has 20 years of experience in materials development and research and assisted in packaging a laser-diode system for military uses. Mr. Langill has represented the hot-dip galvanizing industry at the AGA for the past 7 years. He has a PhD in materials science and engineering and is a member of NACE.

John W. Krzywicki

A graduate of the University of Wyoming with a degree in chemical engineering, John W. Krzywicki joined AGA as a corrosion engineer in 2001. While working for there, he has become a member of NACE and has published numerous articles and papers on the hot-dip galvanizing process, which include its various applications and corrosion protection.

Chapter 2.9.2
Chemical Stripping

John Steinhauser

Basic Principle of Operation

Chemical strippers are typically used for two generic applications: removing old oil-based (alkyd) paint and removing other coatings, such as epoxies, urethanes, vinyls, coal tars, elastomerics, and/or other chemically resistant coatings.

In either application area, very few restrictions apply as to which substrates are present, with the major exception that caustic strippers will attack aluminum and/or aluminum paint, and precautions must be taken in those applications.

For those applications involving removal of oil-based paint, caustic strippers have proven to be both productive and economical. These strippers contain one or more common caustic chemicals, such as sodium, calcium, and magnesium hydroxide. They are formulated as heavy pastes so that they will adhere well to vertical as well as over-hanging surfaces such as may be found on the underside of an elevated water storage tank.

For applications other than oil-based paint, the two most common strippers are those that contain n-Methyl-2-Pyrrolidone (NMP) and those based on selective adhesion-release agents, known as SARA strippers. Both of these generic strippers have proven effective for removing chemically resistant coatings as described above.

The effectiveness of SARA strippers on different generic coating types is covered in reference 1. SARA strippers are not effective on rigid urethanes and aromatic Novolac amine epoxies.

It should be noted here that since both stripper types have either low or no volatile organic compounds (VOCs), they typically react more slowly than the early generation toxic strippers, sometimes taking as long as 48 hours for complete removal.

SARA strippers are biodegradable and can be left to soak into the ground. A permeable membrane (e.g. cheesecloth) can be spread on the ground to filter out debris as the SARA stripper and paint are removed by water cleaning.

Historical Development

The use of chemicals for paint removal is not new, as paint strippers containing solvents have been in use for a number of decades. Most of these early chemical strippers, which still exist today, contain one or more chemicals designated as being toxic, such as methylene chloride, toluene, methyl ethyl ketone, and methyl alcohol. The Occupational Safety and Health Administration (OSHA) has placed tight restrictions on permissible exposure limits (PELs), which apply to painting contractors, requiring them to use strippers that are less hazardous, both from worker safety as well as environmental standpoints. [2,3,4]

During the 1990s, this new generation of paint strippers has been used on industrial and commercial job sites, ranging from large steel structures, such as bridges and storage tanks, to masonry structures, such as warehouses, water treatment plants, school buildings, and churches.

Stripper Selection, Process Equipment, Procedures

Chemical stripper selection is based upon a number of variables that can be best assessed by performing patch tests on the actual surface to be stripped. End users should seek the assistance of a trained manufacturer's representative, who can adjust the application parameters such as formulation, stripper thickness, and/or dwell time in order to determine which product best fits a particular application. To account for variations of both paint type and paint thickness, which can occur frequently on old structures, patch tests should be conducted in more than one location; and each test should cover at least one square foot of surface.

Since many older structures have multiple layers and types of paint, more than one application of a stripper or more than one type of stripper may be required; and therefore, the owner should rely on testing done by the manufacturer to determine which product(s) work most effectively. By performing pre-job testing, the owner can be best assured that the proper

stripper has been selected to suit the particular application and job scope.

In specifying process equipment, consideration must first be given to containment structures and materials. Containment guidelines for chemical stripping involve: containment during stripper application; during stripper removal; during surface preparation for painting; and during painting. In general, the containment structure should be in accordance with SSPC-Guide 6, *Guide for Containing Debris Generated During Paint Removal Operations*, Class 1C, 2C, or 3C.[5] Additional containment guidelines are also discussed in SSPC-TU 6, *Chemical Stripping of Organic Coatings from Steel Surfaces*.[6] Typical chemical stripping containment structures require only that the solid and liquid waste products be contained within the structure for easy collection and disposal.

Remaining process equipment used for chemical stripping includes either hand tools or paint pumps for application of strippers, hand tools for bulk removal of stripper wastes, and equipment for rinsing or otherwise removing remaining stripper residues in preparation for subsequent painting. For stripper application, typically airless paint pumps can be used to provide adequate production rates; however, most caustic strippers are quite thick and require air spray pumps modified to handle thicker materials. Either type of pump is readily available through the distributors who market the stripper products. Stripper manufacturers, during test patching, can assist in recommending proper application equipment. For rinsing and removing remaining stripper residues, a number of options exist, with an objective to keep liquid wastes to a minimum.

Commercial and industrial paint stripping projects have successfully employed a number of processes for cleaning stripper residues. These include sponges, hand spray pumps or bottles, paint pumps using water, ice blasting, carbon dioxide blasting, pressure washing, steam cleaning, and vacuum rinsing. Each method should be evaluated on its own merit as it would pertain to a particular paint stripping job. Again, owners should contact stripper manufacturers, who can demonstrate these processes at the job site, in order to determine which provides the best scenario regarding cost and productivity.

At the job site, the stripper is applied to the old paint using one or more of the techniques described above. Thickness and dwell time will have been predetermined by patch tests. Daily production rates will also have been pre-determined. In general, productivity is limited to that amount of surface area to which stripper has been applied that can be effectively cleaned within the timeline set by dwell time. While this guideline is relatively flexible, some strippers, in particular caustics, if left to dwell for too long a period, can create extra labor and/or waste liquids. Since the NMP and/or SARA strippers typically have low VOC content, they can be left to dwell for longer periods without creating added labor for removal. Also, when some strippers are applied to concrete and/or other masonry surfaces, a covering material may be required in order to prevent the stripper from drying before the old paint has completely reacted with it. Manufacturers will determine this during patch test procedures.

Following the proper dwell period, the stripper is removed using one or more of the processes described above. As with stripper selection and application, optimum removal techniques can be determined during the patch-test phase. Consideration is given to waste (quantity as well as hazardous/non-hazardous), containment requirements, and/or other worker safety and environmental considerations. Finally, the substrate is inspected for cleanliness and surface conditions such as proper pH and/or any existing corrosion. The substrate, at this point, is ready for coating application.

Application Considerations

Chemical stripping offers many application advantages when used for removing old coatings. Since it is a wet process, it presents little or no airborne exposure to any hazardous materials that may be present in old coatings, which, if removed with dry processes, require expensive ventilation and filtration equipment.

The most limiting factor when considering use of chemical stripping is that the process does not leave a profile on any substrate, metal or otherwise. However, moisture-cure polyurethanes and other coatings technology developed in the late 1990s may be used directly on clean steel surfaces without significant profile as long as any loose corrosion or mill scale has been removed, as described in SSPC-SP 3, *Power Tool Cleaning*.

In addition to these coating advances, many coatings are available which can be used directly on

bare, clean, masonry surfaces, avoiding the need for using floor blasting equipment to remove the old coatings.

Another limiting factor involves weather. Most of the strippers discussed should be used at ambient temperatures above 50°F (10°C). These chemicals actually prefer warm moist weather but they work well in dry areas if application cycles are compatible with weather conditions. Chemical strippers are not immune to rain, but production cycles can be adjusted during the job to account for weather problems as is done with other paint removal processes. Weather limiting factors, as with other considerations, can be adequately assessed during the patch-test phase of a project.

Chemical stripping offers production rates that are competitive with dry abrasive blast cleaning, waterjetting, and power tool cleaning. Advantages of chemical stripping include lower costs of waste disposal and containment, with little or no costs associated with dust control. Chemical stripping can also be used on historic structures where abrasive blast cleaning is not recommended.

Cleaning Rates and Costs

Productivity and process costs for chemical stripping can vary greatly depending on a number of factors such as structure geometry, which relates to containment considerations; stripper dwell time; existence of hazardous paint; and weather conditions. Productivity can be reasonably estimated after patch testing. For example, structures that are relatively accessible, such as storage tanks and commercial building exteriors, a three-worker crew can typically produce clean surfaces at the rate of 3000–4000 ft^2 (300–400 m^2) per day. This rate assumes that one worker can spray the stripper at the above rate; the stripper typically dwells overnight; and two workers clean the old paint and stripper residues the following day while another surface is being coated with stripper. On the other hand, complex jobs, such as bridges and internal factory structures, require more difficult scaffolding, and production rates are typically in the range of 1000–2000 ft^2 (100–200 m^2) per day.

Accordingly, costs associated with these production scenarios also vary according to the above listed conditions and can nominally range from $4.00 to $8.00 per ft^2 ($40 to $80 per m^2). Other factors include waste costs (both solid and liquid) and subsequent coating costs. For example, polyurethanes for steel structures are typically more expensive than acrylic or elastomeric coatings used on masonry building exteriors and interiors. Costing these projects relies on data gained from pre-construction testing, again substantiating the importance of that phase of a project.

Final Process Results

While standards do not presently exist for chemically stripped surfaces, quality control guidelines, as specified by manufacturers, typical include visible inspection for complete paint removal, removing existing corrosion or other surface contaminants using hand or power tools, and verification that substrate cleanliness meets requirements for subsequent painting. For example, if caustic strippers are used on either steel or masonry structures, surface pH must be within guidelines prescribed by the paint manufacturer. In the case of masonry structures, acid neutralization may be required. By following these quality control procedures, owners can be assured that the cleaned surface will be compatible with any subsequent coating (See **Figure 1**).



Figure 1. Stripping red lead paint from the beams supporting a bridge deck in Kingston, NY. The bridge beam has had the bulk of the chemical stripper, along with the old paint, scraped away. The remaining lead residue has already been dissolved by the stripper. It was later removed by ice blasting, a cleaning procedure that generates less than 11 gallons (42 L) per hour of liquid waste. This is far less than any other rinsing process. A 3-coat micaceous iron oxide moisture-cure polyurethane coating system was eventually applied.

Expected Advances in Chemical Stripping Technology

While many advances have already been made in the chemistry of paint stripping, such as eliminating the use of toxic products, future technology lies in the process of applying and removing the resultant stripper residues. As more productive cleaning processes, such as ice blasting and steam cleaning, become accepted by contractors, they will improve the existing cost-effectiveness of chemical stripping.

References

1. O'Donoghue, Mike; et al. Chemical Strippers and Surface-Tolerant Coatings: A Tandem Approach for Steel and Concrete. *Journal of Protective Coatings and Linings,* May 2000, pp 74-93. Also in *Protective Coatings Europe,* June 2000, pp 53-63.
2. FIFRA Occupational Safety & Health Standards. *Code of Federal Regulations,* Section 1910, Title 29.
3. FIFRA Occupational Safety & Health Standards. *Code of Federal Regulations,* Section 1915, Title 29.
4. FIFRA Occupational Safety & Health Standards. *Code of Federal Regulations,* Section 1926, Title 29.
5. SSPC-Guide 6. *Guide for Containing Debris Generated During Paint Removal Operations;* SSPC: Pittsburgh.
6. SSPC-TU 6. *Chemical Stripping of Organic Coatings from Steel Surfaces;* SSPC: Pittsburgh

Suggested Reading

Chemical Stripping Removes Lead Paint from Water Tower. *Journal of Protective Coatings and Linings,* March 1996, pp 43-44.

Mickelsen, R. Leroy; Haag, Walter M. Removing Lead-Based Paint from Steel Structures with Chemical Stripping. *Journal of Protective Coatings and Linings,* July 1997, pp 22-29.

About the Author

John Steinhauser

John Steinhauser received a degree in chemistry from Stanford University in 1961. He has thirty-five years experience in materials and processes, both engineering and marketing positions, including 11 years in his current position as sales manager for Dumond Chemicals, manufacturer of chemical strippers, masonry cleaners, and graffiti barrier coatings and removers.

Prior to joining Dumond, Mr. Steinhauser held positions with manufacturers of abrasive blast cleaning equipment, vacuum blasting equipment, and ultra high pressure abrasive waterjet cutting and cleaning equipment. He also spent four years in materials technology engineering at Boeing Company, Commercial Airplane Division.

Chapter 2.9.3
Sodium Bicarbonate (Baking Soda) Blast Cleaning

Mike Doty and Delia L. Downes

Basic Principle of Operation

Sodium bicarbonate blast cleaning is a "line-of-sight" process projecting a pressurized air or water stream containing suspended sodium bicarbonate (SBC) particles at a surface for the purpose of removing a coating or contaminant. It utilizes direct-pressure or suction equipment to meter and deliver SBC (i.e., baking soda) crystals at high speeds to a surface. Typically air driven (compressed air) systems are used, similar to sandblasting. Equipment commercially available includes specially engineered or modified pressure systems operating to 300 psi (2100 kPa). High-pressure water to 25,000 psi (170 MPa) is also available.[1,2,3]

Historical Development

The use of SBC is well known as a mild abrasive cleanser applied manually to a variety of surfaces.[4] It has been very effective as an oral hygiene tool for dentists using micro-blasters to clean teeth without harming gums.[5] The first large-scale use of SBC as an abrasive was during the renovation of the Statue of Liberty (circa 1986) to remove coal-tar epoxy paint and corrosion from the inside of the statue. A modified blast/vac system, liquid nitrogen, and SBC helped to preserve this national treasure.[6] Subsequently, the process was "commercialized" by Church & Dwight Co., Inc., makers of Arm & Hammer products, and Schmidt Manufacturing with technology innovations to both equipment and the SBC formulation.[1,7]

Equipment/Materials

Equipment innovations and engineering modifications have been developed to increase the productivity of an otherwise soft, friable, and not very dense particle by improving the flow, velocity, and pressure of delivering the particle to the surface. Working pressures ranging from 5-125 psi (34-860 kPa) can now be achieved with media delivery of 0.3-3.0 lb/min (0.14-1.4 kg/min). Both parameters are independently adjustable by the operator with minimal effort.[7] Additionally, some systems provide the capability of adding water to the media/air stream on demand, thereby assisting with scrubbing, dust control, and rinsing. Nozzle variation and selection, depending on the surface preparation requirements, can improve performance even further. As a non-wearing abrasive SBC also prolongs nozzle life when compared to harder grit abrasives. Similar modifications are also available in water-driven systems using SBC.[9]

Innovations and variations with regard to SBC as an abrasive media focus primarily on crystal size and shape. However, additives are sometimes employed for flowability, rinsability, or special effects such as profiling steel. One manufacturer offers fourteen media formulations matching inherent qualities such as particle shape and size with additives for specific surface preparation requirements.[7] The softness (2.5 Moh's hardness), the friable nature of the media, its food grade quality and safety, and its water solubility make it a unique media with a vast target base.[7] While all SBC is the same chemically, as an abrasive, physical characteristics and enhancements contributing to its behavior become paramount.

Applications for SBC Blast Cleaning

Advantages of SBC Blasting

• **Sensitive substrates.** SBC media can clean, degrease, or depaint without degrading the surface of an aluminum alloy or composite material.

• **Rotating parts.** Being extremely soft, friable, and water soluble, SBC media can be used safely around rotating parts. It will not damage bearings, wire rope, gears, or turbines. It can be safely used in and around operating equipment minimizing facility shutdowns.

• **Brush blasting.** The removal rate is controlled by adjusting the pressure, the dwell time, and the "stand-off" distance. It is possible to remove only one layer of paint at a time. If desired, only loose, flaking paint or chalkiness will be removed. Top coats may be

removed leaving primer coats intact. Similarly, SBC media can be controlled to remove such things as fire soot or chemical spills from a painted surface without disturbing the protective paint.

• **Cleaning concrete.** SBC can be used on concrete to either clean or depaint the surface or to prepare the surface for a new coating. SBC removes contaminants such as grease, oil, rubber marks, or stains. By increasing the blast pressures or using special media, the surface may be slightly etched without using hazardous or harsh acid chemicals.[7]

• **Prevents warping.** The transfer of energy upon impact shatters the sodium bicarbonate crystal. Therefore little or no heat is generated during use, which prevents warping of thin metals or debonding of composite materials.[10]

• **Non-sparking.** SBC media can be used in volatile or hazardous environments such as refineries or offshore drilling rigs where sparking is a most serious threat. This media is used to depaint and clean the steel superstructure while the rig remains in operation, allowing for continuous corrosion control. Standard bonding and grounding is required to prevent static electricity discharge.

• **One-pass cleaning.** Due to its softness and friablility, SBC media shatters so completely it cannot be recycled. This ensures that clean media is always being introduced into the blasting process, eliminating concerns for re-contamination. Additionally, equipment costs for collection, recycling, and cleaning are eliminated, reducing the costs associated with more complex and less portable systems.

• **Nontoxic.** Being a food grade material, it has a superior safety profile before, during, and after use.[7] The material safety data sheet (MSDS) reads 0,0,0, X, where the "X" denotes only a dust mask level of protection for the operator. Some SBC abrasives have been approved by the USDA for use in food processing facilities. Other applications have been safely conducted around pedestrian traffic.[18]

• **Chemical attributes.** While using SBC as an abrasive is a mechanical process, there are some excellent chemical attributes. Since SBC is a buffer, its use in wet and dry blasting may prevent flash rusting on steel. Trace amounts left on the surface neutralize acid gases in the air allowing much larger areas to be depainted before priming is required. This can be a great cost saving, especially in humid areas. Likewise, SBC can contribute to treatment of wastewater by acting as a buffer.

Limitations of SBC Blasting

• **Heavy paint removal.** SBC media usually performs too slowly on coatings greater than 15 mils (400 µm) thick. In these cases, it is often used to remove only failing, chalky, contaminated paint layers or as a final step following waterjetting.

• **Heavy corrosion.** SBC media by itself can only remove surface corrosion. Removing heavy corrosion or profiling steel requires an SBC media with additives, which are available from some manufacturers.[7]

• **Adverse affect on plant life.** Large amounts of SBC residues left on foliage and grasses may cause phototoxicity resulting in browning that may kill plant life. Protective measures, such as covering plant life and thorough rinsing before and after operations, can eliminate or greatly mitigate damage.

• **Requires specialized equipment.** SBC media does not behave as other harder grit abrasives and therefore does not work as effectively or cost efficiently through standard blast pots and water systems. Using the correct equipment will produce the desired results and a quick return on the investment.

SBC Blast Cleaning Compared to Other Methods

• **Versatility.** SBC media can be effective at a wide range of pressures from 5-125 psi (34-860 kPa) making it possible to use on a wide variety of substrates and soils.

• **One-step process.** Masking and disassembly steps can be eliminated because SBC media will not harm sensitive substrates, including glass. Since it is a one-pass media and it works particularly well on greasy and oil residues, including carbon, the pre-wash step can often be eliminated. Being water-soluble, the risk of particles lodging in critical contours or passageways can be eliminated with thorough rinsing.

• **Portable or contained.** SBC media can be used with portable blast equipment on large structures (with or without containment) and on the smallest of parts using contained equipment or micro-blasters.[1, 5, 8]

• **Equipment life is prolonged.** SBC will not wear nozzles, valves, hoses, or protective equipment like other harder abrasives.[12]

• **Paint adhesion.** Results from standard tests revealed that paint adhesion was the same or better on steel and aluminum surfaces cleaned with SBC media compared to staroulite, slag, or plastic media. [11, 15, 16, 17]

Environmental/Safety Advantages of SBC

• Rated by EPA and OSHA as non-hazardous and non-toxic, the SBC material itself presents no special requirements for use and disposal beyond standard minimal handling.

• The MSDS rating of 0, 0, 0, X conveys its benign nature.

• The pH 8.2 for SBC is far below the EPA limit of pH 10.

• Easier disposal. Due to its benign nature, only the coating or contaminant removed must be considered to determine proper disposal. In dry waste, SBC can oftentimes be disposed of in a sanitary landfill, and in wet waste, contaminants can usually be filtered out and the remaining effluent sent to the drain for further water treatment.

• SBC media is non-sparking and non-combustible under any conditions. Therefore no explosion, burning, or any fire hazard is possible.

• SBC media has no VOC component.

Weather Restrictions for SBC Blasting

SBC is inherently hydrophilic, absorbing moisture from high humidity environments or wet air supply. As a result the media may clump or clog in the machine. It is imperative to keep the media as dry as possible before and during blasting operations. For this reason, some manufacturers have formulated SBC media to resist moisture.[7]

Cleaning Rate and Cost Information for SBC Blasting

Cleaning Rates

For cleaning operations such as chemical spills, stains, paint overspray, or light paint removal (less than 3 mils [75 µm]) expect a production rate of 4 ft^2/min (0.4 m^2/min) under the following parameters:

• SBC media flow @ one lb/min (0.5 kg/min); air pressure (from a direct pressure vessel) @ 60 psi (400 kPa); using a number 8 (1/2-inch [13 mm]) bore nozzle. Water added (at the nozzle) for dust control or rinsing will reduce the production rate about 20%.

• For surface preparation on galvanized steel or concrete, set parameters as listed above except lower the blast pressure to 40 psi (300 kPa). Increase/decrease the pressure on the concrete targets to produce the desired effect, i.e., cleaning or roughening the surface.

• For depainting steel with 10mils (250 µm) of paint, expect a production rate of 1.5 ft^2/min (0.14 m^2/min) with SBC media flow @ 2 lb/min (0.9 kg/min), nozzle pressure @ 90 psi (620 kPa), #8 (1/2 inch [13 mm]) bore nozzle with a direct pressure vessel. (Note: Nozzles designed specifically for SBC media improve performance by over 50%.)[7]

Cost Information

SBC media (in volume) can be purchased for around $0.36/lb ($0.79/kg) and consumed at a rate of 1-2 lb/min (0.5-1 kg/min) in portable applications. As a one-pass media there are no recycling or media cleaning costs. Disposal costs are minimized by the low volume of waste generated and the inherent benign nature of SBC. Proper dispensing of SBC media is essential. Equipment selection can therefore be a cost factor when setting up the first time.

Air costs/water costs are exactly the same as for other abrasives as media choice does not affect air/water flow dynamics. However, since SBC media can be effective and efficient at lower pressures, cost savings may be realized here.

Total project costs go beyond price per pound (kg) for media. Substrate preservation requirements (masking), shutting down equipment, clean up, and disposal costs are minimized. Other costs associated with the safety and protection of workers and the

environment must also be computed to show the real value of using SBC media as a cleaning and/or depainting product.

Surface Conditions Achievable with SBC Blasting

Visible Levels of Cleanliness Achievable

On steel, SBC media by itself will not remove all mill scale, rust, and corrosion nor will it generate a profile. An SSPC-SP 7/NACE 4 (brush-off) rating is produced.[13] The original profile, if any, will be restored. At least one manufacturer offers SBC media enhanced with varied amounts of hard abrasive to allow SSPC-SP 5/NACE 1 (white metal) and SSPC-SP 10/NACE 2 (near-white) finishes with profiles up to 4 mils (100 µm). [7, 13]

Galvanized steel, concrete, and plastics are visibly cleaned. A water break (or similar) test can be used to verify contaminant removal. If desired, surfaces may be etched slightly by adjusting the blast pressure.

Non-Visible (Soluble Salt) Remediation

Spent SBC media (a soluble salt) may be deliberately left on steel surfaces (temporarily) as a flash rust prevention step or thoroughly rinsed off a paintable surface. Troublesome soluble salt residues may require repeated rinsing. A simple test can be utilized to ascertain that only very low levels (lower than will affect paint adhesion) of SBC media remain. A visual inspection of the surface for any remaining "white" crystals can be followed with placing a drop of household vinegar on the surface. Any amount of SBC media will effervesce (fizz) if present indicating more rinsing is required. The test may be enhanced by the use of a flashlight and/or a magnifying glass. Hard water deposits will not effervesce.[14]

Applicable Standards

Surfaces cleaned with SBC media are subject to the same surface preparation standards as surfaces blast cleaned with metallic or other nonmetallic abrasives.

Compatibility With Generic Types of Paint

Virtually every type of coating has been tested after cleaning or depainting with SBC media. If the surface is free of harmful contaminants, no premature failures will occur. All paint manufacturers can provide primers and paints compatible with the specified surface preparation standards. Since most SBC media is used wet, or rinsed later, surface-tolerant primers are normally specified.

Although SBC blasting does not produce a surface profile, most paints will adhere to a surface that is free of dust, loose rust, and detrimental soluble salts.

Expected Advances in SBC Technology

Wider acceptance of SBC as a cleaning and depainting media may lead current technologies, slurry cleaning, to include SBC. Environmental issues may also push the use of SBC. New ways to solve old problems like asbestos abatement will likely occur.

References

1. USFSPG/SMI [U.S. Filter Surface Preparation Group, Schmidt Manufacturing], Accustrip Systems, 11927 S. Hwy. 6, Fresno, TX 77545.
2. Black Diamond Products, L.P., WADU Delivery Device, 5340 Rittiman Rd., San Antonio, TX 78218.
3. Carolina Equipment & Supply Co., Inc., The Aqua Miser B.O.S.S., P.O. Box 40907, N. Charleston, SC 29423.
4. Church & Dwight Co., Inc., 469 N. Harrison St, Princeton, NJ 08543.
5. Prophy Jet System (Cavitron Co.); Micro Abrasive Jet Systems (Texas Airsonics, Inc.), Corpus Christi, TX; Micro Abrasive Blasting Systems (COMCO INC), Burbank, CA; AIRBRASIVE SYSTEMS (Pennwalt Corp.); SWAM BLAST Equipment (Crystal Mark, Inc.), Glendale, CA.
6. Baboian, R.; Bellante, E.L.; Cliver, E.B. *The Statue of Liberty Restoration;* NACE: Houston.
7. ARMEX Cleaning and Coating Removal Systems, The ArmaKleen Co., 469 N. Harrison St., Princeton, NJ 08543.
8. Eagle Industries of Louisiana, P.O. Box 10652, New Orleans, LA 70181.
9. JSA Tube Cleaning Systems, Jetting Systems & Accessories, Inc., Houston, TX.
10. Scott, Todd. *Temperature Affects on Laminated Aircraft Panels;* United Airlines Maintenance: Houston Technical Center,
11. Van Sciver & Associates, 29 Vinton Rd., Madison, NJ 07940.
12. U.S. Navy, North Island. Steel Shot/ARMEX

Blasting Facility, N.A.S.N.I., Coronado, CA.
13. *Surface Preparation Specifications;* SSPC: 1989.
14. *Beyond White Metal;* WhiteMetal Group, SuperClean, Inc.: Houston, 1992.
15. Vogelsang, Bo. Paint Adhesion on Aluminum Panels Stripped with Armex Blast Media. Vogelsang Consulting, 1989 (Reprinted as a supplement to *Aviation Maintenance,* November 1997).
16. Comparative Corrosion and Paint Adhesion Tests [ARMEX]. Van Sciver & Associates: Madison, N.J., 1993.
17. Operations Technology Development Report No. 046044. *Surface Preparation of 2219-T87 Aluminum for BMS 10-79 Epoxy Primer Application on ISSA Structures;* Boeing/NASA, 1995.
18. Preservation Techniques. *Stone World Magazine,* Reprinted in March 1996 by Church & Dwight, Inc. and Young Restorations.

About the Authors

Mike Doty
Mike Doty is ARMEX technical field support manager for ArmaKleen Co., a joint venture between Church & Dwight Co., Inc. and Safety-Kleen Corp. Mike has been with Church & Dwight for 25 years and has been involved with the ARMEX product line since its beginnings in 1989.

Delia Downes
Delia Downes is ARMEX product manager for ArmaKleen Co. Delia has been with Church & Dwight for 15 years and with the ARMEX product line since 1989.

Chapter 2.9.4
Pliant Media Blasting

Tony Anni

Basic Principles of Operation

Pliant media blasting is a dry, air-driven mechanical process similar to conventional abrasive blasting where abrasive media are propelled from a pressure vessel onto a surface for cleaning, paint stripping, and/or profiling.

Pliant media blasting is different from conventional dry abrasive blasting in that the media used is a composite of conventional abrasives bonded to polyurethane **(Figure 1)** to form particles in sizes between 0.125 inch (3.2 mm) to 0.25 inch (6.5 mm) **(Figure 2).**

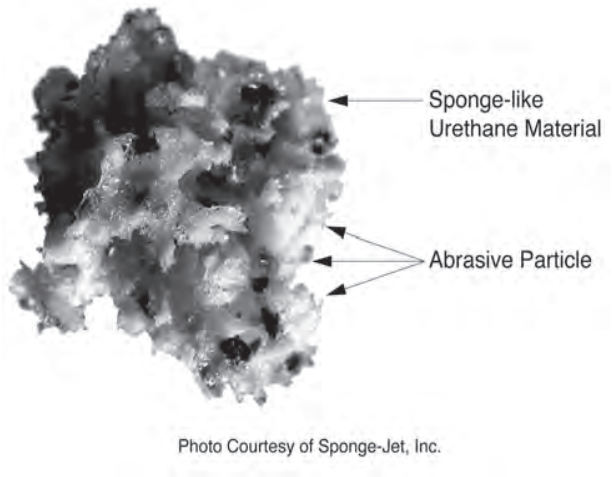


Figure 1. Pliant media.

The pliant nature of this media allows particles to absorb collision energy, which, in turn, lowers the rebound speed and ricochet distance from the surface **(Figure 3).** During the impact process, the bonded particles are shot at the surface to clean, strip, and/or profile. Immediately following impact, the sponge-like urethane returns to its original shape, entrapping contaminants that might have become airborne.

Historical Development

Sponge-Jet, Inc. developed pliant media during the late 1980s in response to key environmental



Figure 2. Pliant media particles.

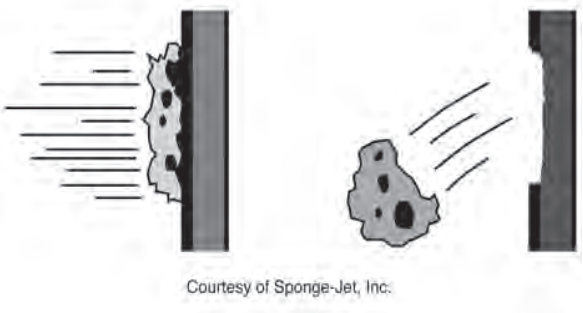


Figure 3. Pliant media impact process.

forces surrounding work place safety and waste generation/minimization. During the early 1990s, changes to media particle size made pliant media abrasive easy to separate from spent media and the removed contaminant or coating. Certification for incinerability for primary use in radionuclide-contaminated applications was granted.[1] In the mid 1990s, certain pliant media abrasives were found to remove significant levels of chlorides even without subsequent washing.[2] In the late 1990s, pliant media recyclability and low rebound benefits began allowing contractors to use less media and therefore transport, handle, clean-up, and dispose of less.

Equipment/Materials

Pressure Vessel (Blast Pot)

Pliant media blasting requires a modified blast pot, which conveys media to the surface by the use of

compressed air and conventional blast hoses and nozzles. These pressure vessels are different from conventional abrasive pressure vessels in that they include mechanisms that actively control media flow into the air stream.

Media Classifier

Pneumatic or electric classifiers allow for quick, easy, and economical recycling. Pliant media classifiers separate spent media and surface contaminants from reusable media using screens. The top sieve typically ejects particles like nuts and bolts while reusable media fall below for further classification. The second screen is typically designed to eject reusable media. Smaller sized particles, like coating chips or spent abrasive media, are ejected for disposal.

Compressed Air

Clean, dry compressed air is required to use pliant media pressure vessels and pneumatic classifiers. A typical system requires a minimum of 250 CFM (7m^3/min) at 110–120 psi (760–830 kPa) of clean, dry air (refer to ASTM D 4285, *Test Method for Indicating Oil or Water in Compressed Air*). Additional air may be required for classifiers and/or vacuum recovery systems. Requirements vary based on system configuration.

Applications for Pliant Media Blasting

Uses

The pliant media blasting technology is usable in a wide range of industries and is well-suited where hand-tooling, hand-wiping, and abrasive blast cleaning are typically used. For example:

- In environmentally or equipment-sensitive areas where dust, leaching, slurry, or process rebound should be minimized
- On sensitive substrates requiring selective stripping (e.g., removing the topcoat, while leaving the base or primer coat)
- In areas where nearby trades or equipment must continue operating
- On substrates requiring extra clean, high-quality surface preparation or on projects limited to single-pass blasting
- In locations where freight to and from the site and on-site media handling costs need to be minimized
- On projects with limited time for project setup and cleanup
- On projects that require the removal of hazardous material-based coatings
- In many offshore/marine, lead abatement, and historical restoration/renovation industry applications

Advantages

- Pliant media blasting technology allows for improved quality surface preparation, high efficiency, flexibility, and controllability.
- The low dust attribute provides enhanced visibility and real-time observation of the surface being prepared while blasting. Therefore blasters can prepare a uniform surface on the first attempt. A better, more consistently prepared substrate limits the need for rework.
- Dry and low dust attributes mean users can often blast near electrical conduit and junctions without interrupting live circuitry.
- Low rebound and low dust attributes allow blasting in environmental and equipment-sensitive areas with less need for sophisticated containment. These same attributes provide greater operator control, which limits the need for unscheduled rework from overblasting.
- Because pliant media particles are larger than traditional abrasives, support personnel can easily sweep or vacuum pliant media abrasive (and the entrapped contaminants), making it comparatively faster and easy to clean-up.
- The pliant and porous nature of certain pliant media have been shown to effectively remove chlorides to levels at or below 5 µg/cm^2.[2]
- Equipment operators can easily make field adjustments to achieve the desired balance between production rates and dust suppression.

Limitations

Special equipment is required for pliant media blasting. In most applications, media recovery is required for pliant media blasting to be cost-effective.

Two functional variables of pliant media abrasives are the ability to suppress dust and to clean, strip, and/or profile the surface effectively. After media classification, new media must be added to the working mix (media that has already been recycled). This process is known as “media management.” Management of the working mix can optimize dust suppression and production rates, which are determined by specific application requirements.

Pliant Media Blasting Compared to Other Methods of Surface Preparation

• **Compared to Abrasive Blasting.** Dry abrasive blasting is typically a high-dust process, while pliant media blasting is a low-dust process suppressing up to 99.9% of the dust.[2] Dry abrasive blasting is typically a high-rebound process that can cause skin abrasion and eye injures, while pliant media absorb up to 50% of the collision energy on impact with the surface making it a low rebound process.[3]

• **Compared to High-Pressure Waterjetting.** Pliant media are typically easier and less costly to contain, especially when removing hazardous compound-based coatings because it is a dry process—adding no leachates, slurry, or fluid run-off. Pliant media are capable of producing a wide variety of anchor profiles, while high-pressure waterjetting does not produce a profile unless a solid abrasive is added to the water stream. Pliant media can be used near active electrical components, while high-pressure water blasting cannot.

• **Compared to CO_2 (Dry-Ice) Blasting.** Pliant media blasting equipment is less costly than dry- ice blasting units. Pliant media blasting can produce a profile, while dry-ice blasting media cannot. Pliant media blasting can be purchased and easily stored for future use, while dry-ice blasting media, by their physical nature, requires complex, on-site manufacturing equipment. Dry-ice media have a very short on-site shelf life. Most industrial coatings take longer to remove with dry-ice blasting media.

• **Compared to Sodium Bicarbonate (Soda).** It is difficult to remove residual soda blasting material from masonry substrates. Soda blasting may also cause efflorescence on masonry, which is extremely difficult to remove.

Multiple water rinses may be required to adequately remove sodium bicarbonate from masonry. Residual moisture from multiple rinses can migrate further into the substrate, which can cause subsequent damage, especially in temperatures at or below freezing.

Excess amounts of sodium bicarbonate can raise the pH of the prepared substrate and also the waste material stream. When used as a dry process, soda blasting generates significantly more dust than pliant media blasting. Soda blasting media have limited abrasive ability and do not profile steel unless a solid abrasive is added, while pliant media can create a wide range of profiles. Soda blasting media are limited to one use, while pliant media are reusable from seven to ten times, depending on the application.

• **Compared to Chemical Stripping.** Chemical stripping cannot create a profile. The set time and effectiveness of chemical stripping is reliant on ambient environmental characteristics (i.e., temperature and relative humidity). Multiple applications of chemical strippers may be required to completely remove the existing coating, depending upon its type and thickness. Additional cleaning, scraping, and power tooling is often necessary to complete the stripping process, while pliant media blasting is a one-step process.

Environmental/Safety Advantages and Concerns for Pliant Media Blasting

Waste Minimization. Determining the amount of media to be consumed, then comparing the amount of waste disposed as hazardous and non-hazardous can be of value to potential customers. To remove 1 ft^2 (0.1 m^2) of a fully adhered, industrial epoxy coating and achieve an SSPC-SP 10/NACE 2 (near-white blast) requires approximately 10 lb (4.5 kg) of conventional abrasives. Preparing the same representative substrate using pliant media requires approximately 8 lb (3.6 kg), but the effective consumption rate depends on the number of times the media are reused. By reusing pliant media eight times, the effective consumption rate would be 1 lb/ft^2 (4.9kg/m^2) or 10% of the amount of conventional non-recyclable abrasives.

Pliant media particles are many times larger than most conventional abrasives. As a result, users are able to cost effectively classify spent pliant media. By continuously classifying pliant media, it is possible to collect and remove a large portion of contaminants without rendering the entire waste stream as waste. When stripping hazardous contaminants or coatings, users also dispose of smaller amounts of hazardous materials, which could yield even greater savings.

Operator/Workplace Safety. The pliant media blasting process itself is relatively safe for operators, support personnel, and surrounding equipment due to the

Table 1. Pliant Media Profile and Cut Rate.

Pliant Media Abrasive Additive	Maximum Profile [D]		Cut Rate [E]	
	micrometer	mil	m^2/h	ft^2/min
G-40 Steel Grit Abrasive	+100	+4	6-17 [B]	1-3 [B]
#16 Grit Aluminum Oxide	±100	±4	6-17 [B]	1-3 [B]
#30 Grit Aluminum Oxide	±75	±3	6-17 [B]	1-3 [B]
#80 Grit Aluminum Oxide	±50	±2	3-6 [B]	0.5-1 [B]
#120 Grit Aluminum Oxide	±25	±1	3-6 [A]	0.5-1 [A]
#220 Grit Aluminum Oxide	<25	<1	6-17 [A]	1-3 [A]
#320 Grit Aluminum Oxide	<25	<1	6-17 [B]	1-3 [B]
#80 Grit Staurolite	50	2	6-11 [B]	1-2 [B]
#500 Grit Aluminum Oxide	<2.5	<1	n/a [C]	n/a [C]
30-40 Mesh, Type II Plastic Urea	<2.5	<1	6-11 [A]	1-2 [A]
60/80 Mesh, Glass Bead	<2.5	<1	6-11 [A]	1-2 [A]
No Abrasive Additive	<2.5	<1	11-56 [D]	2-10 [D]

Courtesy of Sponge-Jet, Inc.
A Thin coating; <5 mil (125 micron) hard epoxy.
B Fully cured, 15 mil (375 micron) industrial coating
C Not for coating removal
D On mild steel substrate
E Cut rates are based on typical results, using a #8 (1/2 inch or 12.7 mm) nozzle at 80 psi. Each application is different and tests should be performed for estimating purposes.

lower strike and rebound speeds of the abrasive. Pliant media velocity and subsequent rebound are significantly lower compared to conventional abrasive blasting.[3] Lower media rebound means less impact on the blaster and fewer injuries. Less media rebound also means less damage to nearby equipment and lower chances of equipment failure from fugitive dust generated by the blasting process (e.g., rotating equipment, bearings, valves, and air-intake systems).

Dust Suppression. Pliant media blasting produces less airborne and potentially respirable dust in three ways. First, it flattens on impact, acting like a blanket, which inhibits the ricochet of airborne paint and contaminants. Second, it traps a portion of any paint and contaminants in its porous structure. Third, it firmly presents the abrasive particle thereby reducing media break-up, which typically generates as much, if not more airborne dust than the removed coating and contaminants.

One study of airborne dust and contaminant measured airborne lead concentrations generated by pliant media blasting and conventional silica sand blasting. The results indicated that levels of airborne contaminants were significantly lowered when blasting with plaint media. Airborne lead levels were reduced from 69,800 µg/m^3 to 4,990 µg/m^3 at the blaster, or by 93%.[4] Another airborne contaminant study compared outdoor silica sand blasting to pliant media. Passive air sampling devices measured airborne dust concentrations and revealed that sand blasting generated 5,500 times more dust than blasting with pliant media.[5]

Weather Restrictions

As with conventional abrasive blast cleaning, humidity control and shelter from inclement weather are necessary. Pliant media blasting equipment is designed for operation at temperatures above freezing. When blasting in conditions of high air temperature or humidity, the air supply to the pressure vessel must be equipped with auxiliary moisture separation and temperature reduction devices.

Cleaning Rate and Cost Information for Pliant Media Blasting

Cleaning and Cutting

Cleaning production rates using pliant media typically range from 2 to 10 ft^2/min (11 to 60 m^2/h). Stripping and/or profiling production rates using pliant media typically range from 0.5 to 3 ft^2/min (3 to 17 m^2/h). Pliant media can typically be reused from 5 to

15 times depending on the surface, coating, and substrate characteristics of each particular project.

Cost Information

The pliant media blasting technology has beneficial cost implications in a variety of areas (e.g., potential savings in freight, air filter cleaning and replacement, on-site handling, set-up and cleanup, and disposal.) Depending upon recycle rates, total project costs are generally within 20% of the costs of conventional abrasive blast cleaning.

Surface Conditions Achievable with Pliant Media Blasting

Visible Levels of Cleanliness Achievable

The pliant media technology can achieve all SSPC, NACE, and ISO standard levels of visible cleanliness. Users can achieve from SSPC-SP 7/NACE 4, *Brush-Off Blast Cleaning,* to SSPC-SP 5/NACE 1, *White Metal Blast Cleaning.*

Non-visible (Soluble Salt) Contamination

Reports support that some types of pliant media abrasives can remove chlorides from contaminated surfaces to levels at or below 5 µg/cm^2—without water washing.[2]

Applicable Standards

The applicable standards for pliant media blasting are: SSPC-AB 1, *Mineral and Slag Abrasives*; SSPC-VIS 1, *Visual Standard for Abrasive Blast Cleaned Steel*; SSPC-SP 5/NACE 1, *White Metal Blast Cleaning*; SSPC-SP 6/NACE 3, *Commercial Blast Cleaning*; SSPC-SP 13/NACE 6, *Surface Preparation of Concrete*; and SSPC-SP 14/NACE 8, *Industrial Blast Cleaning*.

Compatibility with Paint

Pliant media are compatible with most types of paint because it can achieve from 0 to 4+ mil (100+ µm) profile and any degree of cleanliness up to SSPC-SP 5/NACE 1 (white metal).

Expected Advances in Pliant Media Technology

As state, federal, and national environmental and workplace safety agencies continue to require reporting and improved health and safety practices, pliant media blasting is becoming a preferred technology. The process benefits make pliant media blasting a viable alternative to other technologies because of its pervasive, positive effect on the environment, worker safety, and total job costs.

References

1. Certification of Incinerability granted by GTS Duratek (Oak Ridge, TN) for Sponge-Jet Brown Sponge Media,™ Silver Sponge Media,™ White Sponge Media,™ Green Sponge Media,™ and Blue Sponge Media™ abrasives.
2. Merritt, M.T. Case Histories in Chloride Removal Using Pliant Media Abrasives. In *Proceedings of SSPC '01.*
3. Theoretical Calculations Derived from P. Hewitt. In *Conceptual Physics;* Little Brown & Company: Canada, 1981, pp 109-110.
4. Miles, D. and Anni, T. Offshore Oil Platform Surface Preparation Using the Pliant Media Blasting Technology. In *Proceedings of SSPC '98.*
5. Coffin, D. Todd. *Lead-based Paint Removal with Sponge-Jet System;* Jacques Whitford, Inc.: Buckfield, ME.

About the Author

Tony Anni

Tony Anni specializes in marketing and promotions in the specialty abrasives segment of the industrial coatings industry. Tony is the marketing manager for Sponge-Jet, Inc. and a member of SSPC. He has a BFA in communications design and an MBA with a concentration in marketing and product/service development.

Chapter 2.9.5
Carbon Dioxide (Dry-Ice) Blasting

Robert W. Foster

Basic Principles of Operation

Dry-ice particle blasting is similar to sand blasting, plastic bead blasting, or soda blasting where a media is accelerated in a pressurized air stream (or other inert gas) to impact the surface to be cleaned or prepared. With dry-ice blasting, the media that impacts the surface is solid carbon dioxide (CO_2) particles. One unique aspect of using dry-ice particles as a blast media is that the particles sublimate (vaporize) upon impact with the surface. The combined impact energy dissipation and extremely rapid heat transfer between the pellet and the surface cause instantaneous sublimation of the solid CO_2 into a gas. The gas expands to nearly eight hundred times the volume of the particle in a few milliseconds in what is effectively a "micro-explosion" at the point of impact that aids the coating removal process. Because of the CO_2 vaporizing, the dry-ice blasting process does not generate any secondary waste. All that remains to be collected is the removed coating.

As with other blast media, the kinetic energy associated with dry-ice blasting is a function of the particle mass density and impact velocity. Since CO_2 particles have a relatively low density, the process relies on high particle velocities to achieve the needed impact energy. The high particle velocities are the result of supersonic propellant or air-stream velocities. Unlike other blast media, the CO_2 particles have a very low temperature of –109°F (–78.5°C). This inherent low temperature gives the dry-ice blasting process unique thermodynamically induced surface mechanisms that affect the coating or contaminate in greater or lesser degrees, depending on coating type. Because of the temperature differential between the dry-ice particles and the surface being treated, a phenomenon known as fracking, or thermal shock, can occur. As a material's temperature decreases, it becomes embrittled, enabling the particle impact to break-up the coating and sever the chemical bond that is weakened by the lower temperature. The thermal gradient or differential between two dissimilar materials with different thermal expansion coefficients can serve to break the bond between the two materials. This thermal shock is most evident when blasting a nonmetallic coating or contaminate bonded to a metallic substrate.

Historical Development

In the early 1930s, the manufacture of solid phase carbon dioxide (CO_2) became possible. During this time, the creation of "dry ice" was nothing more than a laboratory experiment. As the procedure for making dry ice became readily available, applications for this innovative substance grew. Obviously, the first use was in refrigeration. Today, dry ice is widely used in the food industry for packaging and protecting perishable foods.

In 1945, the U.S. Navy experimented with dry ice as a blast media for various degreasing applications. In May 1963, Reginald Lindall received a patent for a "method of removing meat from bone" using "jetted" carbon dioxide particles.

In November 1972, Edwin Rice received a patent for a "method for the removal of unwanted portions of an article by spraying with high velocity dry ice particles." Similarly, in August 1977, Calvin Fong received a patent on "sandblasting with pellets of material capable of sublimation."

The work and success of these early pioneers led to the formation of several companies in the early 1980s that pursued the development of dry-ice blasting technology.

Dry-ice pelletizers and blast machines entered the industrial markets in the late 1980s. At that time, the blast machines were integrated with dry-ice production machines and therefore physically large and expensive, and they required high air pressure (greater than 200 psi [1.4 MPa]) for operation.

As the CO_2 blast technology advanced, the blast machines were separated from the production of dry ice and the size and cost dropped. Improved nozzle technology and production of high-density dry ice pellets has made blasting effective at shop air pressures (80 psi [550kPa]).



Figure 1. Dry ice blasting machine. Courtesy Cold Jet Inc.

Equipment/Materials

There are two general classes of blast machines as characterized by the method of transporting pellets to the nozzle: two-hose (suction design) and single-hose (pressure design) systems. In either system, proper selection of blast hose is important because of the low temperatures involved and the need to preserve particle integrity as the particles travel through the hose.

In the two-hose system, dry-ice particles are delivered and metered by various mechanical means to the inlet end of a hose and are drawn through the hose to the nozzle by means of vacuum produced by an ejector-type nozzle. Inside the nozzle, a stream of compressed air (supplied by the second hose) is sent through a primary nozzle and expands as a high-velocity jet confined inside a mixing tube. When flow areas are properly sized, this type of nozzle produces vacuum on the cavity around the primary jet and can therefore draw particles up through the ice hose and into the mixing tube where they are accelerated as the jet mixes with the entrained air/particle mixture. The exhaust Mach number from this type of nozzle is, in general, slightly supersonic. Advantages of this type of system are relative simplicity and lower material cost, along with an overall compact feeder system. One primary disadvantage is that the associated nozzle technology is generally not adaptable to a wide range of conditions (i.e., tight turns in a cavity, thin-wide blast swaths, etc.). Also, the aggression level and strip rate of the two-hose system is less than comparable single-hose blast machines.

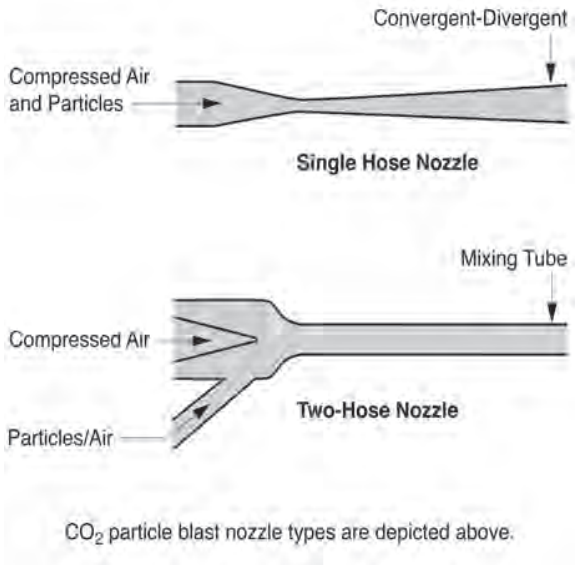


Figure 2. Single- and two-hose systems. Courtesy Cold Jet Inc.

In a single-hose system, particles are fed into the compressed air line by one of several types of airlock mechanisms. Reciprocating and rotary airlocks are both currently used in the industry. The stream of pellets and compressed air is then fed directly into a single hose followed by a nozzle where both air and pellets accelerate to high velocities. The exhaust Mach number from this type of nozzle is generally in the 1.0–3.0 range, depending on design and blast pressure. Advantages of this type of system are wide nozzle adaptability and the highest available blast aggression levels. Disadvantages include relatively higher material cost due to the complex airlock mechanism.

Blast machines are also differentiated into dry-ice block shaver blasters and dry-ice pellet blasters. The block shaver machines take standard 60 lb (27 kg) dry-ice blocks and use rotating blades to shave a thin layer of ice off. This thin sheet of dry ice shatters under its own weight into sugar grain-sized particles that fall into a funnel for collection. A two-hose delivery

system is used to transfer the particles at the bottom of the funnel to the surface to be cleaned. The low mass of these particles combined with the inefficient two-hose system limits the block shavers to light-duty cleaning. Because the shaved ice machines deliver a particle blast with high flux density (number of particles striking a square area of surface per second), they are effective on thin, moderately hard coatings such as an air-dried, oil-based paint. The disadvantage of the ice shaver is the particle size and flux density is fixed as well as the particle velocity.

In contrast, pellet blast machines have a hopper that is filled with pre-manufactured CO_2 pellets. The hopper uses mechanical agitation to move the pellets to the bottom of the hopper and into the feeder system. The pellets are extruded through a die plate under great pressure. This creates an extremely dense pellet for maximum impact energy. The pellets are available in several sizes ranging from 0.040 inch (1 mm) to 0.120 inch (3 mm) in diameter. The 0.120 inch (3 mm) in diameter pellets are commercially available and are shipped as freight or delivered by the vendor's trucks. With a single-hose delivery system, the blast hose diameter and interior wall roughness and nozzle used govern the final pellet size and blast flux density exiting the nozzle. Because of its design, the single-hose pellet blast units are capable of "dialing-in" the correct blast type needed for a wide range of individual coatings or contaminates.

The equipment and materials needed for operation, aside from the blasting machine and accessories, are the supplies of dry ice, compressed air, and often single-phase 115 VAC electricity.

The dry-ice supply may be either pre-manufactured pellets or block, or pellets manufactured at the point of use. The pre-manufactured dry-ice pellets or block are stored and shipped in special insulated containers. These containers are typically large, double-wall construction molded polyethylene boxes with urethane foam insulation between the inner and outer walls. They are fitted with special gaskets and vapor barriers to maintain a very tight seal on the tote box lid after the pellets have been produced. The boxes typically contain from 400 to 1200 lb (180 to 540 kg) of product and are equipped with fork-lift channels. While quality, as measured by particle density and water content, may vary, dry ice is essentially a commodity and variations in price by geography are fairly significant.

The compressed air requirements will vary somewhat depending on the application and the particular blast machine and nozzle. For most applications with moderate difficulty or located within a manufacturing plant, requirements are approximately 80 to 100 psi (550 to 690 kPa) at 200 CFM (5.7 m^3/min). Removal of paint and other well-bonded coatings will usually require higher pressures and flow rates that fall between those and 300 psi (21 MPa) at 350 CFM (9.9 m^3/min).

Major Markets for Dry-Ice Blasting

Molded Products

Dry-ice blasting cleans unwanted release agents ("parting agent") and/or residual material build up from the product contact surfaces. That is, the build-up of release agents or residual product from the hot mold is easily removed. Dry-ice blasting allows the tools or molds to be cleaned while the mold is hot and still in the press. This reduces the "press down time due to cleaning" by 80 to 95%. Since the process is non-abrasive, the CO_2 blast cleaning will not wear the tools or open critical tool tolerances. Furthermore, "micro vents" are typically cleaned by dry-ice blasting. This eliminates hand drilling of plugged vents needed for optimum gas escape. Types of molds cleaned by CO_2 blasting include:

- Rubber molds, mixers, and other process equipment
- Tire molds
- Automotive interior and other urethane molds
- Molds for bottles and other blow molded products
- Core boxes and permanent foundry molds.

Food Industry

Residual sugars left behind from baking can be readily removed from their fixtures in most cases. Here, as in molding, heat may enhance removal speed and characteristics. In many cases, the application may be performed on-line.

A key benefit in using dry-ice blasting to replace some of the general cleaning done with water, detergents, and sanitizers is a moisture reduction, thereby, inhibiting the growth of bacteria—particularly salmonella. Economics have directed on-line cleaning of fixtures including waffle irons and other similar batter or dough baking and product-forming fixtures, oven bands, and conveyor belts.

CO_2 blasting has been proven to remove

and/or destroy significant biofilm build-ups of listeria and salmonella. Typical applications are performed without shutting down or disassembly and include:
• Wafer plates—carbon build-up removal
• Cookie oven bands, baking ovens, shelves, and trays
• Flight and conveyor cleaning
• Ingredient build-up from tanks and vessels.

Miscellaneous Tooling

There are many names and types of production fixtures, but virtually any item that is part of the production process and is difficult to clean on-line or during production hours by traditional means may be an excellent dry ice application, such as:
• Conveyor components and other materials handling equipment
• Weld slag removal from robotics, fixtures, carriers
• Removal of oils and grease from chains, machinery, etc.
• Cleaning packaging equipment
• Removal of adhesives

Printing Industry

In the printing industry, inks and varnish polymers are designed to adhere to most surfaces, resist scratches, and, in some instances, be solvent resistant. These characteristics, which make their use attractive, also make the removal of dried ink very difficult. Ink buildup on the gears and deck guides causes poor alignment and results in low print quality. To compensate for these phenomena, plate mounting generally needs adjusting several times to register critical graphics in order to produce an acceptable quality level. Generally, each "press run" to check the register of the colors results in thousands of feet of wasted material. This inherently wasteful process may be eliminated by the on-line precision cleaning ability of dry-ice blasting.

Applications for Dry-Ice Blasting

In simple terms, dry-ice blasting is not a paint stripper. While isolated success cases exist in paint stripping using blast pressures from 150 to 300 psi (1 to 2 MPa), most results indicate partial to complete failure to remove topcoats at profitable rates, and failure is even more likely when the goal is to completely remove a primer. Successful applications in painting-related projects are the rule rather than the exception when:
• Dry-ice blasting is employed to prepare a surface for painting without the need to completely remove a coating
• The work surfaces are near sensitive machinery or other circumstances where airborne grit or water would be detrimental
• Over-spray accumulates in thick layered deposits such as paint booths. (Thick coatings respond to the thermal effects better than thin coatings.)

Hazardous Coatings and Materials

Due to media vaporization, removed materials such as lead paint, asbestos, or coatings that are radioactive or contaminated with PCBs need no further separation before processing for disposal, nor is the volume increased as a result of being mixed with water, grit, chemicals, or other cleaning agents.

Greasy Factory Ceilings

Dry-ice blasting is effective on greases and oils and is now being used to prepare greasy factory ceilings for repainting. The effluent from the operation is negligible so that the need to cover sensitive machinery is minimal. After blasting with dry ice, the surface is ready for coating and no rinsing or other operation is needed.

Flaking Factory Ceilings

While dry-ice blasting is not effective at stripping well-bonded coatings, it is very effective at removing a coating that is flaking or not well bonded.

On areas of the ceiling that have good paint adhesion, preparation involves just cleaning those areas so they are ready for coating. The machinery on the shop floor can be loosely covered.

Repainting Machines, Machine Tools, and Equipment

Complete machines can be cleaned without removing the factory paint and made ready for repainting with little or no other preparation such as masking or rinsing.

Dry-ice blasting is much faster and more thorough than manual preparation, has no airborne grit to ruin bearings and other moving parts, and does not "short-out" motors and electrical controls like water blasting does.

New Construction Structural Steel Paint Preparation

Red iron joists that become muddy during storage are cleaned just prior to installation. By avoiding the alternative of using pressure washing, not only is there less mess, but also the surface is free of flash rust and ready for installation and topcoat if desired.

Concrete Floor Preparation for Paint (Oil Removal)

Whether using sand blast, shot blast, or acid to roughen the surface for painting, those areas that have oil embedded in the concrete will not bond to the coating to be applied.

Dry-ice blasting is being used on the oil and grease stained areas with great success compared to chemical or citrus-based degreasers. The oil that often has leached deep into the concrete is drawn out and blasted away so that the area can be coated with uniform appearance and bonding.

Wrought Iron at Historical Sites

Wrought iron (circa 1930) is being restored using dry-ice blasting as the paint preparation in a botanical garden setting. Not only is grit blasting detrimental at this location due to the plant life and some of the historic structures, but also the iron itself is thin in many areas due to years of corrosion. Dry-ice blasting has just enough abrasive to remove the flaking rust and loose paint without eroding too much of the deteriorating iron as stronger abrasives can. It is also much faster and more thorough than manual methods and better at getting into hard to reach portions of the iron.

FLASHJET®

This patented coatings removal process uses pulsed-Xenon light combined with a dry-ice blast stream to strip all types of coatings from both composite and metallic substrates without damage. Both the Department of Defense and the Federal Aviation Association have approved the system for aircraft.

Advantages of CO_2 Blasting

Cost Reduction. The natural sublimation of dry-ice particles eliminates the cost of collecting the cleaning media for disposal. In addition, containment and collection costs associated with water/grit blasting procedures are also eliminated.

Improved Productivity. Because CO_2 blast systems provide on-line maintenance capabilities for production equipment, timely and expensive detooling procedures are kept to a minimum. Dedicated cleaning cycles are no longer required as preventative maintenance schedules can be adopted that allow for equipment cleaning during production periods. As a result, throughput is increased without adding labor or production equipment.

Extension of Equipment's Useful Life. Unlike sand, walnut shells, plastic beads, and other abrasive grit media, dry-ice particles are non-abrasive. Cleaning with dry ice will not wear tooling, texture surfaces, open tolerances, or damage bearings or machinery. Blast nozzles and hoses do not wear and need to be replaced. In addition, on-line cleaning eliminates the danger of molds being damaged during handling.

A Dry Process. Unlike steam or water blasting, CO_2 blast systems will not damage electrical wiring, controls, or switches. Also, any possible rust formation after cleaning is far less when compared to steam or water blasting. When used in the food industry, dry-ice blasting reduces the potential for bacteria growth inherent to conventional water blasting.

Limitations Compared to Abrasive Blast. Because of the lack of hardness inherent in the media, coatings removal rates are significantly less than that for dry or wet abrasive blasting and due to the lack of particle hardness, no surface profile or anchor patterns result from dry-ice blasting metal surfaces.

Environmental/Safety Advantages and Concerns for CO_2 Blasting

Environmental Safety: Carbon dioxide is a non-toxic element that meets EPA, FDA, and USDA industry guidelines. By replacing toxic chemical processes with CO_2 blast systems, employee exposure and corporate liability stemming from the use of dangerous chemical cleaning agents can be materially reduced or eliminated completely. The vaporization of the media is an environmental advantage since most surface preparation methods exhibit a dust or fume attributable to the media used.

Since CO_2 gas is heavier than air (CO_2 gas displaces oxygen) care must be taken if blasting in enclosed areas or down in a pit. As dry ice is very cold, insultated gloves should be worn as a precaution. Other personal protective equipment includes face shields, hearing protection, and long-sleeve clothing. Noise levels are high, but within OSHA guidelines when the operators use properly fitted hearing protection.

The effects of accidental personal contact with the blast stream are certainly not pleasant but are not life threatening, being limited to skin surface lesions or welts rather than breaking skin. As with most blasting, electrostatic discharge can occur when the target is not well grounded. In theory, the concentration of carbon dioxide minimizes the danger of explosion. The carbon dioxide used is food grade and is obtained as a byproduct of other industrial processes and therefore does not contribute to "the greenhouse effect."

Waste Containment and Disposal. Waste containment and disposal is limited to the substance being removed, since dry ice completely vaporizes. Containment or covering of adjacent items may be necessary if the material being removed is either wet or viscous, or becomes small airborne particles when blasted. Studies have shown that the average particle size of removed coatings is larger than that of abrasive blasting particles so that dust containment is much less challenging when blasting particle vaporization is considered.[1]

Weather Restrictions

Dry-ice blasting may be employed in most weather circumstances. Rain poses the challenge of keeping the media dry before it is in the machines hopper. Extreme heat and high humidity are challenging since the media is a desiccant and absorbs moisture that causes clumping and can interrupt the blast flow.

Cleaning Rate and Cost Information

Acquisition, rental costs, and cleaning service vary by manufacturer or contractor.

Operating Costs

The major operating cost is the dry-ice media. Most users purchase dry ice as needed and either have it delivered or use their truck and driver. While supply and demand does cause considerable geographical pricing variations, 25 cents per pound ($0.55/kg) with a usage of 3 pounds per minute (6.6 kg/min) are good budgetary averages. Therefore, hard operating costs are $45 per hour of continuous blasting.

Maintenance and depreciation are less than for most equipment in this category because the non-abrasive media does not cause wear on the flow-path components.

Paint Removal

If a coating is removed at the rate of 0.25–0.33 ft^2/min (0.023–0.031 m^2/min), this is the best that can be expected on a relatively new, properly applied finish. When the removal rate is low it will decrease over time as the substrate becomes extremely cold and the thermal effects diminish. Sometimes it may take one minute just to break through the coating film with the nozzle remaining stationary over a single point. Primers often respond this way.

On a coating that is weathered or was applied improperly, results can be significantly better, up to 1 ft^2/min (0.09 m^3/min) or more. In some cases, it may be advantageous to use chemical agents to pre-treat (soak) the surface, with some of the agents citrus-based.

Surface Preparation

When the objective is to remove dirt, grease, oil, and loose paint so the surface can be repainted, rates will most often be in the range of 3–6 ft^2/min (0.28–0.56 m^2/min). After treatment, the surface is ready to paint and no final rinse or any other preparation is needed.

Nonvisible Contamination

When dry-ice blasting is applied to a surface, no residue from the blasting agent remains and therefore, notwithstanding any oil or other contamination from the compressed air that could remain, the surface is free from any visible or non-visible contamination.

Compatibility with Paint Types

Dry-ice blasting is compatible with all types of paint in that there is no danger of a secondary compound being formed. It may not be able to remove all types of paint with significant removal rates, but it can

create a clean, rinse free, and water-break free surface ready to be coated.

Expected Advances in Dry-Ice Blast Technology

Systems are expected to become more efficient in terms of media and air consumption as well as smaller, lighter, and less expensive to purchase and to operate. Similarly, operator comfort and convenience should improve as well with progress on noise reduction and ergonomics heading the list. The expected trend is for the supply of dry-ice media to increase while cost-effectiveness improves.

References

1. Dabolt, Richard J. *Evaluation of Pelletized Carbon Dioxide as a Fluidized Abrasive Agent for removal of Radioactive Contamination;* Chem. Nuclear Systems, Inc and Martin Marietta Energy Systems: Decatur Georgia, 1989.

Bibliography

Fong, Calvin C. United States Patent Office, Patent 4,038,786, August 2, 1977
Moore, David E. United States Patent Office, Patent 4,744,181, May 17, 1988
Cold Jet Inc., 455 Wards Corner Rd., Loveland, OH 45140.

About the Author

Robert W. Foster
Robert W. Foster is a marketing representative with Cold Jet, Inc. and has worked with dry-ice blasting applications and markets since 1987. He has been employed in coatings or surface preparation industries since 1982 and has a BS degree in business administration.

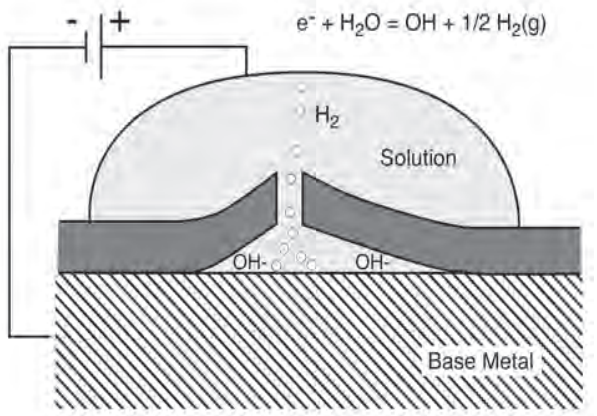
Chapter 2.9.6
Electrochemical Stripping

Dr. Rudolf Keller and Brian J. Barca

Basic Principles Of Operation

Electrochemical stripping, or electrochemically assisted paint removal, is a non-abrasive, clean and quiet method for removing paint coatings, employing electricity and benign chemicals. In this method, the metal substrate becomes the negative electrode (cathode) of an electrode pair, the other electrode being incorporated in a pad covering the painted surface.

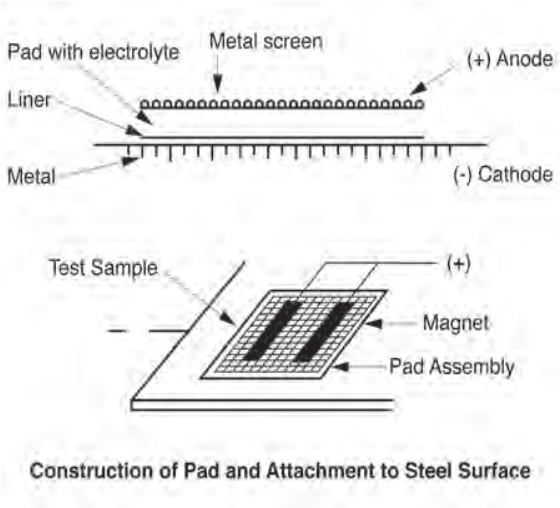
Electrochemical stripping can be considered a fast, forced version of cathodic debonding, a known, slow corrosion phenomenon. As **Figure 1a** illustrates, hydrogen is evolved in an electrochemical reaction at the metal surface and leaves an alkaline or caustic condition at the surface. This results in paint debonding at the metal-coating interface.



Principles of Electrochemical Stripping

Figure 1a.

In the technical application, a surface to be depainted is covered by pads, as shown schematically in **Figure 1b.** A metal screen is attached to a liquid-absorbent material that holds the electrolyte, typically an aqueous sodium sulfate solution. A second outer layer holding liquid prevents the pad from drying out too easily. In operation, the pad is sprayed about every fifteen minutes with electrolyte or water. While pad size and shape are flexible, a convenient size measures 1 ft^2 (0.09 m^2). Such pads are magnetically attached to the steel surface, using plastic backings with mounted magnets. **Figure 2** shows a 1 ft^2 (0.09 m^2) test run to establish the feasibility of the method for a certain coating.



Construction of Pad and Attachment to Steel Surface

Figure 1b.

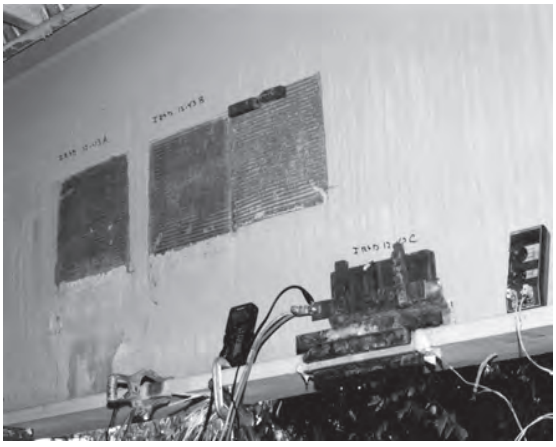


Figure 2. Testing the feasibility of electrostripping.

For depainting a structure, arrays of pads are operated simultaneously, as shown in **Figure 3,** and the total area covered is mainly limited by the capacity

of the rectifier. A cathodic connection is made to the structure; normally one stationary connection at any location of the steel structure is sufficient. The anodic current is led through bus bars or cables to the application area and connected with leads to the metal screens on the pads. To initiate the current, a coherently painted surface has to be scored. This is not necessary with deteriorated and rusty surfaces. Scratches or holidays about 1 cm apart, penetrating to the metal surface, are sufficient. A shrouded hand tool is equipped with rows of star-wheel cutters to give an adequate scoring pattern in one pass. The pads are energized for 1 to 1.5 hours. The cleaned surface is ready for repainting with a suitable paint system. Since there usually is no flash rusting, painting does not have to occur immediately.

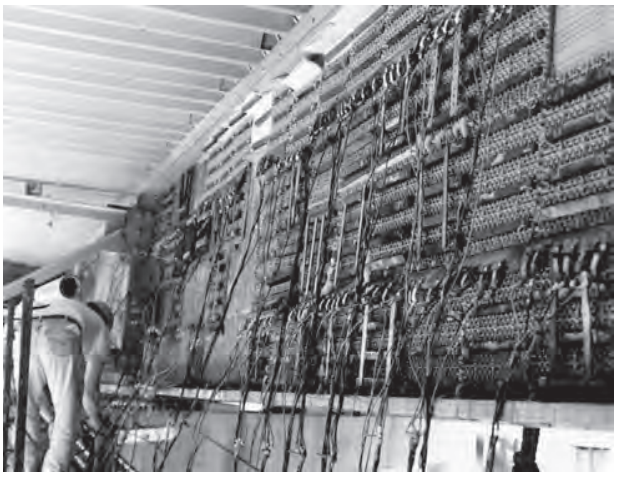


Figure 4. Virginia DOT test of electrostripping.

Historic Development

This process was invented and developed by EMEC Consultants, with a U. S. patent granted in 1996.[1] Initial support was provided by the Transportation Research Board. A demonstration of the technology in Arlington, Virginia, in May 1998 **(Figure 4)** was sponsored by the Virginia Department of Transportation with financial support of the Federal Highway Administration.

Since that time, EMEC Consultants developed the process further, testing it on a rusty railroad bridge **(Figure 5),** on the I-beams of a residential structure, and on various field samples. The approach worked with all lead-based coatings tested, yielding repaintable surfaces. The technology was introduced at the 1996 SSPC Conference and other professional meetings. An update was presented at the 1999 SSPC Conference.



Figure 5. Testing electrostripping on a railroad bridge.

Equipment/Materials

The method uses pads consisting of a liquid-absorbent material holding the electrolyte and a metal anode, e.g., a steel screen functioning as the positive electrode.[2] The pads are held to the surface by physical means or, more conveniently, by magnets that are mounted in a stiff plastic backing. Direct current is supplied at low voltage by a rectifier which can be powered by a generator or by line voltage. The time required to achieve complete debonding depends on the paint and typically ranges between 45 minutes and 1.5 hours. Auxiliary equipment includes scoring tools to prepare the surface if necessary to initiate current flow. A needle gun in conjunction with a HEPA vacuum may be used to remove minor paint remnants if debonding is not complete. A power-wash unit may be used to wash the surface at the end of the treatment.

Applications for Electrochemical Stripping

Advantages of Electrochemical Stripping

The method has been developed primarily for the safe removal of lead-based coatings. As no particulates enter the air, no containment is necessary and measures to protect personnel can be kept minimal. As a consequence, mobilization efforts and costs are low, an aspect becoming particularly significant for smaller jobs. The relatively low equipment costs makes the method affordable for maintenance and repair jobs. Absence of flash rusting can facilitate scheduling of the repainting process.

Limitations of Electrochemical Stripping

Before committing to do a job with the electrochemical stripping method, a test should be conducted to assure feasibility for the targeted system. While typical lead-based paint systems can be readily stripped, attempts to remove modern marine and epoxy-type coatings have not been successful. Size and shape of pads can vary widely. Pads can be bent into corners and wrapped around pipes. While rivets may be handled with special designs, other protrusions may require treatment with hand tools or a chemical stripper.

The method can be used on steel and other metals. Some metals, including aluminum, are attacked by the alkalinity created. In this case, the process can only be used if some corrosion can be tolerated (e.g., for street signs), or if it can be suppressed by adding inhibitors. Efforts are in progress to adapt the method for use on nonconductive substrates such as concrete, brick walls, and wood.

Electrochemical Stripping Compared to Other Methods

For large-scale applications, abrasive blast cleaning is the paint removal method used predominantly. In the case of lead-based paint, toxic particulate material enters the air and extensive, expensive precautions have to be taken to prevent environmental contamination and occupational health damages. Such precautions have not always been fail-safe and alternative methods may be considered, particularly in sensitive areas. Removing lead components with electrochemical stripping has been shown to be more complete, but it does not create a surface profile or necessarily remove all mill scale. Good repaintability, however, has been demonstrated.

Waterjetting alleviates some of the problems associated with blasting with a solid media. Yet containment and collection of waste remains a serious issue. The cleaned surface is similar to the one produced by the electrochemical approach, except that it has a very strong tendency to flash rust. Flash rusting has been delayed for long periods with the electrochemical stripping approach.

Because of its debonding mechanism, the electrochemical method is related to chemical caustic stripping, but the alkalinity is very localized. Electrochemical stripping works directly on the substrate surface, whereas chemical strippers have to work from the outside through the entire coating. Chemical stripping, furthermore, requires more time and is weather-dependent. Hazardous, corrosive chemicals have to be dealt with, whereas a benign aqueous solution is used in electrochemical stripping.

Environmental/Safety Advantages and Concerns

Electrochemical paint removal has decisive advantages, as no particulate material is emitted. There are no electrical shock hazards because voltages are low. Work is not ergonomically challenging, particularly when operators alternate between various manipulations of the process.

Waste volumes generated are considerably reduced compared with that produced in traditional abrasive blast cleaning.[4] A beneficial feature is the possibility of recycling process waste. If no chromium or aluminum is present in the coating, spent pads with paint residue can be used in a secondary lead smelter, without further pad preparation. The lead is recovered and used in batteries.

Weather Restrictions

If desirable, this method of paint removal can be practiced in any weather, except if the temperature is below the freezing mark of the electrolyte. Extensive early tests were conducted in winter. Absence of flash rusting may present other weather-related advantages, as surfaces may not have to be painted immediately.

Cleaning Rate and Cost Information

Full-Size Equipment

A crew of 3 to 4 workers operates full-size equipment, placing 120 to 140 ft^2 (0.09 m^2) pads per run. The team of workers rotates between tasks of scoring, placing pads, switching leads, removing spent pads, cleaning debonded surfaces, and needle gunning any remaining paint fragments. There is always a bank of pads running. Painting can be done in batches after sufficient area has been stripped, as flash rusting does not occur.

The equipment needed for this full-size mode is an 8,000-Amp rectifier with power supplied by a three-phase power source, scoring tools, pads, backings, magnets, sprayer, power-wash unit, tarp to catch any accidentally dropped pads, and other miscellaneous tools, plus scaffolding as required. The cost of a complete set-up is in the range of $ 55,000 to

$ 70,000. The estimate cost of paint removal, not including repainting and waste disposal, is $ 7-10 per square foot ($75-110/$m^2$).

Maintenance and Repair Unit

To accommodate jobs of limited size involving paint removal, a maintenance and repair unit has been designed. Use of this unit circumvents containment efforts and associated expenses. All components are portable. A special, light-weight 500-Amp air-cooled rectifier weighs 95 lb (43 kg). Other components include scoring tools, electrolyte container, HEPA vacuum, and a power-wash unit for the final wash. It sells for $40,000.

In the following estimate of operational cost, it is assumed that two people operate the process in an 8-hour shift and set-up and commissioning occurs daily. Five batches cover 10 ft^2 (0.9 m^2). With labor, including overhead budgeted at $550, and cost of supplies and miscellaneous expenses at $3-4 per ft^2 ($30-40/m^2), a total cost of $14 to 15 per ft^2 ($150-160/m^2) results. This estimate does not include depreciation or equipment rental, waste disposal cost, nor repainting.

Surface Conditions Achievable with Electrochemical Stripping

Visible Levels of Cleanliness Achievable

Under normal circumstances 95 to 100% of paint is removed. Most paint remnants stick to the pad upon removal, the rest can be wiped and washed off. A clean bare metal surface results.

Nonvisible (Soluble Salt) Contamination

Since the electrolyte contains sodium sulfate, a sulfate contamination results. In repaintability studies, it was shown in laboratory tests that cleaning with wet paper towels can produce an acceptable surface. In the Arlington demonstration, the untouched paint before treatment showed the same sulfate concentration of 8 µg/cm^2 as determined after electrochemically stripping and pressure washing the surface.[4] The chloride content was 0-2 µg/cm^2, i.e., below detection limits. It is expected that the cathodic treatment actually results in a chloride-cleansing action, as the current will draw anions away from the cathodic surface.

Applicable Standards

This method is novel and no standards have been developed. Surface appearance is similar to pressure washing. No profile is created. Mill scale is removed to a varying extent, depending on the characteristics of the scale. Rust is chemically changed and washes off. Flash rusting is often absent.

Compatibility with Generic Types of Paint

Electrochemical stripping is effective if alkalinity in combination with elevated temperature causes debonding. This has been the case for all traditional lead-based coatings tested so far. Epoxy-type coatings respond to varying degrees. The method has been ineffective in tests with modern marine-type coatings.

Expected Advances in Electrochemical Stripping

Electrochemical stripping is being introduced commercially. It is expected to become an effective paint removal method, particularly for the maintenance and repair of steel structures where the emission of lead-containing particulates presents problems. Developmental efforts will lead to customized applications, such as the depainting of pipes or submerged surfaces. Adaptation to nonconductive surfaces such as concrete is also being explored.

References

1. Keller, R.; Burleigh, T. D.; Hydock, D. M. U.S. Patent No. 5,507,926 (1996-04-16). *Electrolytically Assisted Paint Removal from a Metal Substrate.*
2. Keller, R.; Barca, B. J.; Hydock, D. M. U.S. Patent No. 6,030,519 (2000-02-29). *Electrode Pad for Debonding Paint from a Metal Substrate.*
3. Keller, R. IDEA Project Final Report (Contract NCHRP-94-ID023). *Paint Removal from Steel Structures;* May 1996.
4. Bushman, W. H.; Jackson, D. R. FHWA/VTRC 00-R19. *Field Test of a New Procedure for Removing Lead-Based Paint from Bridges;* Virginia Transportation Research Council, June 2000.
5. Keller, R.; Hydock, D. M.; Burleigh, T. D. Electrochemically Assisted Paint Removal: An Emerging Technology to Remove Lead-Based Paint From Metals. In *Proceedings of SSPC '96,* pp 243-247.
6. Keller, R.; Barca, B. J. Electrochemically Assisted Paint Removal—And More. In *Proceedings of SSPC '99,* pp 344-348.

About the Authors

Dr. Rudolf Keller
Educated in Switzerland, Dr. Rudolf Keller received a doctorate of science from the Swiss Federal Institute of Technology. As an electrochemist with experience in the aluminum smelting industry, he founded EMEC Consultants in 1984. Electrochemical stripping technology was invented, developed, and patented by this entity. He is also president of the ElectroStrip Corporation, formed to commercialize this technology.

Brian J. Barca
Brian J. Barca joined EMEC Consultants in 1996 where he has participated in the development of electrostripping technology, co-authoring of one of the patents as well as some papers dealing with the process. Mr. Barca is the secretary/treasurer of the ElectroStrip Corporation. He holds a BS degree in environmental science from Allegheny College.

Chapter 2.10
Solvent and Chemical Pre-Cleaning

Melvin H. Sandler and Samuel Spring (original chapter)
Charles S. Bull (2002 revision)

Introduction

As noted throughout this book, surface preparation is a primary factor relating to the durability of any coating system. Without proper surface preparation, the finest coating applied with the greatest of skill will fall short of its maximum performance or may even fail miserably. In fact, a "medium-quality" coating applied over optimum surface preparation will invariably outperform the highest quality coating applied over deficient surface preparation.

Surface preparation generally must provide two main results for proper adhesion of applied coating films:

- Removing contaminants
- Producing a surface profile that increases the surface area and provides an anchor pattern or "tooth" for enhanced coating adhesion.

Creating a surface profile requires the use of energy sufficient enough to remove tightly adherent contaminants, such as mill scale, and a small amount of the substrate itself, so that a dense pattern of peaks and valleys is produced on the surface. Although the depth of the surface profile may vary from a light etch up to average profile depths of 5 mils or more, the main goal is a substantial increase in surface area.

High energy mechanical cleaning methods are efficient for removing primary metal contaminants, such as rust and mill scale. However, oils, greases, finely divided soils, and mildew are not readily removed in this manner. In fact, using mechanical cleaning methods before removing these contaminants may force them into the depths of the surface profile, where they are much more difficult to remove.

Thus, the initial step in any surface preparation operation is pre-cleaning the surface to remove any contaminants that cannot be removed by subsequent mechanical cleaning and surface profiling This chapter describes solvents, chemical cleaning materials, and pre-cleaning methods with an emphasis on pre-cleaning prior to mechanical cleaning. There are numerous industrial finishing applications where chemical cleaning is the only cleaning step required for adequate coating system performance. However, detailed descriptions of these methods are outside the scope of this chapter.

General Considerations

During manufacture, fabrication, and service, surfaces become soiled when they pick up foreign matter, including corrosion products, that must be removed before final finishes or refinishes can be applied. There are countless contaminants, or soils to be removed, but in general, they may be categorized as oily and semi-solid soils and soils containing solids.

Oily Soils

Hydraulic, lubricating, and light oil and oil-based rust preventers are some examples. When present as thin films or small residues, and when very viscous in nature, these soils may be removed with alkaline cleaners. On more stubborn areas, solvent cleaners may be needed because the longer a soil ages the more difficult it is to remove.

Semi-Solid Soils

Viscous oils, greases, and heavy rust preventers are some examples. These soils are often removed with heavy-duty alkaline cleaners or a combination of solvent followed by an alkaline cleaner.

Soils Containing Solids

Some examples are mud, carbonized oils, tape adhesive, and corrosion products. These soils are usually the most difficult to remove and may require a combination of solvent, alkaline-pressure spray, and scrubbing, and, in the case of corrosion products, acid pickling to complete the cleaning process.

Aged or impacted soils are generally the most difficult to remove. It is necessary to remove not only the soil but also any cleaner residues, which may subsequently contribute to further corrosion or adversely affect coating performance.

Types Of Chemical Cleaners

Solvents

Aliphatic petroleum solvents (kerosene, VM & P naphtha, mineral spirits), aromatic solvents (toluene, xylene), ketones (Acetone, MEK, MIBK), chlorinated solvents, or a combinations of these, are used to dissolve and remove oily soil. Petroleum solvents may be used in hand, soak, or spray cleaning and are efficient in removing oils and greases. Chlorinated solvents are generally used in vapor degreasing units but may also be used at ambient temperatures by immersion or spray. They are effective in removing heavy oils, greases, and waxes. Chlorinated solvents should be inhibited against hydrolysis to prevent hydrochloric acid from forming in the presence of water. Acidity may etch the metal. Solvent cleaners offer the advantage of leaving the surface dry after cleaning and eliminating the need for additional rinsing.

Environmental and health regulations restricting the use of organic solvents have become very stringent in recent years Thus, with the exception of solvents used to clean small areas, water-based alkaline or acidic cleaners are more common today.

Alkali

Alkaline cleaners are composed of highly alkaline salts, such as sodium hydroxide, silicates, and carbonates along with surfactants, sequestering agents, inhibitors, wetting agents and/or soaps. They function by wetting, emulsifying, dispersing, and solubilizing the soils. These are generally more efficient at elevated temperatures.

Acids

Acid cleaners are usually composed of fairly strong acids with small quantities of surfactants, water-miscible solvents, and organic wetting and emulsifying agents. Acid cleaners remove a soil by chemical attack, dissolving the reaction products. They are used primarily to remove corrosion products that cannot otherwise be efficiently removed by mechanical cleaning methods.

Detergents

Detergent cleaners are composed of buffering salts, sequestering agents, dispersants, inhibitors, and wetting agents and/or soaps. They function by wetting, emulsifying, dispersing, and solubilizing the soil, generally becoming more efficient when used at temperatures ranging from 150°F (66°C) to boiling.

Cleaning

Pre-Cleaning

Prior to using any of the removal methods noted in the previous section, it is generally advisable to wipe, brush, or scrape away any heavy soil deposits by hand to improve subsequent cleaning efficiencies and reduce both the consumption of cleaning agents and the volume of the associated waste streams.

In the use of any cleaning method, appropriate safety precautions must be taken to protect personnel from materials and conditions that may present fire hazards, cause skin irritation, or have a toxic effect when breathed in high-vapor concentrations.

There is no single method of cleaning that will properly condition all surfaces prior to preservation. The choice of cleaning method will depend upon the size and type of structure as well as other factors, including:

- Type of soils
- Need for spot cleaning only, or 100% surface cleaning
- Type of subsequent mechanical cleaning to be performed
- Level of cleanliness required
- Equipment and cleaning agent availability
- Containment and disposal of waste streams

Surfaces cleaned after assembly or in the field can require cleaning methods quite different than those for parts processed in a factory. Moreover, large parts may require different procedures than small ones, but the principles governing cleaning are similar. In general, cleaners are more effective at higher temperatures and higher concentrations. When using elevated temperatures with hydrocarbon solvents remember to consider their volatility and potential to produce toxic and flammable vapors. Applying cleaners under high turbulence or force will dislodge the soil loosened by the chemical action.

When cleaning with alkaline or acidic materials, every effort should be made to thoroughly rinse the surfaces, not only to minimize the amount of soil remaining, but also to remove any cleaning material residue that may adversely affect subsequent a

Table 1. U.S. Government Chemical Cleaning Specifications.

Specification Number	Title	Material	Application	Purpose
P-C-111D (2)	Carbon Removing Compound	Single phase liquid	Soak	For use in softening and removing carbon gum & other contaminants (except rust and corrosion)
MIL-HDBK-509	Cleaning and Treatment of Aluminum Parts Prior to Painting	None Specified	Immersion	Cleaning aluminum prior to painting
A-A-59146	Cleaning Compound, Alkali, Boiling Vat (Soak) or Hydrostream	None Specified	Immersion or Spray	Hot soak tank cleaning or hydrostream of ferrous & non-ferrous materials
A-A-59133	Cleaning Compound, High Pressure (Steam) Cleaner	Alkaline	Spray	For use in steam cleaning machines for cleaning various ferrous & non-ferrous surfaces
TT-C-490D	Cleaning & Pretreatment of Ferrous Surfaces for Organic Coatings	Solvent, Alkaline emulsion & phosphoric acid	Immersion, spray or brush	Cleaning Methods are intended for cleaning, rust removing, descaling or surface etching
MIL-PRF-1109G	Cleaning Compound, Degreasing & Depreserving Solvent	None Specified	Soak, brush or spray	For use in removing oils, greases, asphalt, tars & rust preventive compounds, other than wax type, from metallic & painted surfaces
A-A-59260	Corrosion Removing Compound, Sodium Hydroxide Base for Electrolytic or Immersion Application	Sodium hydroxide base	Electrolytic or immersion	Rust removal from bare and painted iron and steel
SAE-AMS-C-22542	Cleaning Compound, High Pressure Cleaner, Liquid	Optional	High pressure steam cleaning machines, coil type	Painted and unpainted aircraft surfaces
MIL-C-43616C	Cleaning Compounds, Aircraft Surfaces	Optional	Spray, brush or foam	Intended for cleaning painted and unpainted aircraft surfaces
A-A-59261	Corrosion Removing Compound, Sodium Hydroxide Base for Electrolytic or Immersion Application	Sodium hydroxide base	Immersion	At elevated temperatures, will remove rust, paint, scale, grease, dirt, asphalt & carbon

coating's performance.

Another consideration is the ionic content of the rinse water. All "tap water" has some soluble salt with considerable variation in amount and content. Most potable water will not leave enough detrimental residues of soluble salts on the substrate to affect coating applications. However, exceptionally "hard" water, or repeated re-use of rinse water can cause soluble content to build to detrimental levels. If soluble salt residue from rinse water is likely to be a problem, the cleaned substrate should be tested for unacceptable levels of soluble salts, and the quality of the rinse water adjusted accordingly.

Solvent Wipe

A second wipe with clear solvent or removing excess solvent with a clean cloth can be effective. Mineral spirits and Stoddard solvent are relatively convenient and inexpensive to use. The quality of cleaning depends largely upon the severity of the soiling and the expertise of the operator. Some soils may require more aggressive solvents such as aromatic, ketone, or chlorinated solvents. Solvent cleaning is most effective for removing oils and greases from limited areas of structures and for occasional spot cleaning prior to painting. Where the complete structure is to be cleaned, other methods are more practical.

Steam Cleaning

A high-pressure jet of steam, with or without a cleaning compound, is used to clean ferrous, non-ferrous, and painted surfaces. Steam removes grease, oil, and dirt by a combination of detergent action, water, heat, and impact. Alkali cleaners used with steam will attack aluminum and zinc alloys, unless specifically inhibited against such action. Use alkalis selectively over painted surfaces to assure no damage to the paint if removal is not desired.

A pressure jet steam cleaner **(Figures 1 and 2)** often includes a separate solution tank or drum for the cleaning compound. One type of steam cleaner

stores the concentrated cleaning solution and mixes it with water at a constant rate to produce a uniform cleaning solution through a heating unit in which it is partially vaporized and put under pressure. The hot solution and steam are forced through the nozzles onto the surface to be cleaned. The same equipment can be used for cleaning with dry steam or with cold water under high pressure. This type of steam cleaner may be either portable or stationary.



Figure 1. Steam cleaning of large or assembled structures. The steam cleaner may be directly fired or use plant steam as in the above photograph. When the distance from the gun to the surface is small, the temperatures are close to 200°F so high-melting soils can be removed more readily. At more normal gun-to-surface distances, the temperature may be 160° to 180°F but a larger area is covered. Well-trained operators who know how to properly vary the spray nozzle distance from the work and the dwell time in each area are necessary for thorough and efficient cleaning.

Another type of portable pressure jet steam cleaner, sometimes called a hydro-steam unit, requires an outside steam source. The cleaning solution is mixed and stored in a container or tank that is not part of the steam cleaner. No water is mixed with the solution in the steam cleaner, so the solution is used at a lower concentration. The solution and steam are mixed in the cleaner and discharged through the nozzle of a steam-cleaning gun. The same equipment can be used for cleaning with dry steam.

In steam cleaning, a stream of steam, with or without cleaning compound, is directed under pressure through a cleaning gun or guns against the surface to be cleaned. The pressure should be adjusted so that the area can be cleaned without requiring repeated or prolonged spraying. The cleaning guns may have interchangeable nozzles. A round one is used for most cleaning with flat nozzles used for flat surfaces. The material and surface finish determines whether drying after cleaning is necessary.

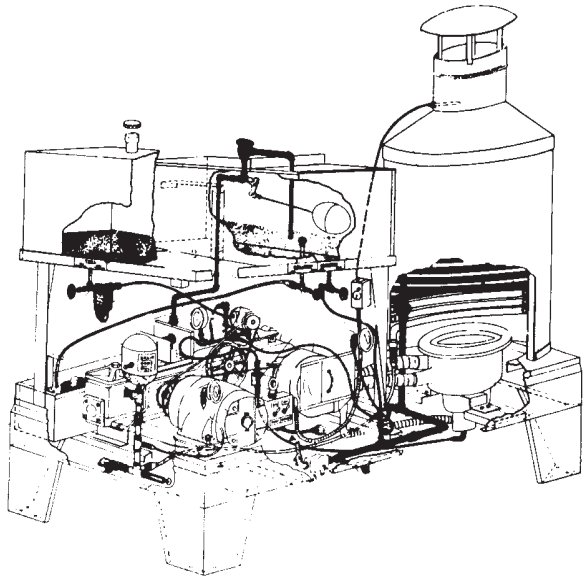


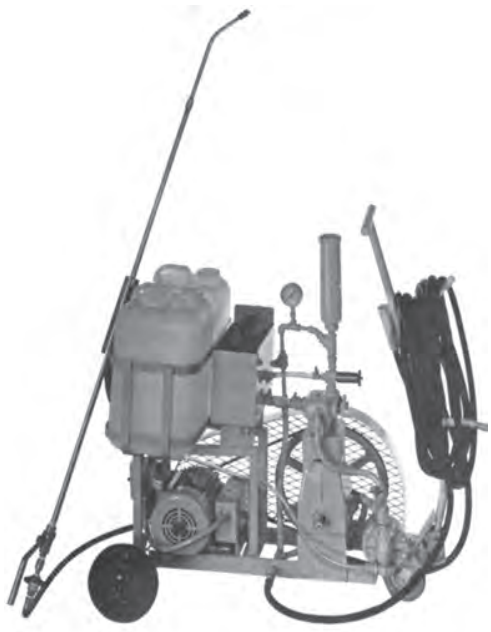
Figure 2. Functional perspective of an oil-fired steam cleaner

High-Pressure Hot Detergent

Hot detergent machines **(Figures 3A and 3B)** use pumps at pressures of 500 to 3,000 psi. Solution volumes vary with the larger machines **(Figure 4),** delivering 3-5 gallons per minute. The cleaning procedure is basically the same as in steam cleaning with the detergent spray directed under high pressure through a cleaning gun against the surface to be cleaned. As with solvent and steam cleaning, the skill of the operator determines in large part how effective the procedure will be. There is an inexpensive unit that uses water line pressure for dispensing the detergent. The solution is metered into the water line before spraying. In order to obtain reasonably good cleaning,

the detergent solution is used at a considerably higher concentration, usually 1 to 2 ounces per gallon.





Figures 3a and 3b. Portable hot detergent machines that can be hooked into a plant's hot or cold water line for convenient spraying of a high-pressure detergent solution.

Foam Cleaning

Foam detergent solutions are popular for cleaning food processing plants and automotive equipment such as trucks**.** They are also used to acid clean the insides of process towers, filling the tower with foam instead of liquid. The advantage of foam is that it will cling to vertical surfaces long enough for detergency to take place. If a longer surface contact time is required, a gel may be sprayed onto the surface. In general, the foam is neutral and a limited residue may not adversely affect paint if rinsing is not complete. However, any decision to allow incomplete residue removal must be coordinated with the coating manufacturer.

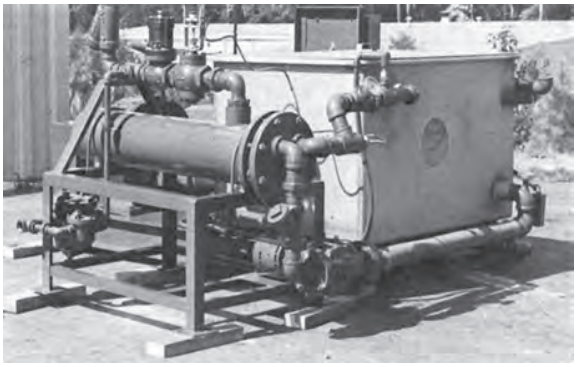


Figure 4. High-pressure spray machines in which the hot detergent solution is contained in a reservoir rather than injected into hot steam. This provides a more predictable concentration of detergent and permits spraying of a high-volume solution in a known concentration.

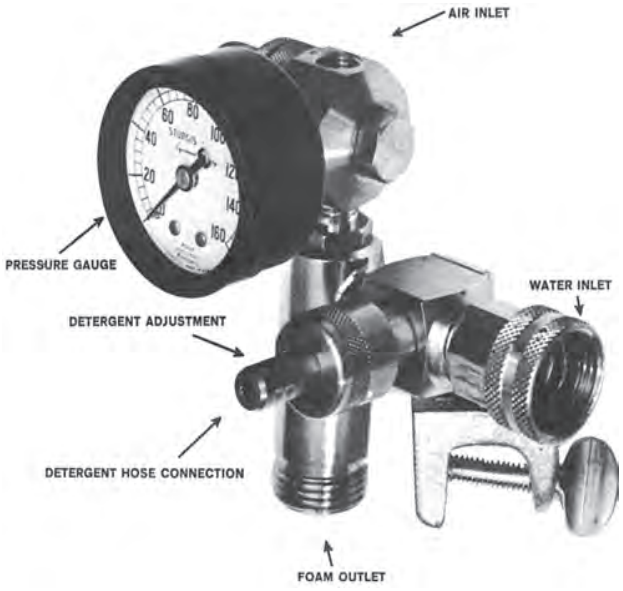


Figure 5. Foam cleaning device.

In this process, foam is generated by mixing a surfactant, often containing a stabilizer and detergent builder, with water and compressed air. There are three types of foam cleaning units:

- A small unit has a tube to retrieve foaming concentrate from a drum
- A unit that pumps diluted foaming agent and detergent from a drum
- A self-contained (mobile) unit in which a foaming agent and detergent concentrate is mixed with water and air prior to spraying

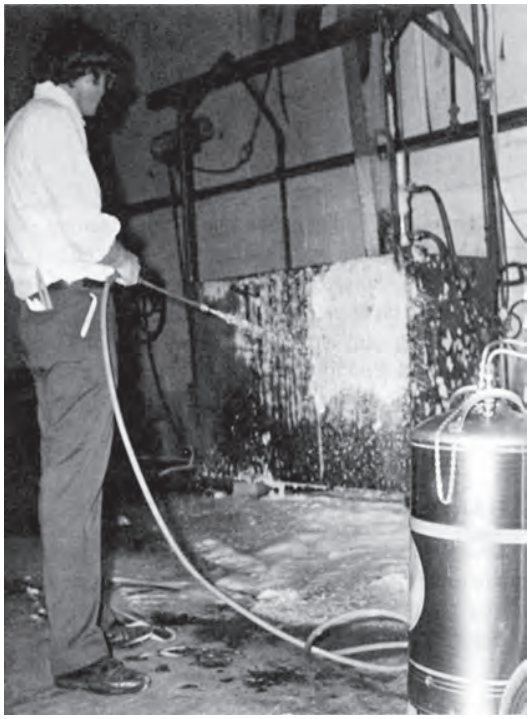


Figure 6. Use of portable foamer.

Brush Cleaning

Brushes and sponges are a useful complement to other methods of cleaning in removing stubborn soils and spot cleaning highly soiled areas. Fiber, wire, or plastic brushes may be employed, depending upon the type of cleaning required. **Table 2** lists the various brush materials available. Brush cleaning should be followed by wiping with clean rags or sponges to remove loosened soils from the surface. Sponges are also available in a variety of forms and compositions, including some with abrasive surfaces attached to one side.

Table 2. Types of Brush Material Used in Cleaning.

Natural Fibers	Tampico Fiber	Good durability and water resistance, soft to medium stiffness
	Patent Fiber	Select grade tampico, stiffer and more durable than tampico
	Paymyra Fiber	Lower cost, stiffer, reasonably durable
	Palmetto Fiber	Very good durability and water resistance
Animal Bristles	Horsehair	Soft to slightly stiff, good durability, fair water resistance
	Boar Bristle	Excellent durability and resistance to chemicals
Plastic Bristles	Nylon	Very good durability, wide selection, resistance to alkaline cleaners but not to solvent, excellent water resistance
	Acrylic Plastics	Excellent durability and residence to chemicals
Wire Brushes	Carbon Steel	Very stiff, tends to rust, high cutting action, heat resistant
	Brass	Very stiff, durable
	Stainless Steel	Very stiff, durable, expensive, non-corroding

Cleaning Previously Painted Surfaces

If the painted surface is clean and intact, it may be possible to paint with little or no chemical cleaning. However, if the surface has been exposed outside for any period of time, it has probably accumulated detrimental amounts of atmospheric contaminants or corrosion products that must be removed before repainting. Any of the chemicals and cleaning methods mentioned in this chapter may be used, but take care to ensure that chemical cleaning procedures does not attack the sound paint.

Handling The Clean Surface and Disposing Of Chemical Wastes

Cleaned surfaces should be painted as soon as possible after cleaning or otherwise protected, to prevent atmospheric rusting or resoiling. Dispose of cleaning wastes in full compliance with federal, state, and local regulations.

About the Authors

Melvin H. Sandler
Author of more than 50 technical publications, Melvin H. Sandler developed coatings for the preservation of Army materials during his service as chemist and division chief at the former U.S. Army Coating and Chemical Laboratory, Aberdeen Proving Ground, MD. His career in the coatings industry spanned more than 40 years.

Dr. Samuel Spring
Chemist, college instructor, and laboratory technical director, Dr. Samuel Spring also served as president of Southeast Laboratories, Inc. prior to his retirement in 1977.

Charles S. Bull
Charles S. Bull first became involved in chemical process and corrosion-related research for the Chicago Bridge and Iron (CBI) Company in 1967. Returning to CBI after 4-1/2 years with the United States Air Force, Bull was assigned to a variety of research, sales, and coatings-related technical and management positions. He served as manager of the CBI Corporate Painting Group from 1992 until his retirement in 2000. Currently an independent consultant for CBI and other firms, Bull remains active on a number of surface preparation and coatings committees at SSPC, NACE, and AWWA. He earned his BA degree in chemistry from MacMurray College in 1969.

Chapter 2.11
Dehumidification During Coating Operations

Art Pedroza, Jr., James D. Graham, and Richard W. Drisko

Introduction

Dehumidification is the process of removing moisture from air in enclosed spaces to reduce its humidity, while depressing the dew point significantly below the surface temperature. Thus, water will not condense on surfaces or otherwise cause adverse effects during surface preparation and coating operations.

The technology of dehumidification and temperature control in enclosed spaces continues to change rapidly and be more commonly used during coating/lining operations to enhance working conditions and performance and to reduce costs. This chapter describes how dehumidification can best be utilized for this purpose.

Benefits of Dehumidifying Enclosed Spaces

Dehumidification of enclosed spaces may provide several benefits during surface preparation and coating operations, as described in the paragraphs below. It may also improve productivity by increasing worker comfort and reducing fatigue.

Controlling Rust Bloom

Reducing relative humidity below a critical level can control rust bloom for several days to permit an entire tank to be abrasive blast cleaned before priming. Typically, rust bloom will be prevented from forming on an abrasive blast cleaned steel surface with a dew point 15 to 20°F (9 to 12° C) below the prevailing surface temperature and a relative humidity not to exceed 55%.[1] Surface contamination will lower the critical relative humidity.

Preventing Moisture Condensation on Uncured Coatings

Most coating specifications require that the steel surface temperature be at least 5°F (3°C) above the dew point before abrasive blast cleaning or applying coating to prevent moisture condensation. The same criteria may be required for a period of several hours after completing the application to prevent moisture from condensing on the incompletely cured coating. The dew point can be easily reduced by dehumidification.

Effects on the Curing of Coatings

Dehumidification can control the following effects of moisture on coatings:

- Ethyl silicate inorganic zinc-rich coatings require moisture for curing, while high humidities may retard the curing of water-borne inorganic zinc-rich coatings.
- Moisture-curing polyurethanes require a relative humidity range of 30 to 75% for optimum curing.[2]
- High humidities may retard the curing of water-borne coatings.
- High humidities can cause amine blush or carbamation (clouding) of amine-cured epoxy coatings.[3] U.S. Navy specifications require a 50% minimum relative humidity during application and curing of solvent-free epoxies.[4]

Removing Excess Moisture from Concrete

Excess moisture in cured concrete may cause blistering of coatings.[5] Dehumidification can remove this water effectively.

Definitions of Commonly Used Terms

Absorbant. A desiccant, such as lithium or sodium chloride, that undergoes a reversible chemical or physical change as it absorbs moisture.

Adsorbant. A desiccant, such as silica gel, that reversibly absorbs moisture like a sponge without physical or chemical change.

Dehumidification. The removal of moisture from the air.

Desiccant. A material used to absorb/adsorb moisture from the air and later release it when heated.

Dew Point. The temperature at which air becomes saturated with water (when the air is 100% relative humidity). Below this temperature, moisture condensation on surfaces will occur.

Flash Rusting. Steel rusting that occurs within

minutes to hours after surface cleaning. It is accelerated by salt contamination and high humidities.

Relative Humidity. The ratio of actual pressure of existing water vapor to the maximum possible (saturation) pressure of water vapor in the atmosphere at the same time, expressed in percentage.

Rust Bloom. See **Flash Rusting**.

Measuring Environmental Conditions

There are several instruments available for measuring relative humidity, dew point, and temperature. Each instrument has different levels of accuracy.

Psychrometers

A psychrometer is an instrument used to determine relative humidity and dew point by measuring the difference (depression) in readings from dry to wet bulb thermometers. There are three basic types: the sling psychrometer, the psychrometer with thermometers and a battery or electrically powered fan, and the battery-powered, digital psychrometer. These are described in ASTM E 337.

Today, the sling psychrometer is the most common in industrial coating work.[6] It utilizes a wet bulb (in a clean cotton wick saturated with distilled water) and a dry bulb thermometer that are spun rapidly through the air until constant readings are reached on each. Typically, the relative humidity and the dew point calculated from their measurements will vary about 5% from actual values.

Psychrometers with fans blowing air across the wet and dry bulb thermometers require about two minutes for stabilization. These instruments have advantages over the sling psychrometer of (1) being able to get closer to the surface being cleaned or coated and (2) being easier to use in tight places.

The digital psychrometer operates much more quickly than other psychrometers, requiring only 1 to 2 seconds for each measurement. It also does not require water for a wet thermometer bulb, and some store measurements for later retrieval.

Psychrometric charts must be used to relate thermometer readings to relative humidity, dew point, or absolute amount of moisture in the air. These charts may appear to be complex but are really straight forward to use.

Electronic Hygrometers

Electronic hygrometers are also available for measuring moisture conditions in air. The accuracy, reproducibility, and response time of these instruments vary widely, so that their readings may be no more accurate than good psychrometer measurements.

Surface Temperature Measurements

Bimetallic magnetic surface-contact thermometers are widely used during industrial coatings operations. They are inexpensive instruments that require calibration for accuracy.

Electronic surface-contact thermometers are inexpensive and feature a faster response time than the bimetallic magnetic surface-contact thermometers. Neither these thermometers can be used to monitor surface temperatures as during coating.

Infrared instruments for measuring surface temperatures do not have to remain in contact with the surface during measurement and thus can be used during coating operations. They are more costly than other thermometers but are much more convenient.

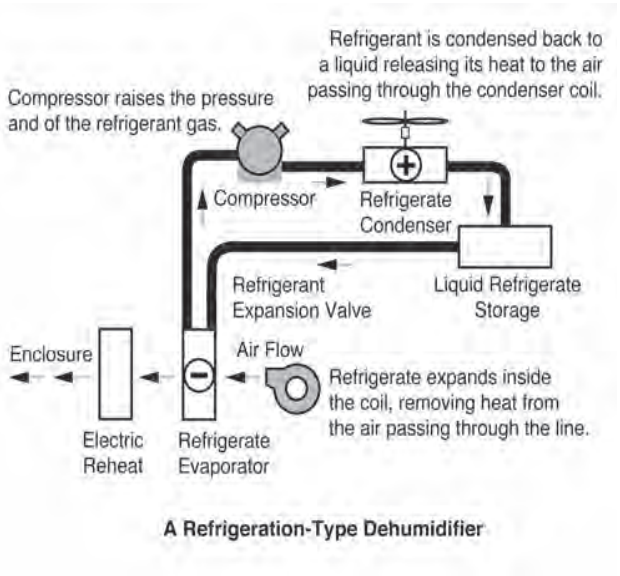


Figure 1. Refrigerant dehumidifier.

Types of Dehumidification Equipment

The dehumidifiers currently used for industrial purposes are described below.

Direct-Expansion Refrigerant Dehumidification

In the refrigerant method of dehumidification, ambient air is circulated over refrigeration coils at a significantly lower temperature. As the cooled air reaches its saturation point, the moisture is con-

densed, collected, and removed from the system. The refrigerant method provides cooling as well as dehumidification, and thus on hot days, is sometimes used with the desiccant system to reduce the temperature. This system is not recommended when outside ambient air temperatures are below 65°F (18°C) and the dew point difference between the surface temperature and the ambient interior air is specified as 45°F (27°C), because water may freeze on the coils. Typical refrigerant dehumidification equipment is shown in **Figure 1.**

Desiccant Dehumidification

The desiccant dehumidification system utilizes solid or liquid materials that have a high affinity for water that they can adsorb from the air. The water can later be removed by heating and the desiccant regenerated for reuse. For liquid desiccants, the air is passed through the liquids; for solid desiccants, granular beads or fixed desiccant structures are used in automated machines. The most commonly used desiccants are silica gel and lithium chloride, both become hydrated while removing water.

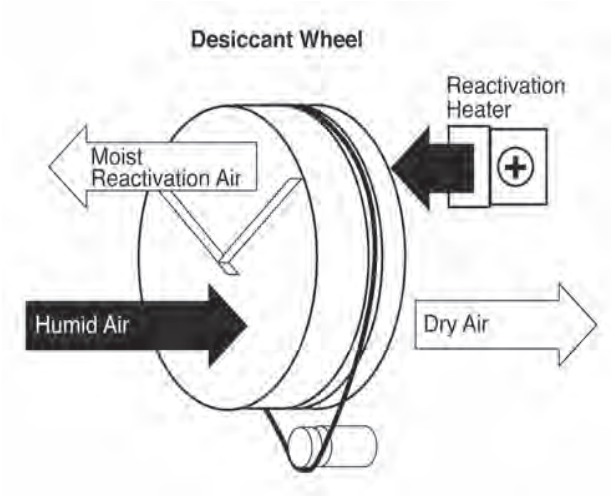


Figure 2a. Desiccant principle.

On large coating/drying projects, modern dehumidification equipment uses a special rotating wheel coated with the silica gel desiccant. As the moist air passes through the wheel it is adsorbed into the desiccant. As the wheel rotates past a set of seals, hot air from the reactivation heater is blown in the opposite direction, drying and reactivating the silica gel. The react air can be heated in various ways: electric heaters, steam coils, or natural or propane gas-fired heaters. The react air is hot and wet—120°F and 90–100% relative humidity. This react air must be discharged out of the enclosed space and away from the supply air intake. Silica gel desiccant is preferred as there is no chance of chlorides getting into the produced air stream. The reaction of drying the silica gel typically raises the temperature of the processed air stream by 10 to 15°F (8 to 12°C). These units are effective for dew point depression at all times of the year. Some cooling may be desirable in warm climates. The desiccant principle and typical desiccant dehumidification equipment are shown in **Figures 2a and 2b.**

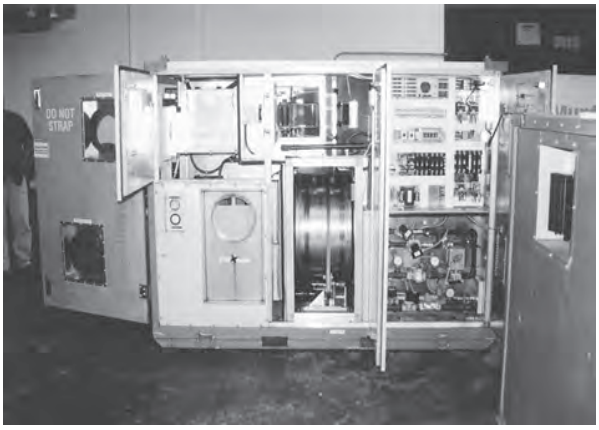


Figure 2b. Typical desiccant dehumidification equipment. Courtesy Munters MCS.

Combined Refrigerant and Desiccant Dehumidifier Systems

By pre-cooling the air and condensing some of the moisture before passing it through a desiccant, maximum efficiency in dehumidification is often achieved. It will also reduce the number of air changes necessary to maintain a 15°F–20°F (8–15°C) dew point difference between the internal surfaces and the internal ambient air temperature.

Choosing the Best Type of Dehumidifier for a Job[7]

Some criteria for selecting the best type of dehumidifier for a particular job are:

• Refrigerant dehumidifiers are more economical than desiccant dehumidifiers at high air temperatures and humidities. They are seldom used at dew points below 40°F (4°C) because condensed water freezes on the coils.

• Refrigerant dehumidifiers are more efficient when drying air to saturated conditions, and desiccant dehumidifiers are more efficient when drying air

to low humidities.

• The refrigerant and desiccant dehumidifiers can be used together most economically by utilizing the advantages of each. The relative costs of electrical power and thermal energy will often determine the most economical mix.

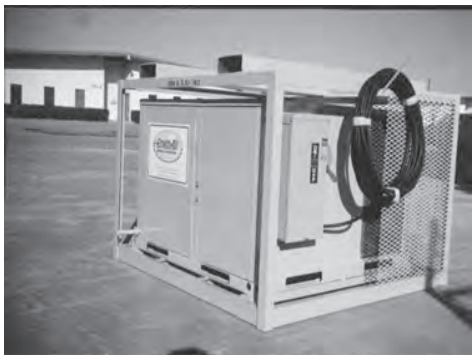


Figure 3. Enviro-Air 1000 CFM DH unit. Courtesy Enviro-Air Control Corp.

Closed-Loop System

A closed-loop dehumidification system is one in which the exiting air is routed through an appropriate filter media and used as feed air for the dehumidifier.

During abrasive blast cleaning, the exiting air contains particulate matter consisting of spent abrasive, paint and rust particles, etc. This matter must be filtered through a dust collector before the air is passed through the dehumidifier and recirculated or exhausted. During coating application, solvent vapors will also enter the exiting air. These must be removed from air to be recirculated because the solvent fumes may be unhealthy, combustible, retard curing, and damage the desiccants.

Solvent fumes may be adsorbed on charcoal filters that must be replaced periodically, as their capacity is reduced. The increased use of high-solids (low-solvent) coatings may reduce this problem significantly.

Dehumidification Limitations in Producing Quality Air

While dehumidifiers may introduce copious quantities of fresh air into an enclosed space, the quality of the resultant air does not eliminate any requirements for respirators associated with the coatings being applied. Despite many changes of air, residual solvent will remain in the working area during the curing. Similarly, respirators or dust masks required by the material safety data sheets of the abrasive and coating manufacturer should be used during abrasive blast cleaning and coating, whether or not dehumidification is being conducted at the time.

The introduction of large volumes of dehumidified air into the work area may disturb blasting debris and reduce visibility, even though dust collects or dust socks are being used to remove these particulates. Therefore, the dust collectors must be properly sized to perform effectively with the dehumidifiers so that no more outside air is introduced than can be handled by the collectors. During inclement weather, the efficiency of the dehumidifier can be increased by reducing the air flow of the dust collector.

Sizing Dehumidification Equipment

There are many factors involved in properly sizing dehumidification equipment for a specific job. In addition to the air flow rate through dust collectors, other factors affecting the sizing include the season, the weather, the location, the volume of enclosed air, the number of enclosure openings, the distance from the dehumidification equipment, and the presence of other equipment (e.g., in-line electric heaters and chillers) being used in conjunction with the dehumidifier.

Typically, fewer changes of air are required for larger volume enclosures. Enclosed spaces that are more air-tight require less dehumidification. A dehumidifier's ability to produce volumes of dehumidified air in ft^3/min. is specified on the equipment's data plate, as well as in the equipment data sheet.

Equations for Calculating Dehumidifier Air Flow Capacity

The necessary air flow capacity of a dehumidifier for a specific number of air changes per hour can be calculated using equation (1):

$$(V_1)(AC)/60 = X \qquad (1)$$

where:

V_1 = the internal volume in cubic feet of the enclosed space minus the
volume of all obstructions within the space

AC = the specific number of air changes per hour

X = the air-flow capacity in cubic feet per hour that corresponds to the specified air change rate

If the metric system is used, the necessary capacity of a dehumidifier for a specific number of air changes can be calculated using equation (2):

$$(V_1)(AC) = X \qquad (2)$$

where:
V_1 = the internal volume in cubic meters of the enclosed space minus the
volume of all obstructions within the space
AC = the specific number of air changes per hour
X = the air flow capacity in cubic feet per hour that corresponds to the specific air change

Example of Calculation of Dehumidifier Capacity Requirements

Calculate the required capacity of a dehumidifier to dehumidify a cylindrical tank 100 ft in diameter (50 ft in radius) and 10 ft in height for 4 air changes per hour.

Step 1. Volume of tank (V_1) = $\pi r^2 h$

where
r = radius
h = height
Volume of tank (V_1) = 3.14(50)(50)(10) = 78,500 ft^3

Step 2. Using equation (1), dehumidifier capacity (X) = 78,500(4)/60 = 5,233 ft^3/hr



Figure 4. DH equipment installed beside shrouded tank. Courtesy Enviro-Air Control Corp.

Installing Dehumidification Equipment

Ideally, the dehumidifiers should be placed as close to the enclosed area as possible to reduce losses of air pressure by friction or leaks in lengthy air ducts. This is especially important when in-line heaters are used, because the heat can be readily lost over long distances, even when insulated ducts are used. High-voltage electric heaters and those utilizing indirect fired natural gas or propane inline heaters can be dangerous to workers who are not fully trained or do not properly utilize their training. Indeed, local government agencies may require operating permits for dehumidification equipment.

The air duct from the dehumidifier should be carefully placed in the enclosure for optimal air flow within the space to assure removal of water from all areas. Alignment of the duct along tank walls will cause the air to flow in a funnel pattern and permeate all areas as it circulates around the enclosure. There must always be an exit point for air in the enclosed area in order to affect an air change.

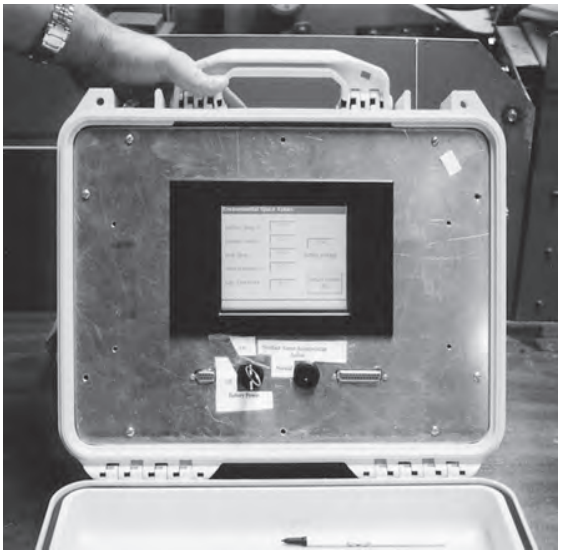


Figure 5. Exactaire instrument for monitoring environmental conditions in enclosure. Courtesy Munters MCS.

Monitoring

In addition to monitoring the relative humidity, dew point, and temperature, as described earlier, carefully monitor the equipment itself in the event that unexpected shut-downs occur from mechanical problems or fluctuations in the power source. Dehumidifiers have multiple banks of fuses that can shut down the equipment when power fluctuations occur.

Once a dehumidification unit shuts down, the air conditions may change so as to permit rust blooming of uncoated steel or adverse effects

on uncured coatings.

A new remote monitoring system currently available can inform responsible individuals when control of space conditions are lost, when equipment fails, or when fuel is low. It can also stop and start the D/H equipment, as the dew point spread indicates, to save fuel.



Figure 6. DH unit with dust collector in place. Courtesy Enviro-Air Control Corp.

References

1. SSPC-TR 3/NACE 6A192. *Dehumidification and Temperature Control During Surface Preparation, Application, and Curing of Coatings;* SSPC: Pittsburgh, 2001.
2. Hare, Clive H. *Protective Coatings: Fundamentals of Chemistry and Composition;* Technology Publishing Company: Pittsburgh, 1994, pp 252-254.
3. Keehan, David; Wyatt, Charles H. Humidity—It Affects More Than Just Surface Preparation. In *Proceedings of SSPC '99,* pp 323-334.
4. Dehumidification. In *Procedure Handbook: Surface Preparation and Painting of Tanks and Closed Spaces;* SSPC: Pittsburgh, 1999, pp 41-58.
5. Schnell, Don J. Utilizing Desiccant Dehumidification to Remove Excess Moisture from Concrete. In *Proceedings of SSPC '00,* pp 25-28.
6. *The Inspection of Coatings and Linings;* Bernard R. Appleman, ed.; SSPC: Pittsburgh, 1997, pp 365-366.
7. *The Dehumidification Hamdbook, 2nd Edition;* Lewis G. Harriman III, ed.; Munters Cargocaire: Amesbury, MA, pp 3-21.

Acknowledgements

The authors and SSPC gratefully acknowledge Charles Wyatt's comprehensive peer review.

About the Authors

Art Pedroza, Jr.

Art Pedroza currently works as a project manager for an industrial contractor that specializes in surface preparation and coating services for the southern California petrochemical industry. He was previously employed by Munters MCS and Dehumidification Tech., Inc. Mr. Pedroza is a board member of the SSPC Southern California Chapter and the NACE L.A. Section. He is also a member of the California-Nevada Section of American Water Works Association, the L.A. Society for Coatings Technology, and the Southern California Chapter of the Western States Petroleum Association.

James D. Graham

Jim Graham is the western area outside marketing representative with Corrosion Control Products Company, Gardena, CA. He is responsible for coating inspection, instrument sales, and training throughout the western U.S. and providing support for the company's other offices. Currently vice chair of the Southern California Chapter of SSPC and the AWWA CAL-NEV corrosion control committee, Mr. Graham has also served on the board of the Channel Islands Section of NACE International since 1984 and is the former chair of the Western Area NACE Section. He is an SSPC certified protective coatings specialist (PCS) and a NACE International certified coatings inspector. He also authored a chapter on water and wastewater treatment plants in SSPC's *The Inspection of Coatings and Linings*.

Richard W. Drisko

Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society for Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy's center of expertise on coatings for shore structures. He is a professional corrosion engineer in the state of California, an SSPC certified protective coatings specialist (PCS), and a NACE International certificated corrosion specialist. Dr. Drisko received his BS, MS, and PhD degrees from Stanford.

Chapter 3.1
Concrete Surface Preparation

Benjamin S. Fultz

Introduction

The unique chemical and physical nature of concrete surfaces dictate that special considerations be given to surface preparation. Many of the same techniques used for cleaning steel can be applied to concrete; however, understanding the differences between concrete and steel is essential. Both materials are hard, but steel is ductile, whereas, concrete is brittle. Steel is chemically neutral; concrete is alkaline. Steel is dense and nonporous; concrete is porous. Even though relatively homogenous, each concrete placement varies widely in chemical composition and hardness, primarily due to differences in the types (grades) of cements, aggregates, and other additives used in the concrete mix design.

With this in mind, the surface preparation and treatment of concrete prior to applying coatings or linings is affected by a number of factors:

- Concrete composition and strength
- Concrete placement, finishing, and curing
- Concrete age (old or newly placed) and condition
- Coating or lining system to be applied

The method selected for surface preparation varies considerably with each factor. Methods may range from simple high-pressure air “blow-down” to mechanical cleaning and acid cleaning. This chapter will focus on the factors that influence surface preparation and some of the available surface preparation techniques.

Concrete Composition and Strength

In order to be able to understand why there are differences in surface preparation requirements for concrete and steel, an understanding of the composition of concrete is required. Concrete is mainly a mixture of Portland cement and aggregates, usually silica sand and gravel. Portland cement types are selected to improve chemical resistance, early cure, and strength. The dry concrete components are mixed with water and then cure by hydration. Sometimes additives known as admixtures are included in the concrete mix design to increase early strength, increase density, decrease porosity, or to improve handling and finishing. Admixtures include such materials as air entrainment, synthetic fibers, freeze-protection agents, resins, fly ash, silica fume, microsilica, or natural pozzolans. Pozzolans are siliceous or siliceous and aluminous materials, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Some additives result in hard, slick surfaces that are difficult to clean and to produce a suitable surface texture (profile) for coating application. A review of the concrete mix design will help to determine any potential impact on surface preparation.

Concrete Placement, Finishing, and Curing

In addition to the general physical and chemical properties of concrete, the method used to place the concrete and the coating system to be applied will determine the required surface preparation technique.

Placement

Structural concrete used for walls, piers, tanks, and machinery pads is usually poured and shaped through the use of forms. When vertical pours are made, such as walls, the concrete must be vibrated to improve flow and consolidate the mixture. This eliminates or reduces the number of voids. While vibration is necessary to consolidate the concrete, vibration can also cause water and air bubbles to move to the form face, resulting in tiny voids or holes in the concrete surface. The vibration can also cause water and fine particles to move to the surface (sometimes called bleed-water), which often results in a deposit of non-reacted cement gel at the concrete form interface. This material is called laitance, a very weak layer of fines that may extend 1/16 inch (0.06 mm) or more into the surface. It is essential that laitance and the weak surface layer be removed during surface preparation.

Most formwork is constructed using commercially available plywood, steel, or even plastic form sections that can be keyed together. Occasionally, however, plywood or wooden planks may be butted together and nailed into place. If the boards do not fit tightly together, are warped, or if the joints are loose, concrete can penetrate the cracks and harden, resulting in concrete fins. These fins must be removed after the forms are stripped and, preferably before the concrete fully cures.

Horizontal surfaces such as floors and ceilings are also formed surfaces. Floors are generally poured into limiting forms, and the upper surface of the concrete is spread using a bull float and then troweled smooth using either metal (steel or magnesium) trowels, plastic trowels, or wooden floats. As with formed surfaces, laitance may be brought to the surface during the working of the concrete. The degree of laitance is determined by the amount of excess water (bleed-water) and the degree of overworking. Ceiling surfaces are in contact with the form and take the shape of the form. The form finish determines the surface finish. Generally ceilings have less surface voids than walls and less laitance than floors.

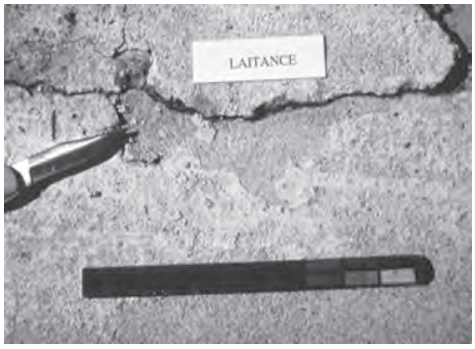


Figure 1. Laitance.

Finishing

Power-driven metal trowels are sometimes used to finish horizontal concrete surfaces. This process generally results in a harder, denser surface, which is more difficult to prepare for coating application. Steel, plastic, and wooden floats followed by broom finish can result in surfaces that can be coated with minimum surface preparation. Sometimes surface hardeners such as silicates and metal fines are used. These materials chemically react with the concrete and result in an extremely hard, wear-resistant surface that is difficult to distinguish from normal concrete. The coating manufacturer should be consulted as to the recommended finishing technique.

The minimum cure time for concrete is generally accepted as being 28 days. This cure duration is based on the time normally required for concrete to achieve sufficient physical strength to allow various trades to perform work on the concrete without damaging it. Although this is a civil/structural requirement and not a coating requirement, the 28-day cure period has been generally accepted as a limiting factor for the coating of concrete as well; however, the most important point is to assure that the concrete has the physical strength to support surface preparation activities, that the maximum cure shrinkage has occurred, and that the surface is sufficiently dry. There have been successful coating applications in shorter cure periods; however, even after 28 days, sufficient free moisture may still be present in the concrete to preclude commencing with surface preparation activities. Surface preparation of uncured concrete can result in the complete removal of the surface layer, exposing the underlying aggregate layer. This will result in extensive repair prior to standard surface preparation.

Curing

The method used to cure concrete can also be a major consideration in selecting an appropriate surface preparation technique. The curing method is designed to retain the water of hydration until such time as the water reacts (hydrates) with the cement and aggregate. Water curing is one technique. Excess water is kept in contact with the concrete for approximately two to three days (Type I Portland Cement), depending on the type and thickness of the pour. If the surface is not kept wet during the cure cycle, excessive bleed-water with uncured cement occurs as with formed and vibrated walls. Curing agents are also employed to seal the surface and hold or retain the water of hydration. These curing agents range from moisture-tolerant reactive epoxies to chlorinated rubbers and oils.

Sometimes the forms are left in place until the concrete reaches the required hardness. As stated above, these forms can be plastic, coated plywood, steel, or in some cases bare wood. When uncoated wooden forms are used, the forms generally must be pried off the hardened concrete. When this occurs, wood slivers, can be left embedded in the concrete. These must be removed, and the area repaired prior subsequent surface preparation operations.

Normally forms are coated with a bond breaker

Table 1. Typical Surface Properties of Finished Concrete.

Method	Profile	Porosity [A]	Strength [A]	Problems
Formed concrete	Smooth to medium	Low to medium	Medium	Voids, protrusions, release agents
Wood float	Medium	Medium	Medium	Very dense
Metal trowel	Smooth	Low	High	
Power trowel	Smooth	Very low	High	
Broom finish	Coarse to very coarse	Medium	Medium	
Sacking	Smooth	Low to medium	Low to high [B]	Weak layer if not properly cured
Stoning	Smooth to medium	Low to medium	Low to high [B]	Weak layer if not properly cured
Concrete block	Coarse to very coarse	Very high	Medium	Pinholes
Shotcrete [C]	Very coarse	Medium	Medium	Too rough for thin coatings

(A) These surface properties are based on similar concrete mix, placement, and vibration, and are prior to surface preparation.
(B) Strength depends on application and cure.
(C) Shotcrete may be refinished after placement, which would change the surface properties shown in this table.

(form release compounds) to facilitate removal following cure. The bond breaker can be a slick material such as Teflon, cured epoxy, or a wax or oil that is partially retained on the surface of the cured concrete. Bond breakers may result in walls being contaminated with oil, grease, or incompatible curing membranes. One other curing technique that is used primarily with pre-cast sections is steam curing. Steam curing can result in a denser, more difficult to clean surface.

Because of the weight of the concrete, forms must be braced to resist bowing or distortion. Forms can be internally braced or, as is usually the case, metal tie rods or tie wires can be used to tie the inner and outer forms together. These rods, or snap ties, are designed to be pulled out and broken off after the forms are stripped. Holes or small craters are left which must also be filled.

One prevalent concrete imperfection is called “egg shell.” This eggshell condition consists of laitance, which forms a very thin cover over pits or air pockets in the concrete, adjacent to the form concrete interface. When forms are first removed, the surface may look continuous, with only an occasional hole. Probing a small hole or visible pinhole with a rod or even the finger often reveals a sizeable hole. These holes are referred to as “bug holes” or “honeycombs.” Such areas must be opened up and patched prior to coating application. The size of the hole requiring patching is dependent on the coating or lining system selected. Thin film coatings (up to 40 mils) are especially sensitive to surface voids. The guidance provided by the manufacturer of the coating should be followed.

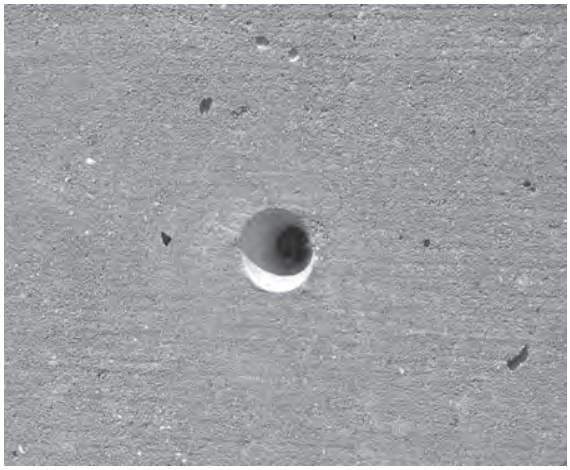


Figure 2. Tie-rod hole.

Age and Condition

For both structural concrete and concrete for flooring, the age of the concrete, including cure time also affects the timing and type of surface preparation. With increasing age, the likelihood of contamination increases. The longer the concrete remains before coating, the greater the possibility of contact with oil, grease, or soluble salt contaminates. The quantity of non-adherent cement spatter from adjacent pours may also increase with time. Old concrete, i.e., concrete that has been in service for an extended period of time, may also exhibit a variety of surface conditions. These range

from a smooth aged surface to an unsound or deteriorated surface with exposed aggregate, efflorescence, carbonation, chemical contamination, and hydrocarbon contamination.



Figure 3. Bug holes.



Figure 4. Honeycombing.

Another commonly encountered problem with old concrete is the use of water-repellent compounds that penetrate into the concrete. These materials include such chemicals as silicones, silanes, siloxanes, and siloxiranes. A water drop test can be used to assist in detecting the potential presence of these compounds; however, it may also be necessary to apply a mock-up surface preparation and coating system application followed by adhesion testing in accordance with ASTM D 4541, *Pull-Off Strength of Coatings Using a Portable Adhesion Tester*.

The adhesion strength of the coating system to the concrete substrate should be a minimum of 6 to 8% of the compressive strength. For 3,000 pounds per square inch (psi) compressive strength concrete, 180 psi would be acceptable.



Figure 5. Wet curing.

Carbonation and efflorescence are more likely to be found on concrete that has been in place for an extended time period. Carbonation results from the reaction of atmospheric carbon dioxide with the unreacted water and calcium within the concrete to form a carbonate. Excessive carbonation can lead to surface crazing or softening of the concrete's outer layer. Concrete also contains unreacted water-soluble compounds such as salts and silicates. As water from the interior of the concrete migrates through the pore structure to the surface and evaporates, these alkaline salt compounds are deposited on the surface, usually as a white stain that may degrade the adhesion of a applied coating system.

One technique, which has been proposed to check the soundness of aged concrete, is the adhesion pull-off test discussed above to determine acceptability. Adhesion test dollies are glued directly to the concrete. If the average readings of three or more tests equal 180 psi for 3000 psi concrete or more, the surface is suitable for surface preparation and coating application. The failure mechanism can also be an indication of the

concrete condition. If the failure occurs in the first 1/16-inch (0.06 mm) of depth, it may be the result of laitance, carbonation, or efflorescence. If the failure occurs within the aggregate matrix and is consistently below 180 psi, the structural integrity of the concrete may be in question. In this case, a concrete structural engineer should be consulted. In general, wall and ceiling adhesion results will be less than floor results.

Coating System To Be Applied

Once the cure is complete and the soundness of the concrete has been determined to be adequate, the coating system to be applied becomes the next determinate in selecting the appropriate surface preparation technique. The coating manufacturer includes this information in either the material product data sheet or application data sheet. These should be referred to when making the appropriate surface preparation selection.

Pre-Surface Preparation

Usually the structural or cosmetic repair of concrete will precede other surface preparation activities. Structural repairs consist of filling large voids and honeycombs, and grouting cracks larger than 0.0625 inches in width. Cosmetic repairs consist of filling of tie holes, form tie holes, snap tie cavities, rock pockets larger than 0.25 inches in diameter, and removing form nails, embedded form material, and tie wires, etc. Concrete repair is a separate operation from concrete finishing and surfacing. Many times the craft that repairs and finishes the concrete is different from the craft that applies the surfacer or the coating. Different standards may apply for the quality of repair grouting. The patch grout must be compatible with the specified coating. The degree of surface preparation used for concrete repair must be appropriate to the coating system to be applied. For this reason, coordination between the concrete finishers and the coatings applicators is a necessity.

Sometimes sacking is used to finish the concrete. Sacking consists of rubbing a mixture of cement and sand wet with minimal water into the surface to fill surface voids. The amount of rubbing or sacking plus the correct ratios of sand, cement, and water are important. The skill level of the worker performing the activity is also critical. This activity, if allowed, must be correctly accomplished, but may not be appropriate for some high performance coating systems. Sacking and cementitious grouting is best accomplished while the concrete is still green but sufficiently hard to support the necessary activities. Once concrete repairs are complete and properly cured, the next step is to remove fins, protrusions, bulges, and similar surface defects higher than 1/16 inch (0.06 mm) followed by removing surface contamination.

Removing Surface Contaminates

Surface contaminates consist of dirt, oils, and greases and soluble salts. Several methods are available to determine the presence of oil and grease contamination. One such method uses a water drop. If the water beads on the surface and does not wet the concrete there is a good chance that the concrete is contaminated.

A second method to check if oil or grease are present uses a heat source such as an incandescent light bulb. The lamp is placed approximately six inches above the surface to raise the surface temperature to 140°F. Oil or grease contamination will appear as a greasy film under the source. Ultraviolet (black) lights are also sometimes used to determine the presence of oil or grease contamination; however, not all hydrocarbon materials will glow under ultraviolet light. This procedure is performed is darkness.

Oil and grease deposits cannot be removed from concrete by power tool cleaning and abrasive blasting any more than they can be removed from a steel surface using these techniques. The contaminants will merely be driven deeper into the concrete by blasting. Because solvents may carry the oil deeper into the concrete, detergents or emulsifying agents are recommended for chemical cleaning prior to abrasive blasting. Detergent washing, hot water caustic washing with trisodium phosphate, steam cleaning, and in limited cases, solvent wiping are used for removing oil or grease. Two pounds of trisodium phosphate (TSP) per gallon of water applied at a temperature of 160°F has been successfully used. In areas where the use of trisodium phosphate use is restricted, substitute phosphate-free detergent products.

Proprietary cleaners are also available to remove organic contamination from concrete. Remembering that concrete is porous and subject to solvent penetration, directions for use must be strictly followed.

Allowing some cleaners to remain on the surface for too long may drive oil deeper into the surface instead of floating the oil to the surface for

removal. Allowing cleaners to dry on the surface can also worsen the problem.

Being porous, concrete is also an ideal surface for mildew, moss, and other biological growth. Mildew and biological growth can be removed using a 1 to 5 percent solution of sodium hypochlorite (dilute one part 5.25% household bleach with three parts water). The bleach solution should be applied to the contaminated surface using a pressurized garden sprayer or other application technique.

The surface should be thoroughly wet and allowed to stand for 24 hours or until the growth is no longer visible. More than one application may be necessary to kill all organisms before rinsing with fresh water.

When chemical cleaners are used, provisions must be made to prevent harmful cleaning solutions and rinse water from environmental spillage from entering the plant drainage system.

Soluble salts such as chlorides and sulfates can be removed by water washing. One effective technique is to use a hot (140°F to 180°F) water pressure washer. Since soluble salts have a tendency to be absorbed into the porous concrete, this process may require multiple attempts.

Surface Preparation Techniques

Following the removal of surface contamination, the next operation consists of surface preparation. Concrete surface preparation techniques can be divided into two general categories: mechanical and acid cleaning. As discussed earlier, the concrete must be free of oil and grease or other penetrating materials.

Laitance, efflorescence, incompatible form release agents, curing compounds, and similar materials are to be removed and the surface texture (profile) created as recommended by the coating manufacturer. Generally the surface roughness required for high performance coating systems should be representative of 40 to 60 grit sandpaper.

The profile may be evaluated by comparing the resultant profile with the profile of graded abrasive paper in accordance with ANSI B74.18, *Specification for Grading of Certain Abrasive Grain on Coated Abrasive Products* or by comparing the profile with International Concrete Repair Institute (ICRI) Guideline No. 03732, *Selecting and Specifying Concrete Surface Preparation for Sealers and Polymer Overlays.*

Mechanical

Mechanical methods include:

- Compressed air “blow-down”
- Abrasive blasting
- Impact tools
- Wire brushes (power and hand)
- Grinders and disc sanders
- Water blasting

Compressed air. Loose dirt and dust can be removed by sweeping, vacuuming, high pressure (100 psig) air “blow down,” or water hosing. Wire brushing may be necessary for tight dirt and contamination. For many architectural and some high performance systems pre-surface preparation and compressed air “blow-down” are adequate. The use of curing agents, hardening agents, and steam curing may result in a surface incompatible with the selected coating system and may require removal. Again the coating manufacturer should be consulted for specific recommendations.

Abrasive blasting. Standard open-air blast, wet abrasive air blast, vacuum air blast, and contained centrifugal wheel blasting can accomplish abrasive blasting of concrete surfaces. Each technique has advantages and limitations. In addition to removing contamination, removing the weak surface layer, and providing a suitable surface texture, abrasive blasting will also open surface voids.

Conventional abrasive air blasting can be accomplished using the same equipment that is used for steel surface preparation. Selection abrasives by following the same guidelines used for steel. (See *SSPC Volume 2: Surface Preparation Specifications—Surface Preparation Commentary.*) Ambient humidity checks are not as important as in steel blasting; however, abrasive blast media checks for contamination such as oil are just as important as in steel blasting.

A sweep blast is sufficient in most instances; however, since concrete is not uniform in surface hardness, care must be taken to avoid over blasting and gouging. It is also extremely critical that each square inch of the surface be contacted by the blast pattern. An improper sweep blast contacts only a portion of the surface, resulting in an irregular pattern. The surface texture must be relatively uniform over the entire surface area cleaned. Generally, the blast nozzle is held further away from the concrete surface being cleaned than would be the case with steel. As stated

earlier, concrete should be cured sufficiently before abrasive blasting is performed, so that the surface is not damaged by surface preparation. Over blasting will result in aggregate, and sometimes, rebar exposure. Surface voids should be open with rounded edges.

SSPC-SP 7, *Brush-Off Blast Cleaning,* is sometimes referenced in specifications for preparing concrete. This standard was specially developed for cleaning steel; tightly adherent paint is allowed to remain. Intact coatings may not be appropriate for many concrete applications. If used, an explanation should be added to the specification defining exactly the cleanliness of the resultant surface and the degree of roughness (profile).

Abrasive blasting concrete can produce clouds of dust. For this reason, wet abrasive blasting is sometimes used. In addition to the standard types of mineral abrasive used in steel surface preparation, water-soluble abrasives such as sodium bicarbonate are also used. It is more practical to use wet blasting methods on concrete surfaces than on steel surfaces since no corrosion inhibitors are needed for concrete surfaces.

There are two basic types of wet abrasive blasting techniques. One uses compressed air to propel the abrasive. Water is injected to eliminate dust. The water injection equipment is sometimes called water-entrained abrasive blasting. This process uses a conventional abrasive blasting pot. In some cases a special nozzle that contains a mix chamber for the addition of high-pressure, low-volume water (1/2 to five gal./min., or gpm) is used. The abrasive exits the nozzle wet.

The second type uses high-pressure water as the propellant. Abrasive is included in the water stream. This recent development mixes water into the abrasive in the blast pot. Yet another type of equipment, referred to as slurry blasting, injects abrasive into a high-pressure (5,000 to 20,000 psig) water stream (five to twenty gpm) without air. In all cases the abrasive is wet and free of most dust.

Equipment is also available that wets the abrasive after it exits from a conventional nozzle. Some are fitted with a simple water ring or donut. The abrasive is wet after leaving the blast nozzle. When using wet abrasive blasting techniques, exercise care in the timely removal of the wet abrasive residue from the surface. If allowed to dry, the residue is difficult to remove.

Abrasive blasting techniques can also consist of self-contained pneumatic blast units with vacuum recovery. These units are virtually dust free. The pneumatic unit consists of a conventional air blast nozzle surrounded by a vacuum recovery shroud. The abrasive and generated dust is drawn through a filter unit or dust collector, and the residue deposited into a container for disposal. These units are generally bulky and difficult to use in confined areas. Special nozzles and nozzle shrouds are available to facilitate cleaning in corners, and around attachments.

Self-propelled centrifugal wheel blast units use recycling steel shot (170 up to 460) and a dust collection system. These machines are extremely effective on flat surfaces for removing laitance as well as existing coatings, but are not suitable for walls or overheads. The areas around foundations and adjacent to walls require supplemental cleaning techniques because the wheel blast units can only clean surfaces up to one-half inch from the floor to wall intersection.

Table 2. Some Types of Abrasive Blast Cleaning.

Some Types of Abrasive Blast Cleaning
Conventional Open Dry Blast Cleaning
Water-Entrained Compressed Air Blast Cleaning
Vacuum Blast Cleaning
Centrifugal Wheel Blast Cleaning
High Pressure Water with Injected Abrasive
Slurry Blast Cleaning
Wet Soluble Abrasive Blast Cleaning
Wet Ring or Donut Abrasive Blast Cleaning

Power tools. Another method of abrading concrete surfaces is with power or hand tools. Power tools are divided into two types—impact and grinding. Many manufacturers are fitting tools with effective vacuum recovery to reduce the volume of dust. Generally these vacuum tools are more bulky and difficult to maneuver; however some are fitted with backpacks to contain vacuumed dust. Some machines are self-propelled, but are generally only effective on flat, horizontal surfaces. As in the blasting of steel, the air source should be checked periodically for the presence of oil.

Impact tools are capable of removing laitance, glaze, efflorescence, and incompatible curing compounds, as well as fins and sharp projections. Some impact tools include scabbling, rotary peening, or scarification. These tools, while capable of accomplishing the same task as abrasive blasting, generally result

in a courser, deeper surface texture (profile). Scarification is also used to remove excessive layers of contaminated concrete. Surface preparation may be accomplished by vertical impact (needle guns), rotary impact (bush hammer), or rotary peening (tungsten carbide shot brazed to a hardened steel rivet and supported by a flexible material), depending on the type of equipment used.

Since each type of tool is capable of producing only a limited range of textures or profiles, a determination is required in advance to assure that the machine selected will produce an acceptable surface texture (profile). It is also critical that the equipment not damage the concrete surface, such as can happen with large, blunt needles in needle gunning.

Some impact tools have been reported to fracture the underlying concrete structure. The potential tool should be evaluated prior to use. One proof test is to prepare and coat a representative area followed by an adhesion pull-off test such as ASTM D4541, *Pull-Off Strength of Coatings Using Portable Adhesion Tester* or by following one of the procedure listed in SSPC-SP 13/ NACE 6, *Surface Preparation of Concrete.*

If pull sample fractures within the concrete at a value less than 6 to 8% of the tensile strength of the concrete, additional evaluation is required.

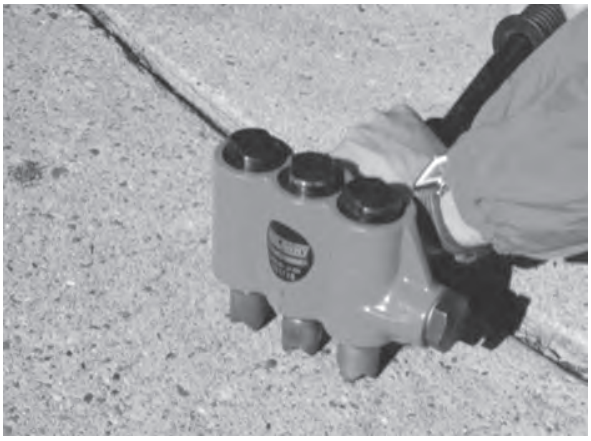


Figure 6. Impact tool.

Impact tools. Impact tools can be effective in restoring old concrete floors that have been severely attacked by corrosive chemicals. Usually, the disintegrated concrete is removed by scarification down to sound concrete. Then, a new surface is poured to bring the floor up to its original grade.

Epoxy bonding agents are often used to assure a bond between the old and new concrete. After the concrete is repaired, the usual methods of surface preparation are employed prior to coating.



Figure 7. Needle scaler.

Power wire brushes. Though not truly a grinding tool, power wire brushes do scour the surface. Both power and hand-held wire brushes are used for removing loose contamination. The surface is polished and no surface profile is produced. These tools are better suited to removing deposits of mud and dirt.

Grinders and sanders. Hand-held grinders and sanders perform on concrete in a similar manner as on steel except that the grinding tool may load up with concrete residue, thus reducing the effectiveness of the grinding action. These tools are primarily used to remove existing coatings or to roughen up old coatings for recoating. One limitation is that the grinding media rides over and is restrained by the high point within the uneven concrete substrate. Material is not removed from between the high points. The resultant surface may have a detectable etch but is normally smooth and unsuitable for most coating applications. The primary limitation is slowness of operation in comparison to abrasive or water blasting. This technique is normally limited to small, difficult to reach areas or recoating activities.

Larger walk behind units can remove adhesives and coatings by using tungsten carbide slicing blades and diamond plugs or discs. Some units offer floating attachment points for the tools and will com-

pensate for most of the floor's unevenness. The surface is left with a noticeable etch, which is suitable for adhesion of subsequent coatings. These units are intended for larger areas and can polish the surface quite smooth when required or remove thick layers of coatings when needed.

High-pressure water blasting. Water cleaning is generally divided into four categories: low- pressure water cleaning, high-pressure water cleaning, high-pressure waterjetting, and ultrahigh pressure water blasting or waterjetting. This is discussed in depth in a separate chapter.

SSPC-SP 12/NACE 5, *Surface Preparation of Steel and Cleaning of Steel and Other Hard Materials by High- and Ultrahigh-Pressure Water Jetting Prior to Recoating,* covers the use of water blasting as a surface preparation technique. This standard is primarily directed toward paint removal from steel surfaces but can be used a starting point for high pressure water cleaning of concrete.

Table 3. Water Blast Pressure Ranges.

Type of Water Blast	Pressure Range
Low Pressure Water Cleaning	< 5000 psig
High Pressure Water Cleaning	5000 to 10,000 psig
High Pressure Waterjetting	10,000 to 25,000 psig
Ultra High Pressure Waterjetting (Blasting)	>25,000 psig

Flame Cleaning

Another technique, which has not found wide use, is flame cleaning. Flame cleaning consists of the rapid heating of the top layer of the concrete resulting in the formation of trapped steam that expands and removes a layer of the substrate. The water exists either as pore water or the surface is wet prior to flame cleaning. Care must be exercised to preclude damage to the underlying concrete structure. Profile cannot be controlled.

Acid Cleaning

Because concrete is an alkaline (high pH) material, acids are used for cleaning and etching concrete. Acid cleaning will not evenly remove old coatings, sealers, or curing membranes. If present, the material will insulate the concrete from the acid. These materials must be removed by mechanical means. A concrete surface to be acid-etched must also be free of water proofing, sealers, grease, oil, and similar contaminants.

Acid etching of horizontal concrete surfaces using hydrochloric (muriatic) acid, sulfamic acid, phosphoric acid, or citric acid creates a surface texture (profile) or tooth suitable for the adhesion of coatings to concrete floors or slabs plus opens the surface, increasing porosity. Acid etching on vertical concrete surfaces is neither practical nor recommended. When acid is being used, care must be taken to protect the operator from both the liquid and the fumes. Proper safety precautions must be exercised.

The concentration of the acid solution varies, depending on the concrete texture and degree of etching needed. Hardened or very slick steel-trowel floors, for example, may require a higher concentration of acid to effectively break the surface glaze.

Muriatic acid can be purchased in concentrated forms up to 37%. The acid is then diluted one part acid to four parts tap water. More or less concentrated solution is also acceptable. Always add acid to water and not water to acid, as a violent reaction will take place resulting rapid boiling and splash. Many nuclear power plants have used the safer citric acid (20% to 25% weight solution of citric acid in water) to reduce some of the hazard. Phosphoric acid is normally used at 10% solution.

The area to be acid cleaned is first marked off in sections and wet with water. Standing water must be removed. The acid solution is then applied and allowed to bubble. Areas not showing bubbling of the acid indicate some contaminant on the surface that prevents contact. Some very dense, smooth surfaces may need more than one application of acid. The acid solution should be kept agitated with a broom or other technique to maintain fresh acid contact with the surface.

The most important requirement in acid etching is surface cleaning after the acid etch. The spent acid, together with the salts formed by the reaction, must be completely removed by scrubbing with a stiff-bristle broom or brush and copious water rinsing. The final rinse water should be checked for neutral pH (6.5 to 7.5) before the surface is allowed to dry to verify that all acid residues have been removed. A properly etched surface should have the texture of fine to medium (60 to 80 grit) sandpaper.

Where stainless steel pipe, brackets, or similar

items might be exposed to the acid, such as in a nuclear plant, hydrochloric acid cannot be used. Citric, sulfamic, and phosphoric acids contain no chlorides and are permissible. Citric acid has the advantage of being biodegradable and in many locations can be flushed down the drain. Citric acid is available in powder form and 50% concentration in water.

Citric, sulfamic, and phosphoric acids react more slowly with the alkalinity in the concrete than does the hydrochloric acid but will normally sufficiently etch the surface. Hydrochloric acid cleans within three to five minutes, phosphoric within ten to fifteen minutes, and citric acid within twenty minutes at 75°F. As with most chemical reactions, the rate of the reaction is dependent on temperature. The higher the temperature; the faster the chemical reaction; however, the upper temperature limit should be based on both safety considerations and thermal decomposition of the acid.

Following acid cleaning, the concrete may require neutralization. This is accomplished by washing the surface with a 5% solution of soda ash (sodium carbonate), trisodium phosphate, or potash (potassium carbonate). The solution should be allowed to stand for ten minutes followed by a fresh water rinse. The concrete must be neutral or slightly caustic. The surface neutrality should be checked with pH paper to achieve a pH of 7 to 9 in accordance with ASTM D 4262, *Test Method for pH of Chemically Cleaned or Etched Concrete.* If neutralization is not achieved, the caustic and fresh water rinse must be repeated.

Table 4. Steps in Acid Cleaning Concrete.

Steps in Acid Cleaning Concrete
1. Check for presence of sealers or waterproofing compounds
2. Remove oil and grease contamination using trisodium phosphate or other approved cleaning agent.
3. Mechanically remove loose dirt, laitance, and any sealers and waterproofing compounds
4. Apply acid and keep agitated
5. Neutralize unreacted acid
6. Rinse with copious quantities of water
7. Check surface neutrality

Standards for Cleaning Concrete

There is no industry-wide concrete cleanliness standard that defines required degrees of surface preparation cleanliness as exists with steel. The specification writer can define the allowable surface preparation technique by referencing one of the ASTM standards discussed in this section. In addition, SSPC-SP 1/NACE 6 contains guidelines for inspection prior to surface preparation, surface preparation procedures, and acceptance criteria. Surface profile (texture) is discussed but not established. The specification does establish the requirement to remove surface "contamination, form-release agents, efflorescence, curing compounds, and existing coatings determined to be incompatible with the coating system to be applied." Acceptance criteria distinguish between "light" and "severe" service.

Table 5. Standards for Cleaning Concrete.

Standard Number	Title
SSPC-SP 13/NACE 6	Surface Preparation of Concrete
ASTM D 4258	Standard Practice for Surface Cleaning of Concrete for Coating
ASTM D 4259	Standard Practice for Abrading Concrete
ASTM D 4260	Standard Practice for Acid Etching Concrete
ASTM D 4261	Standard Practice for Surface Cleaning of Concrete Unit Masonry for Coating
ASTM D 4262	Test Method for pH of Chemically Cleaned or Etched Concrete Surfaces
ASTM D 4263	Test Method for Indicating Moisture by the Plastic Sheet Method
ASTM F 1869	Test Method for Measuring Moisture Vapor Emission Rate of Concrete Sub floor Using Anhydrous Calcium Chloride
ICRI No. 03732	Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays

ASTM has prepared several standards for cleaning concrete surfaces. The scope of ASTM D 4258, *Standard Practice for Surface Cleaning Concrete for Coatings,* includes surface cleaning of concrete to remove grease, dirt, and loose materials prior to coating. The practice is not intended to alter the surface profile. Procedures are included for broom cleaning, vacuum cleaning, air blast cleaning, and water cleaning including scrubbing with detergents.

ASTM D 4259, *Standard Practice for Abrading Concrete,* takes the concrete surface preparation one step further by providing for a surface etch or profile. The intent of the standard is to provide for the removing a sufficiently thick surface layer in order to achieve a sound concrete surface free of laitance, glaze, efflorescence, and incompatible concrete curing compound or form-release agents. Included in the allowable tech-

niques are mechanical impact, water blasting, and abrasive blast cleaning. The surface is to have the roughened textured appearance required by the manufacturer of the coating or lining system to be applied.

ASTM D 4260, *Standard Practice for Acid Etching Concrete,* allows for the use of muriatic, sulfamic, phosphoric, and citric acids. The standard states that the concrete surface should be pre-wet with water and acid added as required. The resultant surface condition must also meet the coating manufacturer's requirements for profile. The procedures are very similar to those discussed in this chapter.

The International Concrete Repair Institute (ICRP) Guideline No. 03732, *Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays,* also provides guidelines for preparing concrete for coatings application. Being a guideline, the requirements do not serve as a standard; however, the guide does define nine categories of concrete surface profiles (CSP), ranging from acid etching, grinding, and abrasive blasting to heavy scarification. This guide also discusses many of the techniques for performing surface preparation.

As can be seen from this discussion, concrete presents a much more varied surface than carbon steel when considering surface preparation options and techniques. Both the chemical and physical properties of the concrete substrate must be considered to determine which chemical and physical surface preparation techniques are best suited to the appropriate surface preparation.

Suggested Reading

The Fundamentals of Cleaning and Coating Concrete; Randy Nixon and Richard Drisko, eds.; SSPC: Pittsburgh, 2001.

NACE 6G191 *Surface Preparation of Contaminated Concrete for Corrosion Control;* NACE: Houston.

The Inspection of Coatings and Linings; Bernard S. Appleman, ed.; SSPC: Pittsburgh, 1995.

ASTM D 4541 *Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers;* ASTM: West Conshohocken, PA.

ASTM D 4263 *Test Method for Indicating Moisture in Concrete;* ASTM: West Conshohocken, PA.

ASTM F 1869 *Test Method for Measuring Moisture Vapor Emission Rate of Concrete Subfloor Using Anhyhrous Calcium Chloride;* ASTM: West Conshohocken, PA.

Protective Coatings Glossary; Richard Drisko, ed.; SSPC: Pittsburgh, 2000.

ASTM D 4258 *Practice of Surface Cleaning Concrete for Coating;* ASTM: West Conshohocken, PA.

ASTM D 4259 *Practice of Abrading Concrete;* ASTM: West Conshohocken, PA.

ICRI Technical Guideline 03732 *Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays;* International Concrete Repair Institute, Sterling, VA.

ICRI Technical Guideline No. 0370 *Guide for Surface Preparation for Repair of Deterioted Concrete Resulting from Reinforced Steel Corrosion;* International Concrete Repair Institute, Sterling, VA.

SSPC-SP 7/NACE 4 *Brush-Off Blast Cleaning;* SSPC: Pittsburgh and NACE: Houston.

SSPC-TR 2/NACE 6G198 *Wet Abrasive Blast Cleaning;* SSPC: Pittsburgh and NACE: Houston.

SSPC-SP 12/NACE 5 *Surface Preparation and Cleaning of Steel and Other Hard Materials by High- and Ultrahigh-Pressure Waterjetting Prior to Recoating;* SSPC: Pittsburgh and NACE: Houston.

SSPC-SP 13/NACE 6 *Surface Preparation of Concrete;* SSPC: Pittsburgh and NACE: Houston.

SSPC-Guide 11 *Guide for Coating Concrete;* SSPC: Pittsburgh, 1997.

SSPC-TU 2/NACE 6G197 *Design, Installation, and Maitenance of Coating Systems for Concrete Used in Secondary Containment;* SSPC: Pittsburgh and NACE: Houston.

NACE Standard RP0591-96 *Coatings for Concrete in Immersion and Atmosheric Services;* NACE: Houston.

ASTM D 4260 *Practice for Acid Etching Concrete;* ASTM: West Conshohocken, PA.

ASTM D 4262 *Test Method for pH of Chemically Cleaned Concrete;* ASTM: West Conshohocken, PA.

About the Author

Benjamin S. Fultz

Benjamin Fultz has over 30 years experience as a paints, coatings, and nonmetallic materials specialist. Currently a Bechtel Fellow in Bechtel's Houston office, he has also worked as a formulating paint chemist and has held positions in production and engineering. He is a member of SSPC, NACE, and ASTM and served as a contributing editor to the *Journal of Protective Coatings and Linings.* Mr. Fultz holds a BS degree in chemistry.

Chapter 3.2
Surface Preparation of Nonferrous Surfaces

Norm Clayton

Introduction

While steel is the predominant material of construction requiring industrial painting practices, there are significant uses of other painted substrates in industrial, military, and architectural structures. These include nonferrous metals such as aluminum alloys, copper alloys, nickel alloys and stainless steels, and nonmetallic materials such as wood- and polymer resin-based composites. Other commonly used composites include fiberglass, fiber-reinforced plastic (FRP), and glass-reinforced plastic (GRP). Concrete and masonry represent another major type of nonmetallic industrial material that is frequently painted, but that topic is covered in more detail in a separate chapter.

Steel alloys and cast irons are termed "ferrous" materials because the major alloying element in them is iron. The chemical symbol for iron is "Fe," which comes from the Latin name for iron *ferrum;* hence the term "ferrous." Nonferrous metals are therefore alloys that either do not contain any iron, or those that contain less than 50% iron as one of their alloying elements. Strictly speaking, by this definition most grades of common stainless steels are ferrous materials, although many may call them nonferrous, especially the grades that are not magnetic. Because they have special surface preparation considerations compared to carbon steels, stainless steels are discussed in this chapter.

It is fairly common knowledge that painting wood structures slows their deterioration and makes them last longer. But nonferrous metals and alloys are generally more corrosion-resistant than steel, and composite materials do not corrode at all in the sense that metals do. So why paint these materials? There are a variety of reasons:

• Corrosion protection is still required when these materials are used in immersion service, or in various types of environments where they will be exposed to chemicals or chemical fumes.

• Painting may be performed for cosmetic reasons, either for the aesthetics of matching a surrounding paint scheme, or for color-coding of piping or ducting according to type of service.

• In situations where dissimilar metals are used together in immersion, it is often good corrosion control practice to paint the cathodic material (the one less prone to corrosion) in order to minimize the amount of its bare surface area and therefore help minimize the effects of galvanic corrosion.

• The surface of the structure to be painted may have various functional requirements. These include such diverse properties as being fire retardant, slip resistant, condensation resistant (anti-sweat), resistant to biofouling, and for military equipment in particular, camouflage and signature reduction.

• Painting nonmetallic composite materials used in exterior or immersion service helps protect them from degradation caused by ultraviolet radiation in sunlight, and helps to prevent moisture absorption that can damage and weaken composites.

In terms of uses for nonferrous materials, there are many structures and structural members that are made from aluminum alloys, wood, and composites. The variety of nonstructural components that are painted is as wide as the variety of facilities that they are in: buildings, factories, chemical plants, power and water utilities, aircraft, ships, and offshore structures to name a few. Typical painted nonferrous components can include piping and piping system components, ductwork, tanks, storage and electrical cabinets and enclosures, and walkways and gratings.

The inherent differences in materials, structures, and components helps to define the differences that can be expected in surface preparation methods, materials, and tools. With the exception of stainless steels, steel alloys are generally much harder than nonferrous metallic and nonmetallic materials, and are also frequently used at a greater thickness. There are

further significant differences in the surface preparation of steels and nonferrous materials for new construction and existing structures. New nonferrous materials will not have hard mill scale on the surface like new steel. Corrosion of existing steel structures produces rust on the surface that ranges from tightly adherent layers immediately at the surface, to looser, thick voluminous scale.

While aluminum alloys can produce a voluminous white-gray corrosion product under certain conditions in service, there is generally no equivalent to the thick rust scale on any nonferrous surfaces. The general philosophy that surface preparation should only be aggressive enough to clean the surface and produce any desired profile, and should minimize the removal of sound material, is especially true for nonferrous materials. The ability to do this while preventing contamination of softer nonferrous materials is the focus of this chapter.

Surface Preparation Process

The goals of surface preparation on nonferrous materials are generally the same as those on steel surfaces: remove contaminants, obtain a specified cleanliness level, and obtain a surface roughness profile or other surface condition that will enhance adhesion of a coating system. Therefore, the same sequence of steps generally applies, for both new construction and maintenance painting:

• Sharp edges, burrs, and weld spatter are all potential sources of premature coating failure on aluminum and other metallic surfaces, just as they are for steel. Rounding edges, de-burring, removing weld spatter and similar precautions should be taken prior to coatings work.

• Pre-cleaning to remove oils and greases, in order to prevent them from being embedded in a surface by subsequent hand and power-tool or abrasive blast cleaning methods. This also prevents contaminating tools and blast media. Solvent cleaning, which could include steam cleaning and detergent cleaning, is used for this step.

• Clean to specified cleanliness level using hand or power tools, abrasive blasting, waterjetting, or other, more specialized processes.

• Post-cleaning to remove and collect dust, paint chips, and other debris that may be lying on the surface after the previous cleaning method.

One important difference in the goals of surface preparation on many types of nonferrous structures and components arises in maintenance repainting. Frequently, stripping the old paint from the surface while doing little or no damage to the substrate or any chemical pre-treatment films is the main objective, especially for commercial and military aircraft and other sensitive equipment made from aluminum alloys and composite materials. It is a significant challenge to complete the job in a manner that is both economical and environmentally friendly. This has led to the development of several specialized surface preparation techniques that will be described later in this chapter.

Surface Preparation Inspection Methods

The quality assurance (QA) checks and tests that a coating inspector performs during the surface preparation phase of an industrial coatings job involving nonferrous surfaces will similar to those used for steel surfaces, with a couple of important differences that should be accounted for in a good coating specification.

• Environmental conditions such as relative humidity, dew point, and surface temperature may still need to be measured and monitored. Magnetic surface temperature gauges will not stick to nonmagnetic nonferrous materials, so they may need to be held in place with tape. Of course, make sure that any residual adhesive from the tape is removed from the surface before painting. Another alternative is to use a noncontact surface temperature-measuring instrument.

• Surface profile on nonferrous metallic surfaces can generally be measured the same way, using the common profile tapes described in ASTM D 4417.[1]

• The definitions of surface cleanliness levels pose significant differences between steel and nonferrous surfaces. The well-known industry standards published by SSPC for hand and power tool cleaning, abrasive blasting, and waterjetting or hydroblasting are specific to steel surfaces. The written definitions can be slightly modified in a job specification to account for corrosion products other than rust. Terms such as “equivalent to”

may be used, as in: “abrasive blast aluminum surfaces to a near-white metal condition equivalent to SSPC-SP-10,” but this is not ideal, as it can be subject to interpretation. If waterjetting or wet (slurry) blasting is used for cleaning, the definitions of light, moderate, and heavy flash rusting contained in the standards will not apply.

• Currently available sets of industry visual reference photographs for surface cleanliness as contained in SSPC-VIS-1 (abrasive blasting), SSPC-VIS-3 (hand and power tool cleaning), SSPC-VIS-4 (waterjetting), and SSPC-VIS-5 (wet/slurry blasting) are exclusive to steel surfaces and cannot be used.[2, 3, 4, 5] Facility owners that frequently specify painting of nonferrous surfaces can create their own custom sets of reference photographs for the surface being treated, and invoke their use in a contract or specification.

• Measuring residual surface salts on prepared non-errous metallic materials prior to painting may still be required, especially for structures subject to immersion in fresh or salt water or exterior atmospheric exposure. The methods of salt extraction, and their measurement by either chemical or conductivity techniques, will be similar to those used on steel surfaces.

• Wood surfaces may require a test for moisture content prior to painting. This type of testing will be described later in this chapter.

Specific Surfaces

Hand and power-tool cleaning, abrasive blasting, hydroblasting, and other common surface preparation methods are referred to in discussions here but discussed in detail in other chapters of this book. The intent of this chapter is to highlight key differences in these techniques as they are applied to nonferrous substrates. More specialized surface preparation methods will be described in the next section.

Aluminum Alloys

The surface preparation of aluminum alloys can be divided into three general categories that generally align with the type of structure being painted. Mechanical cleaning methods such as hand and power tools and abrasive blasting can be used on heavy, thicker structures. Nonmechanical, nonabrasive chemical cleaning and pre-treatments are frequently used on thinner sheet metal structures and surfaces of components that will be exposed to less demanding environments and do not require high-performance coating systems. These pre-treatments are also used to support high production rate component coating operations on assembly lines. A variety of methods that can selectively strip existing paint without affecting the substrate or previously applied surface pre-treatment films comprise the third category.

The key to successful mechanical cleaning of aluminum is to avoid excessive metal removal and prevent contamination. Most hand tools used on steel, such as scrapers and chipping hammers, tend to gouge and mar aluminum very easily. One exception is wire brushes; however, special precautions exist for their use. Wire brushes used on aluminum should have stainless steel bristles, in order to prevent contamination of the aluminum with iron. Likewise, these brushes should be designated only for use on aluminum in order to avoid cross-contamination and embedding steel particles in the aluminum. This is because free iron and steel contaminants can rust quickly, and cause the coating to fail prematurely in these spots. Wire brushes and other tools must also not be made from any copper alloys, and must not have been previously used on copper alloys or copper-pigmented paints. The copper-aluminum dissimilar metal combination results in very severe galvanic corrosion of aluminum.

Abrasive mats, papers, and cloths can also be used on aluminum alloys for sanding to remove corrosion products and loose paint, and for feathering the edges of surrounding tightly adherent paint. Aluminum oxide is effective for light corrosion products, and silicon carbide for heavier corrosion. Steel, aluminum, copper, and stainless steel wools are available for hand cleaning. Only aluminum wool should be used on aluminum substrates. As with wire brushes, all of these materials should be reserved for use on aluminum alloys only, in order to prevent cross-contamination.

Power-tool cleaning can be performed on aluminum alloys, using power wire brushes, flap brushes, and orbital sanders. Since these tools generally do not produce a significant surface profile, careful needle-gunning or roto-peening can supplement them on thicker structures. If contamination occurs or is suspected, the surface should be cleaned

prior to painting. For example, Navy ship requirements call for washing with a moderately alkaline detergent (specification MIL-C-85570 Type II), followed by fresh water rinsing.[6] The cleaned surface must be completely dry before painting. Strong alkaline cleaners are usually corrosive to aluminum alloys, and should be used with care or not at all.

Abrasive blasting can be performed on aluminum alloys, provided that the blast media is not too aggressive and does not contaminate the surface, and that blast pressures are reduced to account for the softer surface. When abrasive blasting is performed in order to remove corrosion products and obtain a profile, 80-grit aluminum oxide or garnet are frequently specified abrasives, at pressures of 60-70 psi. Aluminum oxide, Al_2O_3, may also be called alumina, corundum, or emery, depending on whether the abrasive was naturally occurring or manufactured. Steel shot, chilled iron, and metal smelting slags, especially those that contain copper, must not be used as abrasive media on aluminum, since they will cause contamination. Hard, angular abrasives can easily become embedded in aluminum at high blast pressures, as illustrated in **Figure 1.** These embedded particles can be sites for local coating failure. Sponges that have bonded aluminum oxide or garnet abrasive in them can be used on aluminum. The terms “brush blasting” or “sweep blasting” to cleanliness levels comparable to SSPC-SP-7 are sometimes used, and this method is recommended for contamination that cannot be removed by detergent washing.[7]

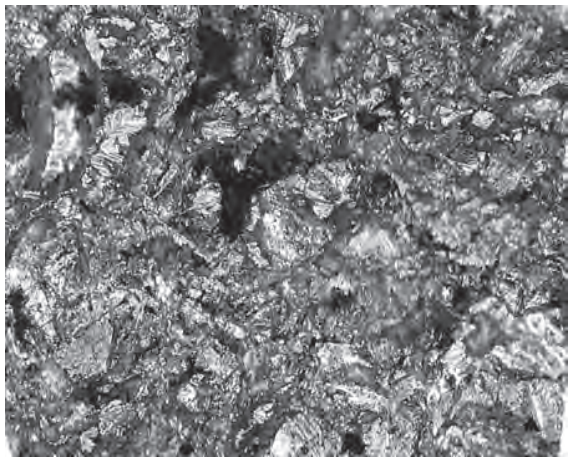


Figure 1. Particles of hard mineral abrasive embedded in aluminum. U.S. Navy Photograph courtesy Jeff Duckworth.

Hydroblasting, or waterjetting, has also been used on aluminum surfaces, ranging from complete biofouling and coating removal and cleaning of underwater hulls, to paint stripping on sensitive aircraft surfaces. It is considered a cleaner technology than those that use abrasives or chemicals, since there are no abrasives or hazardous chemicals to dispose of, no hazardous air pollutants (HAPs) or volatile organic compounds (VOCs) as with many chemical strippers, and the water can be treated and recycled. Depending on the actual pressure and how the equipment is used, hydroblasting can damage softer materials. In addition, it can damage joints and sealants in assemblies, so some masking may be required.

Mild abrasives are used for paint stripping where one of the primary goals is to have little or no risk of substrate damage. This is frequently the case when repainting aircraft. Abrasives used for this purpose can include agricultural products, such as walnut shells, peach pits, corn cobs, and wheat-starch, and manufactured abrasives, such as pellets of plastic media, glass beads, sodium bicarbonate, and carbon dioxide (CO_2), or dry ice. The driving force behind the development and use of many of these alternative paint stripping methods has been to find substitute processes for chemical strippers, methylene chloride in particular. Methylene chloride had been used for many years by the commercial and military aerospace communities for paint stripping. However, in 1986 it was added to the National Toxic Products list of chemicals that are suspected of causing cancer.[8]

Plastic media blasting (PMB) has been in use since the early 1980s, and has been widely used for aircraft paint stripping, and applications on sensitive components.[8,9] The media can be made from a variety of polymeric materials, which include: polyester; urea, melamine, and phenol formaldehydes; acrylic; and a starch-acrylic. Military specification MIL-P-85891[10] describes requirements for the plastic media specifically intended for the removal of organic coatings. Plastic media defined in this specification have varying levels of hardness and aggressiveness to surface, as measured by weight loss from a magnesium test coupon. MIL-P-85891 advises that “the visual appearance of surfaces stripped using this media can vary from no discernible effect to extensive erosion damage.”[10] Therefore, the type of PMB should be carefully matched to the substrate being treated, and process parameters such as media recycling, and nozzle

pressure, angle, and distance need to be evaluated. Furthermore, some of the plastic media can leave a residue on the surface that may require cleaning with a detergent wash or solvent wipe. Acrylic media is commonly used to strip paint from metallic surfaces of U.S. Navy aircraft.[9]

PMB can be performed in glove-box cabinets, in blasting booths, or in large contained areas such as airplane hangers. Typical pressures used are around 40 psi, considerably less than those used for conventional blast media. Plastic media can be recycled and reused a number of times, until the particles become too small to be effective. PMB can generate a significant amount of waste that must be contained, collected, and properly disposed, so research is still being performed on more environmentally friendly paint stripping methods.

Sodium bicarbonate, dry ice (CO_2), wheat starch, and ice have all been evaluated and used to some extent for paint stripping on aluminum. Each has its own advantages and disadvantages. For example, when the dry ice pellets evaporate, they displace air (oxygen), which may require the use of supplemental ventilation. Wheat starch has been found to have lower stripping rates than PMB, and can still generate a significant amount of waste.

Chemical paint stripping has been used for many years on aluminum surfaces prior to repainting. However, their use is not limited to aluminum alloys, since their use may be desirable for any situation where abrasive blasting cannot be performed, such as the nearby presence of sensitive machinery, or difficulties in containment. Chemical strippers have been classified in three generic categories:[11, 12]

• "Bond breakers" are those that penetrate the coating film, causing it to swell, soften, and lift, thereby breaking its bond to the substrate. These have historically included low molecular weight hydrocarbon solvents such as methylene chloride. However, since these solvents are highly toxic, flammable, and high in VOCs, environmentally friendly alternatives are being developed and tested. These include acid or alkali activated benzyl alcohol, and N-methyl pyrrolidone (NMP).[9, 12]

These alternatives are generally slower acting than methylene chloride, and they may also cause corrosion of certain substrates, such as magnesium and cadmium plating. In the case of acid-activated benzyl alcohol types, there is also a risk of hydrogen embrittlement of high strength steels. Federal specification TT-R-2918[13] covers two types of chemical paint strippers that contain no HAPS. One type is to be able to remove epoxy-polyurethane paint systems, and the other is intended for use in removing polysulfide rubber coatings used as sealants.

• Caustic paint strippers are based on alkaline compounds such as sodium, calcium, potassium, and magnesium hydroxide.[12] These materials are best suited for removal or alkyd and polyester coatings, but they should not be used on aluminum alloys since they are highly corrosive to aluminum.

• Selective adhesion release agents (SARA) are a relatively new class of chemical strippers based on alcohol hydroxycarboxylic acid peroxide (AHP).[12] These materials were also developed to be safer to use than methylene chloride, and like many of these alternatives, are slower-acting. The action of these materials is similar to the bond breakers described above, in that the chemical permeates through the coating system and stresses the chemical bonds.

A unique difference in SARA materials is that once they reach the substrate, specific compounds, such as hydrogen peroxide, react with the substrate and forms gas under the film. The pressure of the gas formation works to disbond the coating. SARA materials have been found to be useful in removing alkyds, latexes, urethanes, epoxy esters, and amine and polyamide epoxies, but do not work well on highly cross-linked novolac epoxies and vinyl esters.

Paint stripping technologies for aluminum alloys used in the aerospace industry continue to be researched. Their selection involves a balancing act between meeting environmental and health regulations, achieving economic efficiency, and minimizing any detrimental effects to the substrate. Some of these techniques are briefly described in the section below on specialized surface preparation methods. Refs. 8, 9, and 14 provide more detailed information.

Surface pre-treatments can arguably be considered part of the surface preparation process that takes place prior to the application of a primer. Although they are not unique to aluminum alloys, they certainly have been very commonly used on aluminum alloys. Chemical conversion coatings, anodizing, and wash primers have all been used as pre-treatments on

aluminum alloys to provide enhanced corrosion protection and improve paint adhesion. While they are often used on surfaces that have not been abrasive blasted, this is not always the case. A common example is SSPC Paint Specification No. 27, for a zinc chromate-vinyl butyral wash primer that is also used on steel surfaces.[15] This paint is also known as Formula 117 wash primer per military specification DOD-P-15238.[16] This coating has some drawbacks, since it contains chromates and has a high VOC content. Wash primers are typically applied at less than 0.5 mils (12.7 µm) dry film thickness (dft).

Pretreatments and primers containing hexavalent chromium were widely used on aluminum structures in Navy, aerospace, and other industries. Chemical conversion coatings for aluminum generally contained chromates as a corrosion inhibitor. Therefore, surface preparation performed during maintenance painting of these structures may need to account for this, and use special procedures to contain dust and paint chips, in order to protect workers and the environment. There is much ongoing research on conversion coatings for aluminum alloys that either contain nontoxic forms of chromium, such as trivalent chromium, or do not contain chromium at all.

As a final note, it should be kept in mind that acid cleaning and pickling processes used for steel to remove rust and mill scale must not be used on aluminum alloys, since they are too aggressive and will cause rapid, severe corrosion.

Stainless Steels

Many of the same precautions used for preparing aluminum surfaces also apply to stainless steels, especially those dealing with avoiding contamination by plain carbon steel and free iron. Stainless steels are harder than aluminum alloys, and are closer to steel alloys in surface hardness, especially the heat-treated, high-strength grades. Therefore, embedding abrasive grit and gouging the surface is not as great a risk. The hand and power tools used on stainless steel surfaces should not be used on other types of metals. Aluminum oxide and garnet are frequently recommended for abrasive blasting of stainless steel.

Problems encountered in painting stainless steels are generally associated with poor adhesion, especially for structures that have not been blasted and profiled. This is thought to be due in part to the protective oxides that form on stainless steel surfaces when exposed to air and provide their corrosion resistance. For this reason, acid-etching wash primers, such as the previously mentioned SSPC Paint No. 27, have been used as pre-treatments.

Copper Alloys

Most copper alloys are found on piping systems. This is especially true in marine applications. Copper and copper-nickel alloys are used for piping and tubing, and various grades of copper-nickel or bronze castings are often used valves, pumps, strainers, and heat exchangers. Copper alloys may also be used for other types of components in food processing plants. Architectural components and bronze statuary may likewise need to be cleaned prior to the applying transparent, protective lacquers. Surface preparation methods specified are generally mild compared to those used for steel and structural aluminum. As with other metallic surfaces, solvent cleaning should be performed first. Hand or power tool sanding using abrasive cloths, belts, or pads is often the only other surface preparation method specified.

Wood

Wood can have many different product forms in industrial and architectural structures that are painted: dimension lumber, various grades of plywood, siding, hardboard, flake board, particle board, and others. Since each of these product forms can have special considerations, the discussion here only serves as an overview. For more detailed information on the surface preparation and painting of wood, refer to publications available from the Master Painters Institute.

All oil, grease, dirt, and other contaminants should be removed as one of the first steps in surface preparation. Loose materials can be removed by scraping, or for larger surface areas, by power washing. This is followed by hand or disc sanding. Generally, disc sanding is the only power tool cleaning method that should be used on wood in order to prevent damage. For new wood, 80–100 grit sanding media are recommended. For old, previously painted wood, scraping and coarse (36 grit) sanding media are needed to remove loose paint.

The orientation of the grain in wood may also be a factor in surface preparation in order to promote good paint bonding. Exposed edge grain will be present on the surfaces of lumber that was produced

when a log was sawn radially through the center, while flat grain is exposed on lumber cut from the outer area of the log. This is illustrated in **Figure 2.** Flat grain is more difficult for paint to penetrate and bond to, and may need power sanding to help promote bonding.

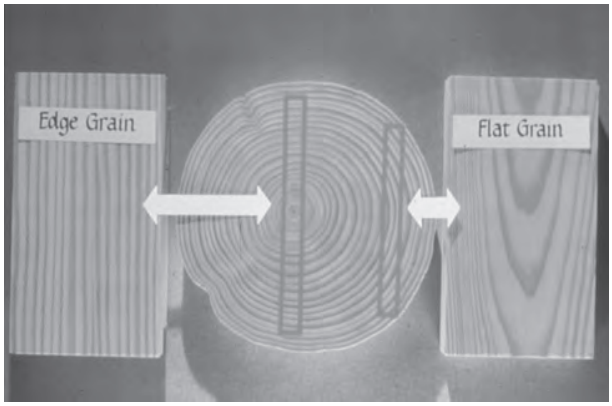


Figure 2. Edge and flat grain in lumber.

Mildew may be encountered during maintenance painting of existing structures. If mildew is present, cleaning with solutions of detergent, trisodium phosphate (TSP), and bleach (hypochlorite) in warm water should kill the organisms that cause mildew.

Wood surfaces are naturally porous, and are therefore prone to retaining moisture. Some specifications may have a maximum moisture content requirement on the order of 10% to 15%. Freshly cut lumber, also sometimes called green lumber, generally contains a large amount of water. Ideally, this wood should be dried before painting, or it will cause blistering and cracking. Special drying or sealing pre-treatments may also be required on existing wood structures to prevent blistering or other problems from moisture content.

If resinous soft woods, such as pine or fir, are to be painted with latex paints, they may need to be sealed first with an oil-base paint or other product to prevent the resin from bleeding through over time and causing staining. Pine and fir boards are also likely to contain pockets of resin or pitch. For work where cosmetic appearance will be important, these pockets can be emptied and filled with putty and sealed prior to painting. Knots in particular have more resin, and may need sealing before finish painting to prevent later staining. Use spot sealing on knots and pitch pockets. Products are available specifically for sealing knots. Be sure to allow these sealers to dry thoroughly prior to painting.

Cracks, nail holes, other defects should be filled and smoothed, as they can be sites for premature coating failure, especially on structures where an aesthetically pleasing surface is desired. Putty should be used for nail holes and gouges but not to fill seams and crevices, since it is inflexible and likely to crack. Caulks and sealants are used for seams and crevices, but silicone-based products must not be used on surfaces to be painted, since the paint will not stick to this material. Sealants are generally elastomeric materials, and are more flexible and rubbery compared to caulks. Therefore, sealants are recommended in expansion joints where flexibility is needed.

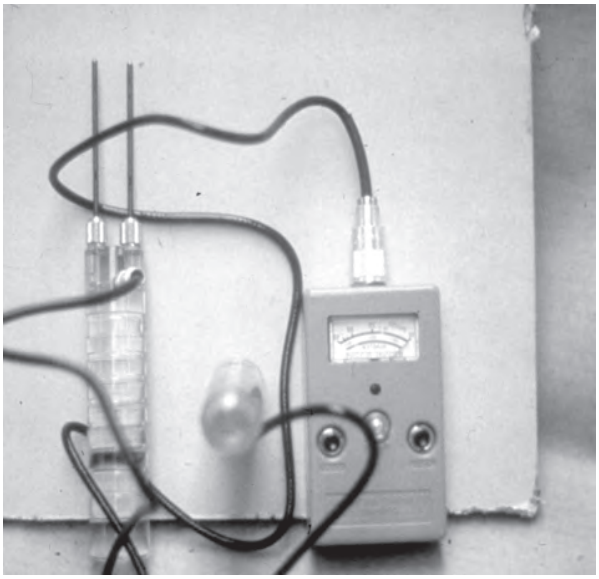


Figure 3. Moisture meter in use.

Fiberglass and Composite Materials

Fiberglass and related composite materials are made from high-strength fibers or filaments that are embedded in a polymer resin matrix, or binder. Most common are short whiskers or long strands glass (hence the name fiberglass); however, graphite or other materials are also prevalent. The polymer resin matrix is most often an epoxy or polyester, but many other types can be custom-selected to meet an application need. Since the fiber reinforcement provides the strength engineered into a composite material, composite materials often have a surface layer consisting only of resin, in order to protect the fibers. This layer is frequently called a gel coat. One of the key aspects in surface preparation of these materials is not to damage or expose the fibers, and

therefore not to penetrate the gel coat.

Surface preparation methods for composite structures partly depend on the type of material that needs to be removed. In the marine and shipping industries, hard and soft biofouling may need to be removed from immersed surfaces. This material is best removed while still wet, since it will harden and be more difficult to remove when it dries. Depending on the amount of surface area to be treated, manual scraping and bristle brushing or low-pressure water blasting can be used. Degreasing may be needed on composite surfaces, and detergent cleaning is often used for this. Solvents for degreasing should be tested on very small areas first to make sure they do not damage the resin matrix. Hand and power tool sanding are used to lightly roughen the gel coat or previously applied and intact coatings prior to topcoating. When stripping old paint, softer PMB materials, such as starch-acrylic, have been used without damaging the surface.[14] If paint needs to be removed from composite surfaces used in aircraft, it is sometimes specified that only the topcoats be removed and the primer left intact in order to help prevent damage to the laminate. Primers on composites are often a different color than the topcoats to help facilitate this process.

Specialized Surface Preparation Methods

The methods described here are primarily concerned with paint stripping from sensitive metallic or nonmetallic surfaces, either to facilitate non-destructive inspection (NDI) or to clean a surface for re-painting. Some of these are already in use in the aerospace industry, and others are still in development. Reference 14 is a good source of information about the methods described here and several others that apply to steel and nonferrous surfaces, such as wheat starch blasting, burn-off systems, molten salt stripping, and liquid nitrogen blasting. It describes pollution prevention benefits and the basics and benefits and limitations of each method.

Bicarbonate of Soda Stripping

Blasting using sodium bicarbonate is also known by the acronym BOSS, which stands for bicarbonate of soda stripping. There are several brand names for the BOSS equipment, including Accustrip, AquaMiser, and Jet Stripper. This process can be used for paint stripping and for general cleaning of steel, as well as nonferrous and nonmetallic surfaces. It may be performed with or without water, but water is often added to help suppress dust. Since sodium bicarbonate is softer than most PMB materials, it is a slower process for paint stripping, and it will not remove tightly adherent corrosion products, but it can be used on softer substrates without damage. The blast media cannot be recycled. When used for surface cleaning of items to be painted, washing to remove residues will be required. The residue from using BOSS with water is a slurry of sodium bicarbonate, water, paint chips, and other debris. Wastewater and particulates still must be collected and properly disposed. Protective equipment for operators should include hearing protection, air-hood blast helmets with air-supplied respirators, and protective clothing such as rubber gloves and safety-toed rubber boots.

Xenon Flash Lamp and Carbon Dioxide Blasting

A commercially patented paint stripping process known as FlashJet™ uses the combination of a high-intensity xenon flash lamp and CO_2-pellet blasting.[9] The pulsed energy from the lamp pyrolyzes the coating and turns it to ash and soot, and CO_2 blasting follows and removes the residue. This technology was developed to address shortcomings of each of the methods when used singly. The low pressure CO_2 blasting helps remove the soot produced by the lamp, cleans the lamp window to maximize light transmission, and cools the substrate. Gantry and mobile manipulator systems have been developed that allow fine control and capture the residue, and they are being used on both airplanes and helicopters.

Laser Stripping

Various types of laser paint stripping systems are commercially available, and have been tested by the U.S. military. Hand-held and limited to use on small areas and components, these systems remove paint by either vaporization or combustion. The types of lasers used include diodes, Nd:YAG (neodymium:yttrium-aluminum-garnet), and pulsed carbon dioxide (CO_2). Depending on the specific equipment, they have been found to be able to strip paint from complex geometries and hard-to-reach areas.

Photochemical Stripping

This process uses ultraviolet lamps and inorganic chemicals for stripping polyurethane, epoxy,

and acrylic paints from aluminum, stainless steel, wood, and composite surfaces.[9] It is currently under development, and is limited to treating parts and the component level rather than large structures. Stripping time is on the order of six hours, and the only waste product is the paint itself. The process is known by the name PhotoStrip.™ An example of a fiberglass radar dome sample that has been treated by this process is shown in **Figure 4.**

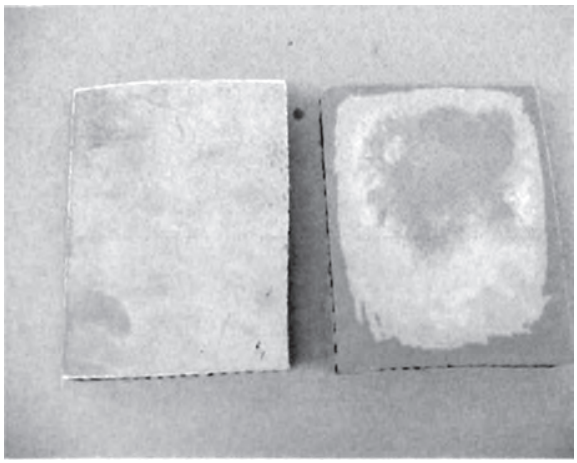


Figure 4: Aircraft radar dome sample before (left) and after (right) treating with PhotoStrip™ process. U.S. Navy Photograph/V. Agarwala.

References

1. ASTM D 4417. *Standard Test Methods for Field Measurement of Surface Profile of Blast Cleaned Steel;* ASTM: West Conshohocken, PA.
2. SSPC-VIS 1-89. Visual Standard for Abrasive Blast Cleaned Steel; SSPC: Pittsburgh, 1989.
3. SSPC-VIS 3. *Visual Standard for Power- and Hand-Tool Cleaned Steel;* SSPC: Pittsburgh, 1993.
4. SSPC-VIS-4/NACE VIS 7. *Guide and Reference Photographs for Steel Surfaces Prepared by Waterjetting;* SSPC: Pittsburgh, 2001.
5. SSPC-VIS-5/NACE VIS 9. *Guide and Reference Photographs for Steel Surfaces Prepared by Wet Abrasive Blast Cleaning;* SSPC: Pittsburgh, 2001.
6. Military Specification MIL-C-85570. *Cleaning Compound, Aircraft Exterior.*
7. SSPC-SP 7/NACE No. 4. *Brush-Off Blast Cleaning;* SSPC: Pittsburgh, 2000.
8. Tipton, Col. R., *DoD Joint Service Report – Paint Stripping Methods;* U.S. Air Force Aging Aircraft and Systems Office; 29 September 1997.
9. Agarwala, V.; Rajeshwar, K. *Paint and Coating Removal Technologies: Past, Present and Future;* In *Proceedings of NACE Corrosion '01,* Paper #01577.
10. Military Specification MIL-P-85891, *Plastic Media for Removal of Organic Coatings.*
11. SSPC-TU 6. *Chemical Stripping of Organic Coatings From Steel Structures*, SSPC: Pittsburgh, 1999.
12. O'Donoghue, M. et. al. Chemical Strippers and Surface-Tolerant Coatings: A Tandem Approach for Steel and Concrete. *Journal of Protective Coatings and Linings,* May 2000, pp 74-93.
13. Federal Specification TT-R-2918. *Remover, Paint, No Hazardous Air Pollutants (HAPS).*
14. EPA/625/R-93/015. *Guide to Cleaner Technologies: Organic Coating Removal;* U.S. EPA Office of Research and Development: Washington, D.C., 1994.
15. SSPC Paint Specification No. 27. *Basic Zinc Chromate-Vinyl Butyral Wash Primer*, SSPC: Pittsburgh, 2000.
16. Military Specification DOD-P-15328. *Primer (Wash), Pretreatment (Formula No. 117 for Metals).*

Bibliography

Naval Ship Technical Manual (NSTM) Chapter 631. *Preservation of Ships in Service;* Volumes 1-3, 1996.
Army TM 5-618/NAVFAC MO-110/Air Force AFM 85-3. *Paints and Protective Coatings;* June 1981.
Naval Air Systems Command Technical Manual NAVAIR 01-1A-509. *Aircraft Weapons Systems Cleaning And Corrosion Control;* May 1996.
Proceedings of the Aerospace Coatings Removal and Coatings Conference, San Antonio, TX, May 22-24, 2001.
Science Applications International Corp. (SAIC). *Potential Alternative Report for the Portable Handheld Laser Small Area Supplemental Coating Removal System;* Technical Report prepared for the Air Force Research Laboratory Materials and Manufacturing Technology Directorate, February 2001.

About the Author

Norm Clayton
Norm Clayton is a senior materials engineer at the Naval Surface Warfare Center, Carderock Division. His experience includes failure analysis, corrosion engineering, coatings specification and inspection, and related training programs for the U.S. Navy and Marine Corps. He is a co-author and instructor for the Navy Basic Coatings Inspection (NBPI) course.

Chapter 4.1
Coatings for Industrial Steel Structures

Richard W. Drisko

Introduction

This chapter provides basic information on coating systems used on industrial steel structures. Subsequent chapters will describe coating systems for different types of steel structures.

Engineering standards maintained by corporations or organizations provide specification writers with lists of the coating system options for plant structures. These options always include a recommended surface preparation level as part of each coating system. This chapter follows this good practice and also includes information on coating selection for different environments. Obviously, different environments require different coating systems with significantly different chemical and physical properties.

Background

Over the years, notable developments have been made both in surface preparation methods and in coating materials to provide longer protection to steel structures. More recently, health, environmental, and safety regulations affecting surface preparation methods, particularly abrasive blasting, and coating materials have greatly restricted the selection of coating systems for steel. These regulations have also made many systems more difficult to apply. Thus, coating contractors must be able to use all of the available information on coating systems to make selections that will result in long-term economical protection.

Removing deteriorated coatings for either repair or replacement can be very expensive. In both cases, the debris removed in surface preparation often requires containment, collection, on-site storage, laboratory analysis, and special treatment or disposal.

In the past, decisions were sometimes made to use cheaper coating materials with shorter protection times and replace them more often. Since the costs of coating materials today may constitute no more than 20% of the total coating costs, a high-performance system that is readily maintained usually provides the lowest life-cycle costs.

Shop Vs. Field Painting

Painting contractors have more choices today than in the past for using shop instead of field painting to coat many steel products in part or in whole. Decisions on the use of shop painting facilities are usually based on both the quality of the work and the economics involved. Shop painting is covered in a separate chapter.



Figure 1. Checking wet-film thickness after shop painting steel. Courtesy HIgh Steel Structures.

Surface Preparation of New Steel

Abrasive blasting is usually the preferred method of preparing steel surfaces for coating because it can provide both the desired level of cleanliness and the desired profile height. The recommended level of steel surface abrasive blast cleaning depends upon three basic factors:

- Generic type of primer
- Severity of environment
- Desired service life

Different generic coatings require different levels of surface cleanliness. Thus, while commercial blast cleaning (SSPC-SP 6/NACE 3) may be adequate for alkyd, drying oil, or water-borne coatings in a mild atmospheric environment, a higher level of cleanliness, such as near-white blast cleaning (SSPC-SP 10/NACE 2) is usually required for higher-performance coating systems in immersion or severe atmospheric

service.[1, 2] Manufacturers of primers for steel coating systems always state both their recommended cleaning levels and profile heights.



Figure 2. Abrasive blasting of railcar in fabrication plant prior to coating.

Waterjetting is water cleaning at high or ultrahigh pressure (above 70 MPa [10,000 psi] to prepare a surface for recoating.[3] Because it will not produce an etch or profile of the magnitude currently recognized by the surface preparation industry, it is not normally used for surface preparation of new steel. SSPC-SP 12/NACE 5 is a standard for waterjetting.[3]

Abrasive may be injected into the steam of water or used separately after waterjetting to remove mill scale and provide a surface profile. SSPC-TR 2/NACE 6G198 describes procedures, equipment, and materials involved in a variety of air/water/abrasive, water/abrasive, and water-pressurized abrasive blast cleaning systems. It also discusses equipment usage and safety.[4]

Lower levels of surface preparation may be adequate for a cheap coating formulated to provide only temporary corrosion protection to steel during construction. This coating may be removed and replaced with a higher-performance coating after the construction is complete.

Surface Preparation for Repair of Damaged Coatings

There are several alternatives available for surface preparation to repair damaged coatings on steel structures. The selection of the most appropriate system usually depends on several factors including the extent and distribution of coating damage, the need for containment of surface preparation debris, and the remoteness of the location to power and other support.

Abrasive blasting usually provides the best level of cleaning and profiling of steel, but it often has limitations:

- Impractical or prohibitively expensive for small areas
- Expensive containment of blasting debris
- Requirement for a power source that may not be readily available
- Difficulties in feathering edges of damaged areas of existing coating

Waterjetting is excellent for total removal of coatings and will restore the initial profile height. However, it has many of the same limitations of abrasive blasting for spot repair of coatings.

Power tool cleaning to bare metal (SSPC-SP 11) provides a level of cleanliness that approximates commercial blast cleaning (SSPC-SP 6/NACE 3) and a profile of 1 mil or more.[5] However, the process is slow and thus expensive.

Power tool cleaning according to SSPC-SP 3 is faster than power tool cleaning to bare metal, but it does not clean as well and leaves a burnished rather than a profiled surface.[6] Chemical cleaning can be used effectively for removal of many but not all coatings. It is also slower and thus more expensive than other cleaning systems.

Primers for Steel Surfaces

Primers for steel surfaces are formulated to bond well to the prepared steel and provide a suitable surface for topcoating. Their most common mecha-

nism for corrosion control is by barrier protection, but they may also protect steel by using corrosion inhibitors or by the cathodic protection provided with a heavy zinc loading.

Surface-Tolerant Primers

Surface tolerant-primers are typically chosen when abrasive blast cleaning cannot be done. Their use is not recommended solely to reduce surface preparation costs because coating performance may be significantly compromised. These primers for steel have been prepared to a lesser degree of cleanliness than provided by SSPC-SP 6/NACE 3 (Commercial Blast Cleaning). They also exhibit a greater propensity toward satisfactory service performance than conventional coatings not intended for such applications. Thus, topcoating with a barrier coat is recommended.

Surface-tolerant coatings are commonly used on surfaces contaminated with rust, soluble salts, petroleum products, and moisture, often occurring together. High concentrations of these contaminants are likely to cause most coatings to fail. There are several types of these primers:

- Low-viscosity (penetrating) coatings such as oil-based, alkyd, and water-borne acrylic coatings that contain corrosion-inhibitive pigments. Some oil-based and alkyd coatings can absorb small amounts of oil.
- Barrier coatings such as epoxy mastics and moisture-cured polyurethanes containing laminar pigments (e.g., aluminum flake and micaceous iron oxide) to impede moisture transmission.
- Unpigmented, low-viscosity (penetrating) two-component epoxy and polyurethane coatings with barrier-type topcoats.

Additional information on surface-tolerant coatings is available in SSPC-TU 1.[7]

Pre-Construction Primers

For more than 30 years, the marine industry has routinely applied pre-construction primers (PCPs) to stock plates and shapes using automatic abrasive blasting (typically to SSPC-SP 10/NACE 2) and coating application equipment.[8-9]

Epoxy, acrylic, alkyd, moisture-curing polyurethane, and solvent-borne and water-borne inorganic zinc PCPs have all been used successfully in shipbuilding. After construction is complete, the PCP-coated surfaces are given a secondary surface preparation. Secondary surface preparation may include complete removal of the PCP but more commonly consists of:

- Surface preparation of weld and areas of damaged PCP (abrasive blasting to SSPC-SP 10/NACE 2 or power tool cleaning to SSPC-SP 3 or SSPC SP 11)
- Light (sweep) blast cleaning of the PCP to remove surface contaminants

Desired properties of PCPs include:

- Corrosion protection of steel during fabrication
- Ease of application in thin continuous films
- Resistance to damage from welding
- Minimal health and safety factors
- Compatibility with high-performance coating system to be applied after secondary surface preparation

Thin films (e.g., 0.6-0.8 mils/15-20 micrometers) of inorganic zinc-rich coatings are commonly used in the U.S. After secondary surface preparation, epoxy systems adhere quite well to them.

Universal Primers

Universal primer is a general term that means different things to different people. Most think of it as a tie coat that permits the use of a topcoat normally incompatible with an existing coating. Others think of it as a surface-tolerant coating.

Coating Systems Used on Steel

Coating systems commonly applied to new steel will be discussed in this chapter. Coating systems used to repair damaged coatings are usually identical or of the same generic type as the original coating system in order to be compatible with it.

Alkyds and Other Systems That Cure by Oxidation of Drying Oils

Alkyds and other drying oil coating systems have been used extensively on steel structures in mild atmospheric interior and exterior service. A silicone alkyd finish coat is often used in exterior service to provide a greater resistance to weathering. It is expected that the use of alkyd systems in the future will decrease significantly because of greater VOC restrictions.

Epoxy Systems

A wide variety of epoxy coating systems are

being used today on steel structures in both atmospheric and immersion service. These include:

- Epoxy polyamides for atmospheric and water and petroleum immersion service
- A range of amine-cured epoxies for chemical immersion service
- Epoxy mastics for use as tie coats, surface-tolerant coatings, etc.
- Phenolic epoxies for a hard, chemically resistant system
- Novolacs for combined chemical, solvent, and heat resistance
- Solvent-free epoxies for edge retention



Figure 3. Elevated water tank with two coats of alkyd and a silicone alkyd finish.

When epoxies are specified for exterior atmospheric service, aliphatic polyurethane finish coats are frequently used to impart greater resistance to weathering. Anticipated lower VOC limits should not adversely affect the availability of epoxy coatings.

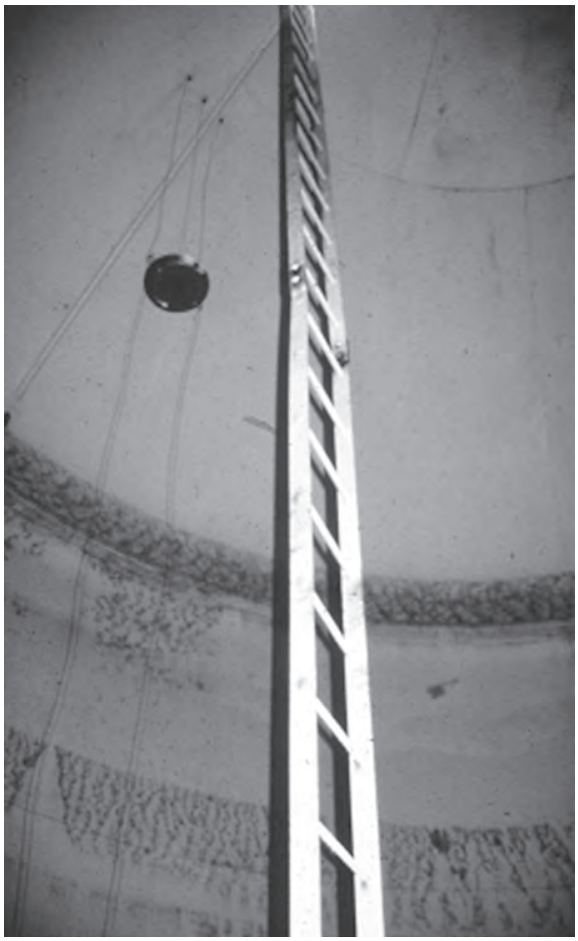


Figure 4. Epoxy-lined water tank after five years of service.

Coal-Tar Epoxy Systems

Coal-tar epoxy coating systems have been used extensively on underground piping, interiors of waste-water tanks, and on steel pilings immersed in water because of these these good properties:

- Good water and chemical resistance
- Good film build
- Relatively low VOC content
- Relatively low cost

Coal-tar epoxy use seems to be diminishing because of concerns about adverse health effects.

Polyurethane Systems

Polyurethane coating systems, both two-



Figure 5. Coal-tar epoxy system on waste water facility.

component thermosetting and single-component moisture-curing, are used extensively on steel surfaces. Polyurethane coatings can range in physical properties from hard to elastomeric. The elastomeric formulations have less chemical resistance than harder formulations, so a compromise must frequently be made to obtain the best available combination of properties for a specific service. Advantages of polyurethane coatings on steel are:

- Available in hard or flexible films
- Good water resistance
- Aliphatic formulations have good gloss and color retention
- Aromatic formulations have good chemical resistance
- Low-temperature curing formulations available
- Currently available in low VOC formulations

There is concern about the toxicity of the isocyanates in some formulations, and polyurethanes are more expensive than epoxies.

Zinc-Rich Coatings

Inorganic and organic zinc-rich coatings may provide cathodic protection to steel surfaces. These coatings are used mostly in mild atmospheric service. Their zinc pigment is subject to attack by both acidic and alkaline chemicals. Organic zinc-rich coatings are almost always topcoated to provide longer protection to steel. Inorganic zinc-rich coatings may be used with or without topcoats. Care must be taken during topcoating of inorganic zinc coatings to prevent small bubbles from forming.



Figure 6. Polyurethane finish coat on elevated water tank.

Siloxane Coating Systems

Siloxane coatings, sometimes called siloxirane coatings, have good chemical, weather, and heat resistance. They are relatively low in VOCs and have been used successfully on steel bridges, storage tanks, stacks, anchor chains, and chemical process equipment. Siloxane coatings are relatively slow to cure and relatively high in cost, as comparted to other coatings.

Water-Borne Acrylic Systems

Several water-borne acrylic coating systems are formulated for use on steel surfaces in relatively mild atmospheric environments. Also, a water-borne acrylic finish coat can be applied to an exterior epoxy

system to impart good weathering properties.

Water-borne acrylic coatings have the advantages of low VOC contents and reduced fire and explosion hazards. However, they do not cure well below 50°F (10°C) and are not as durable as high-performance coatings.

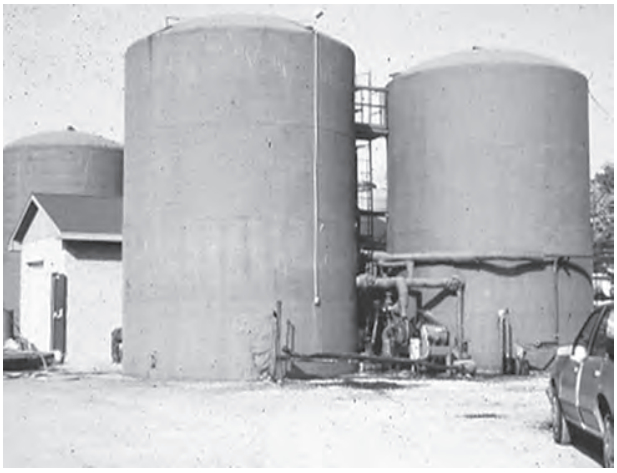


Figure 7. Zinc-rich system on steel tank exterior.

Coating Selection by Environmental Zone

The choice of a suitable coating system is often not easy. One of the chief factors to be considered is the environment in which the protection is to be provided. SSPC defines twelve distinctly different environmental zones and a matrix of coating systems appropriate for each of the zones as shown in **Tables 1 and 2.**[10]

Actual costs for commercially available coating materials can be obtained by contacting manufacturers at the addresses listed in the Annual Buyer's Guide that appears each June in the *Journal of Protective Coatings and Linings.*

Table 1. SSPC Environmental Zones.

0	Dry interiors where structural steel is embedded in concrete, encased in masonry or protected by membrane or non-corrosive contact type of fireproofing
1A	Interior, normally dry (or temporary protection). Very mild (oil base paints now last six years or more).
1B	Exteriors, normally dry (includes most areas where oil base paints last six years or more)
2A	Frequently wet with fresh water. Involves condensation, splash, spray or frequent immersion. (Oil base paints now last five years or less.)
2B	Frequently wet by salt water. Involves condensation, spray or frequent immersion. (Oil base paints now last three years or less.)
2C	Fresh water immersion
2D	Salt water immersion
3A	Chemical atmosphere, acidic (pH 2.0 to 5.0)
3B	Chemical atmospheric exposure, neutral (pH 5.0 to 10.0)
3C	Chemical atmospheric exposure, alkaline (pH 10.0 to 12.0)
3D	Chemical atmospheric exposure, presence of mild solvents. Intermittent contact with aliphatic hydrocarbons and their derivatives (mineral spirits, lower alcohols, glycols, etc.)
3E	Chemical atmospheric exposure, severe. Includes oxidizing chemicals, strong solvents, extreme pHs or combinations of these with high temperatures.

Table 2. Environmental Zones For Which SSPC Painting Systems are Recommended.

Painting System		Environmental Zone (From Table 1)											
SSPC #	Generic Type	0	1A	1B	2A	2B	2C	2D	3A	3B	3C	3D	3E
PS 1	Oil base		X	X									
PS 2	Alkyd		X	X									
PS 3	Phenolic (oleoresinous)		X	X	X								
PS 4	Vinyl		X		X	X	X	X	X	X			
PS 7	One-coat shop	X	X										
PS 9	Cold-applied asphalt mastic				X	X				X	X		
PS 10	Coal tar mastic or enamel						X			X	X		
PS 11	Coal tar epoxy				X	X	X	X	X	X	X		
PS 12	Zinc-rich (untopcoated)		X	X	X	X	X	X		X		X	
PS 12	Zinc-rich (topcoated)		X	X	X	X	X	X	X	X	X	X	
PS 13	Epoxy-polyamide (non-immersion)**				X	X							
PS 14	Steel joist shop paint		X										
PS 15	Chlorinated rubber		X	X	X	X	X	X	X	X	X		
PS 16	Silicone alkyd				X								
PS 17	Urethane		X	X	X	X				X	X		
PS 18	Latex		X	X									
PS 19	Ship bottoms							X					
PS 20	Ship boottoppings					X		X					
PS 21	Ship topsides		X	X	X	X							
PS 22	One-coat preconstruction		X	X									
CS 23	Thermal spray metallic		X	X	X	T	X	T	T	T	T		
PS 24	Latex (performance based)		X	X	X	X			X	X	X	X	
PS 26	Aluminum epoxy (performance based)		X	X	X*	X*							
PS 27	Alkyd (performance based)		X	X	X*	X*							

Zones for use are those recommended by the committee that developed the specification.
PS 4 (vinyl) and PS 15 (chlorinated rubber) do not meet VOC restrictions and are rarely used.
** For immersion service, propietary epoxy and urethane coatings are usually used.
T = Recommended only with proper sealing or topcoating.
PS 26 and PS 27 are material specifications and cover only the paint.
X* = Excluding immersion
For Zone 3E use specific exposure data to select a coating.
Because more than one system is recommended for a particular zone does not mean that they will all perform equally well.

References

1. SSPC-SP 6/NACE 3. *Commercial Blast Cleaning;* SSPC: Pittsburgh and NACE: Houston.
2. SSPC-SP 10/NACE 2. *Near-White Blast Cleaning;* SSPC: Pittsburgh and NACE: Houston.
3. SSPC-SP 12/NACE 5. *Surface Preparation and Cleaning of Steel and Other Hard Materials by High- and Ultrahigh-Pressure Waterjetting Prior to Recoating;* SSPC: Pittsburgh and NACE: Houston.
4. SSPC-TR 2/NACE 6G198. *Wet Abrasive Blast Cleaning;* SSPC: Pittsburgh and NACE: Houston.
5. SSPC-SP 1. *Solvent Cleaning;* SSPC: Pittsburgh.
6. SSPC-SP 3. *Power Tool Cleaning;* SSPC: Pittsburgh.
7. SSPC-TU 1. *Surface-Tolerant Coatings for Steel;* SSPC: Pittsburgh.
8. Fultz, B.S. Retaining Pre-Construction Primers Under Standard Lining Systems. *Journal of Protective Coatings and Linings*, February 1999, pp 30-44.
9. Buesing, Kirby. Installing Marine Pre-Construction Primer Spray Lines: The Basics. *Journal of Protective Coatings and Linings*, February 1999, pp 17-21.

About the Author

Dr. Richard W. Drisko

Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society for Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy's center of expertise on coatings for shore structures. He is a professional corrosion engineer in the state of California, an SSPC certified protective coatings specialist (PCS), and a NACE International certificated corrosion specialist. Dr. Drisko received his BS, MS, and PhD degrees from Stanford.

Chapter 4.2
Coatings for Concrete

Richard W. Drisko

Introduction

Industrial concrete is usually coated to provide resistance to deterioration or other desired properties. Coating material requirements for concrete are significantly different than those for steel. This chapter presents general information that will assist the reader in the selection and use of coatings for specific types of service on concrete structures.

Concrete Properties That Affect Its Successful Coating

Concrete has several chemical and physical properties that affect the selection and use of coatings. These properties must be addressed for successful coating performance.

Alkalinity

The natural alkalinity (as much as pH 13 on newly placed concrete) reacts with coatings containing drying oils to rapidly degrade them. Thus, only alkali-resistant coatings must come into direct contact with concrete.

Porosity

The natural porosity of cured concrete permits water to penetrate into and migrate through it. Water migration through concrete causes alkaline and other aggressive soluble salts to damage coated surfaces. Such contaminents must be removed before recoating.

Surface Texture

The natural roughness of concrete surfaces makes it more difficult to cover completely without film imperfections (holidays). On the other hand, smooth finished concrete may have insufficient profile (roughness) for good primer adhesion. **Table 1** describes typical surface properties of finished concrete.

Reference 2 presents a selection method for matching recommended concrete surface profile (CSP) with coating film thickness; the greater the film thickness, the greater is the recommended profile.

Reasons for Coating Concrete

The reasons for coating concrete are many and varied. Some are distinctly different from uses of coatings on steel, while others are also applicable to steel structures.

Appearance Enhancement

In most exterior and many interior services, the appearance of coated concrete surfaces is very important. This is especially true when there is public exposure. Appearance can be enhanced by proper selection of coating materials to provide desired color, gloss, and/or texture. Smooth coatings are much less susceptible to unsightly mildewing than rough, uncoated concrete and also is much easier to clean.

Reduction of Permeability

All concrete surfaces are permeable to moisture to some extent. Continuous dampness may promote coating deterioration, mildew growth, corrosion of embedded steel, or other undesirable effects. Coatings can be used effectively to control moisture penetration and migration. Water vapor transmission through concrete can be measured using the calcium chloride test, ASTM F 1869.[3]

Substrate Protection

Concrete is subject to deterioration by a number of mechanisms.[4] Coatings most frequently protect concrete from deterioration by providing a protective barrier from aggressive environments.

Dusting Control

Exposed concrete slowly deteriorates to produce dust. Coatings can effectively control this.

Ease of Cleaning

Rooms in hospitals, food processing facilities, nuclear power plants, and electronic equipment manufacturers that contain sensitive components or otherwise require a high level of cleanliness need smooth surfaces. These coatings may also have to be

Table 1. Typical Surface Properties of Finished Concrete.

Preparation Method	When Used	Profile Created [A]	Problems	Solutions
Dry abrasive blasting	Removal, profile, cleaning	Fine (150) to extra coarse (40)	Dust on surface Airborne dust Noise	Vacuum cleaning Vacuum attachments None
Wet abrasive blasting	Removal, profile, cleaning	Fine (150) to extra coarse (40)	Wets concrete Creates sludge	Let concrete dry Cleaning
High-pressure water cleaning	Removal, cleaning	Fine (150) to extra coarse (40)	Wets concrete Creates sludge	Let concrete dry Cleaning
Waterjetting	Removal	Rougher than extra coarse	Creates sludge Wets concrete Coarse profile	Cleaning Let concrete dry None [B]
Impact tools	Removal, profile, cleaning	Rougher than extra coarse	Airborne dust Fracturing Coarse profile	Vacuum attachments Other methods None [B]
Power tools	Removal	Smooth (no grit equivalent)	Airborne dust Fine profile	Vacuum attachments Other methods
Flame blasting	Removal, profile, cleaning	Rougher than extra coarse	Excess removal Damages concrete	Experience [B] Remove damaged concrete
Acid etching	Profile, cleaning	Fine (150) to extra medium (100)	HCl is hazardous Not for vertical or overhead surfaces Neutralization Wets concrete Curing membrane	Other acids Other methods pH testing Let concrete dry Other methods

(A) Profile is described using standard classifications and screen grit sizes for coated abrasive products. These are typical surface profile values only. Results may vary significantly due to concrete properties and surface preparation practices.
(B) May be acceptable for thick coating systems; otherwise, the surface can be patched prior to coating application.

resistant to detergents, disinfectants, and decontaminants.

Improved Lighting

Smooth, reflective epoxy and polyurethane floor coatings have been successfully used on concrete floors in hangars and other work areas to supplement available lighting. These coatings must be resistant to contamination by fuels, hydraulic fluid, and lubricants. They frequently have aluminum oxide grit embedded in them to provide slip resistance.

Chemical Resistance

Coatings for concrete must be resistant to chemical attack. This is especially true for linings used for primary and secondary containment.

Electrical Continuity

Coatings for concrete floors may be formulated with conductive filler materials such as carbon to provide electrical continuity to dissipate static electricity. This is of importance in operating rooms, munitions plants, microchip manufacturing areas, and solvent storage areas where combustible vapors or dusts may be present.

Identification, Delineation, or Other Information

Painted markings on concrete floors, pavements, walls, or other surfaces can provide vital information for traffic control, identification, or hazards. Often, different colors are used for specific identifications.

Thermal Resistance

In some environments, coatings for concrete must have thermal resistance to:

- Continuous high temperatures
- Cycling temperatures
- Thermal shock from sudden temperature changes

Desired Coating Properties

Coatings for concrete must be specially formulated to provide the combination of specific physical and chemical properties required for the intended service. Some of the more important properties are described here.

Good Adhesion

Coatings applied directly to concrete must bond well and provide a good base for subsequent coatings. This requires a clean, profiled surface (as described in Reference 2) and a coating with good wetting and leveling properties.

Ease of Application

It is desirable that coatings for concrete surfaces be relatively easy to apply. The manufacturers' recommended instructions for application should always be carefully followed.

Alkali Resistance

Because concrete surfaces are normally very alkaline, coatings applied to them must have a high level of alkali resistance. This eliminates the use of alkyd and other drying oil coatings that are subject to alkaline hydrolysis (saponification).

Water Resistance

All coatings on concrete should have a low rate of water vapor transmission (WVT). This will control the penetration of water and the subsequent deterioration of coating and corrosion of reinforcing steel. On the other hand, there are times when a "breathing coating" with a higher WVT is desired to permit the slow escape of water vapor. A coating that seals a concrete surface is more susceptible to blistering and delamination from moisture attempting to escape.

Strength and Flexibility

Strong, hard coatings tend to bond well and have good chemical resistance but be relatively brittle and subject to physical damage. More flexible coatings, such as elastomers, resist impact well, can expand and contract with substrate movement, and can bridge small cracks. However, they are generally softer, less chemically resistant, higher in permeability, and less tightly bonded. The proper combination of strength and flexibility must be appropriate for the particular service.

Coefficient of Thermal Expansion

Significant differences in coefficients of linear thermal expansion (CLTE) between the coating and the concrete may cause stresses in the coating that result in loss of adhesion and/or cracking. Similarly, adjacent coats of different materials in a coating system should not have significantly different CLTEs. This may cause cohesive failure within the coating film or the concrete surface.

Chemical Resistance

Coatings for concrete surfaces in industrial environments should resist those stored products with which they may come into contact. Concentrations and temperatures of these products may also affect coating selection.

Resistance to Exterior Weathering

Of course, exterior finish coats must be resistant to weathering. This will protect their appearance as well as their durability. The sun's ultraviolet light will deteriorate aromatic coating materials, such as epoxies, phenolics, and aromatic polyurethanes.

Resistance to Physical Damage

Coatings must also be resistant to impact, adhesion, and traffic.

Definitions of Thin- and Thick-Film Coatings

Currently, there are no accepted definitions for thin- and thick-film coatings for concrete surfaces. For the purpose of this chapter, a thin-film coating is defined as a coating that:

- Is no greater than 20 mils (500 micrometers) in dry film thickness and not reinforced but may be filled with aggregate or other filler material
- Is applied by conventional means comparable to those used for coatings 20 mils [500 micrometers] or less dry film thickness on steel substrates
- Is not generally used in severe industrial service

A thick-film coating, then, would be greater than 20 mils (500 micrometers) dry film thickness and used in severe industrial environments. Obviously, this is an imperfect definition but it will help delinate most of the thick-film coatings that are used for primary and

secondary containment and monolithic flooring.

Thin-Film Coatings

General Compositions

Thin-film coatings for concrete are available in a variety of generic types with different physical and chemical dry film properties. They are much cheaper than thick-film products and have more limited physical and chemical properties, but are often successfully used for specific purposes, usually under mild service conditions. Thin-film coatings are frequently applied in two or more coats to provide (1) good adhesion of primer to the concrete, (2) fewer holidays, and (3) a special property such as slip resistance or electrical continuity.

Organic Binders

Organic binders are largely responsible for most of coating's chemical and physical properties. The binders must be chosen to meet desired environmental and service requirements, such as resistance to specific chemicals.

Pigments and Fillers

Pigmentation can be used to provide variations in color, gloss, and texture. They can also reduce film permeability and increase resistance to ultraviolet light. Fillers (e.g., silica or carbon) can be used to reduce costs or provide special properties (e.g., conductivity). They may constitute more than 50% of the coating weight.

Individual Generic Types

Water-Emulsion (Latex) Coatings. Water-emulsion coatings are used on concrete surfaces to provide an attractive finish or pavement markings. Acrylic coatings provide good flexibility and exterior weathering. Acrylic resins may also be used in block fillers to reduce permeability.

Relatively rigid textured coatings are most often acrylic emulsion formulations. Available in fine, medium, and coarse textures, they seal concrete surfaces from wind-driven rain and bridge fine cracks. The coarser their textures, the more susceptible they are to soiling and mildewing. Thin-film acrylic elastomers also perform well in bridging cracks and waterproofing concrete surfaces. Primers may be used to ensure adequate adhesion of elastomeric materials.

Two-Component (Thermosetting) Epoxies. Two-component, chemically-curing epoxies (not epoxy esters) find general use in waterproofing concrete surfaces and providing good chemical resistance. They are sometimes used to make concrete easier to decontaminate in both the chemical and nuclear industries. Amine-cured epoxies usually provide better chemical resistance than polyamide-cured epoxies. Polyamide-cured epoxies, however, provide better water resistance. They may contain 60 to 100% solids and are frequently topcoated with a coat of aliphatic polyurethane for exterior service.

Coal-Tar Epoxies. Coal-tar epoxy coatings perform well as linings for concrete waste water tanks and other interior industrial services. These linings are not useful in municipal waste water applications where sulfur-oxidizing bacteria are present or where the pH may drop below 3 or 4. During exterior exposures, they are susceptible to deterioration from ultraviolet light, chalking freely, becoming brittle, and losing adhesion.

Chlorinated Rubber and Vinyl Lacquers. Chlorinated rubber and vinyl lacquers were used successfully on concrete surfaces for many years. Their use has been virtually eliminated because of their high VOC content. The one exception to this limitation is the use of chlorinated rubber coatings for exterior swimming pools. Many local air pollution control districts permit this use, because no other generic type performs as well in this service.

Two-Component Acrylics. Two-component, 100% solids acrylics are cured by the further polymerization (cross-linking) of acrylic resins initiated by a peroxide catalyst. Proper formulation can produce such desirable properties as resistance to moisture, chemicals, and ultraviolet light.

Polyurethane (Two-Component and Moisture Curing). Moisture-curing and two-component (chemically-reacting) and polyurethanes (not uralkyds) can be formulated for use on concrete to produce films with a variety of desirable properties. They can range from hard-film to elastomeric products and provide protection equivalent to that of epoxies. However, they are

generally more expensive.

Siloxanes. Siloxane coatings provide good color retention, hardness, and moisture resistance. Because they are relatively new, they do not have the performance records of other coatings.

Thick-Film Coatings

Thick-film coatings for concrete are used most often as linings for primary and secondary containment and on industrial floors.[1, 5] In these and other industrial services, they must have good resistance to chemical attack and physical damage. On floors, they must also be resistant to heavy traffic and loading.

Binders

Most thick-film coatings are based on thermosetting polymers that impart chemical and physical properties that can be modified by the use of fillers, reinforcement, hybrid polymers, and plasticizers.

Pigments, Fillers, and Reinforcements

Pigments. Pigments can provide a variety of colors. They may also increase the coating's resistance to moisture penetration and ultraviolet light.

Fillers. Fillers are most often used to enhance the strength and other physical properties of coatings. Silica fillers are the most commonly used because of their low cost, inertness to chemicals, and other beneficial properties imparted. They are available in several compositions and particle sizes and shapes and may constitute up to 80% of the coating composition. More costly carbon fillers are normally used only to impart special properties, such as conductivity, not achievable with silica fillers. Other fillers may be used to impart special properties to a coating. Thus, an aluminum oxide filler may be added to improve impact resistance. Other reinforcing materials include carbon fiber and veils to provide conductivity, special chemical resistance, or a thicker barrier to the environment.

Reinforcements. Fiberglass is the most common reinforcing material for additional strength. It is mostly used in hand lay-up of woven fabric but may also be applied as chopped strands or loose mats. Fiberglass may constitute as much as 50% by weight of the coating system. On the other hand, resin-rich formulations are used for greater chemical resistance.

Shrinkage Problems

All thick-film coatings shrink to some extent during solvent evaporation and/or cross linking. This may vary with different formulations from less than 1% to more than 10%. Shrinking normally continues during aging by continuous cross-linking or other chemical reactions, producing stresses that may result in loss of adhesion and/or cracking. These stresses can be controlled to some extent by proper selection of polymer, fillers and reinforcement, and use of thinner coats to achieve the desired higher film thickness.

Individual Generic Types

Individual generic thick-film coatings are discussed in References 1 and 5, and this information is summarized here. Most thick-film coatings for concrete are proprietary formulations that may vary widely within a generic type to provide desirable properties and performances in a variety of aggressive environments.

Epoxies. The two-component (thermosetting) thick-film epoxies used for concrete in aggressive environments exhibit high strength, durability, adhesion, and resistance to a wide variety of chemicals but are not generally used in highly acidic service. Most epoxies, however, exhibit low flexibility and resistance to ultraviolet light. Glass or other inert fiber products can impart additional strength.

The two components of epoxy systems are epoxy resins and amine co-reactants (commonly called hardeners or catalysts). Most epoxy resins are derived from bisphenol A or bisphenol F, and phenol Novolac-based (EPN) resin.[6] For the new solvent-free epoxy coatings, a reactive diluent may be used to lower the viscosity to one more easily sprayed. Co-reactants include aliphatic amines, cycloaliphatic amines, amidoamines, and polyamides. Because of their high functionalities, EPN resins react with aliphatic or cycloaliphatic amines to form polymers with high cross-link densities and consequently high chemical resistance. Aromatic amine curing agents were once used extensively to form highly chemically resistant films. However, they are used less today because of their toxicities.

Unsaturated Polyesters. Unsaturated polyesters

exhibit high strength and generally good chemical resistance. Glass or other inert fiber can impart additional strength. They are prone to stress cracking from high shrinkage and low elongation. Polyester resins are produced by the condensation reaction of saturated and unsaturated acids with polyols. These resins are diluted with a vinyl co-reactant, typically styrene, to cross-link to form a larger molecular weight polymer. Methyl ethyl ketone peroxide, cumene hydroperoxide, and benzoyl peroxide are typically used as initiators and cobalt and tertiary amines as promoters.

Vinyl Esters. The properties of vinyl esters are generally similar to those of polyesters. Thermal cycling may further increase the stresses from high shrinkage and low elongation.

Polyurethanes and Polyureas. Polyurethane and polyurea coatings are available in a variety of formulations with differing dry film properties. A major use is as an elastomeric coating (>100% elongation) that can bridge hairline cracks and move with changes in substrate dimensions. These elastomeric products, however, have reduced chemical resistance. Aromatic formulations have poor resistance to ultraviolet light.

Polyurethanes and polyureas are two-component (thermosetting) polymers in which isocyanates are one of the reactants. With polyurethanes, the other reactants are polyols; with polyureas, the other reactants are amines. Often, mixtures of polyols and amines are reacted with isocyanates to produce polyurethane/polyurea hybrid products. Reference 7 describes the many different types of these coatings available for use today.

Polysulfides. Polysulfide elastomeric coatings have high elongation and ultraviolet resistance. As with polyurethane and polyurea polymeric coatings, the polysulfides have reduced chemical resistance.

Selecting Coatings

Coatings for concrete are selected for chemical and physical properties that meet the requirements for a particular service. These include:

- Interior or exterior use (Exterior coatings need ultraviolet protection)
- Thermal effects (temperature range, recycling, thermal shock)
- Contact with chemicals, solvents, and fuels (concentration and temperature)
- Anticipated physical abuse
- Importance of appearance
- Needed repairs and surface preparation before coating
- Expected dimensional changes

Each year, the June issue of the *Journal of Protective Coatings and Linings* contains the names and addresses of manufacturers of coating and lining materials for concrete as well as other substrates.[8] These manufacturers should be contacted about specific products for use on concrete.

Thin-Film Coatings

Information on thin film coatings can often be found in the June issue of the *Journal of Protective Coatings and Linings* as well listed by specific use, such as marking paints, garage deck coatings, and catchments.[9, 10]

Floor Coatings

Information on selecting floor coatings can be found in Reference 11.

Chemically Resistant Coatings

Reference 12 provides selection guidance for coatings and linings exposed to different chemical environments.

Coatings for Primary Containment

Information on linings for primary containment is described in Reference 4.

Coatings for Secondary Containment

Information can be obtained from References 1 and 4.

Summary

Many different compositions of thick- and thin-film coatings for concrete are available for a variety of different uses. Selection of a particular system should be based upon the desired chemical and physical properties for the particular use. General information on selecting appropriate materials is presented here. Contact with manufacturers' technical representatives for more detailed information about specific products.

References

1. SSPC-TU 2/NACE 6G197. *Design, Installation, and Maintenance of Coating Systems for Concrete Used in Secondary Containment;* SSPC: Pittsburgh, 1995.
2. ICRI Technical Bulletin 03732. *Selection and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays;* ICRI: Farmington Hills, MI, 1997.
3. ASTM F 1869. *Standard Test Method for Measuring Moisture Vapor Emission Rate of Concrete Subfloor Using Anhydrous Calcium Chloride;* ASTM: West Conshohocken, PA.
4. *The Fundamentals of Cleaning and Coating Concrete;* Randy Nixon and Richard W. Drisko, eds.; SSPC: Pittsburgh, PA, 2001.
5. NACE RP0892-92. *Coatings and Linings Over Concrete for Chemical Immersion and Containment Service;* NACE: Houston, 1992.
6. Thomas, E. Dail; Webb, Arthur A. The U.S. Navy Advances in Coating Ship Tanks. *Journal of Protective Coatings and Linings*, February 2001, pp 29-41.
7. Hare, Clive H. *Protective Coatings, Fundamentals of Chemistry and Composition,* Technology Publishing Company: Pittsburgh, 1994.
8. *Journal of Protective Coatings and Linings: Annual Buyer's Guide Issue,* Technology Publishing Company: Pittsburgh.
9. Mailvagnam, N. Waterproofing Garage Decks. *Materials Performance;* October, 1996.
10. Drisko, Richard W.; Yanez, Jeffrey R. Coatings for Concrete Surfaces. In *Proceedings of SSPC '89.*
11. Boova, A. A Guide to Selecting Industrial Flooring. *Journal of Protective Coatings and Linings,* February 1990.
12. Aldinger, Thomas I.; Fultz, Benjamin S. Selecting Coatings and Linings for Concrete in Chemical Environments. *Journal of Protective Coatings and Linings*, August 1995.

About the Author

Dr. Richard W. Drisko

Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society for Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy's center of expertise on coatings for shore structures. He is a professional corrosion engineer in the state of California, an SSPC certified protective coatings specialist (PCS), and a NACE International certificated corrosion specialist. Dr. Drisko received his BS, MS, and PhD degrrees from Stanford.

Chapter 4.3
Powder Coating

Albert G. Holder

Introduction

Powder coatings are dry rather than liquid products. The common constituents of coating films (resins, pigments, and modifiers) are also present in the powder. The powder is fused by heating to form a continuous protective or decorative film. This chapter describes different types of powder coatings, methods of applying them, and many of their uses.

Powder Manufacture

The resins, pigments, additives, and curing agents (for thermosetting powders) are mixed, homogenized, and dispersed at a temperature of about 194˚ to 248˚F (90˚ to 120˚C) to provide rapid wetting of the pigment with resin. This molten material is then cooled, ground to the desired particle size, and sieved to remove any course particles.

Types of Powder Coatings

Thermoplastic

As with conventional liquid coatings, thermoplastic powder coatings are not changed chemically during application or film formation. Thermoplastic powders are based on tough, high-molecular weight resins that tend to be difficult and expensive to grind to the consistently fine particles needed for spray application and fusing of thin films. Consequently, they are usually applied as thicker coatings by the fluidized bed application technique, described later in this chapter. Typical thermoplastic powder coatings include polyethylene, polypropylene, nylon, polyvinyl chloride, polyesters, and polyvinylidine fluorides/fluorocarbons. They have quite a few automotive uses, as well as domestic uses.

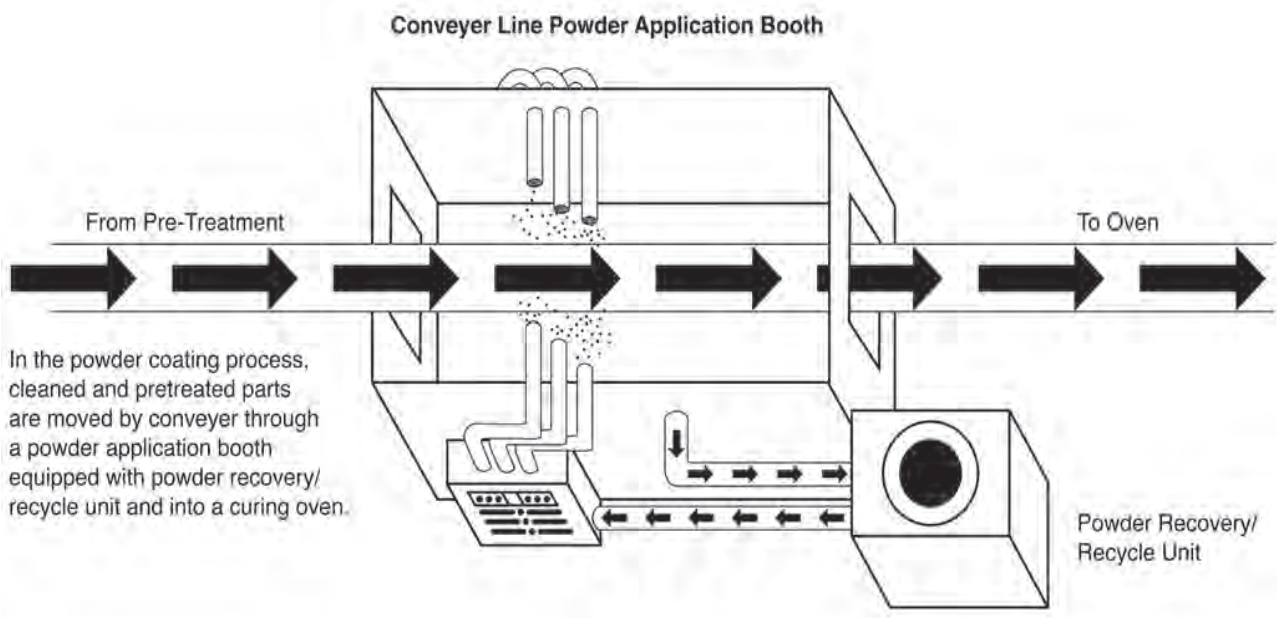


Figure 1. Powder coating is applied to a substrate and fused into a continuous film through the application of heat or radiant energy.

Thermosetting

Thermosetting powder coatings are based on lower molecular weight solid resins. These powders also melt when exposed to heat, forming a uniform thin layer. However, they chemically cross-link to form a reaction product with a much higher molecular weight structure very different from the starting resin. These newly formed materials are heat-stable and, unlike cured thermoplastic products, will not soften back to the liquid phase if heated again. Resins used in thermosetting powders can be ground into the fine particles necessary for spray application. Most of the technological advancements in recent years have concerned thermosetting powders, and they are used much more often than thermoplastic powder coatings. They are usually derived from three generic types of resins: epoxy, polyester, acrylic, and hybrids of these polymers.

Thermosetting powder coatings possess an excellent combination of appearance, corrosion protection, and chemical and physical properties. Thus, they find such versatile uses as coatings for furniture, shelving, plastic bottles, and appliances.

Decorative and Protective Characteristics

Powder coatings provide excellent product aesthetics, high-performance protection, and attractive economics. Characterized by outstanding toughness, corrosion resistance, flexibility, and adhesion, they also come in a variety of finishes: from low-to-high gloss and smooth-to-complex specialty textures. Generally, cured decorative thermosetting and thermoplastic powder coatings range in thickness from 1 to 6 mils and are used on metals, glass, wood, and plastic. Thermoplastic powders have a much higher dry film thickness.

Protective powder coatings are generally applied at a greater dry film thickness (10-20 mils) than decorative ones and provide long-term protection from corrosion on metal substrates. Epoxy powder coatings continue to be most frequently used. Some end uses for thermoplastic and thermosetting protective powders are anti-chip primers for truck seat frames, water heaters, metal cabinets, space heaters, riding mowers, rebar, piping, and lawn furniture.

Storing Powder Coatings

Powder coatings should be stored under dry, cool, clean conditions and at temperatures typically below 77°F (25°C). Typical adverse effects are:

- Excess heat—clumping of powder or partial reaction of fast or low temperature-curing powders to “B” state
- Dampness/water—poor application/appearance/performance
- Contamination—dust or other powders in coating film

Powders should always be stored away from sources of heat, sparks, and open flames with the container closed when not in use. It is good practice to bring quantities of powder into the application room the night before the job begins to promote temperature equalization when opening the container.



Figure 2. A bag of powder rests on a pallet. A hose transports the powder to the hopper where it falls through a vibrating sieve into a fluidized bed (sieve and bed not shown). Courtesy Dura Bond Coating, Inc.

Advantages and Limitations

Advantages include:

- Absence of solvents (virtually 100% solids; no VOCs)
- Transfer efficiency near 95–98 % with overspray recovery and reuse
- Good one-coat thickness (e.g., 6 mils) by electrostatic spray
- No solvent odor or flammability
- Easier compliance with federal and state regulations
- Reduced housekeeping problems
- Good edge application and retention
- Fast-cure, quick turnaround
- Can be applied to metal, wood, and plastic
- Multiple curing options such as heat, infrared (IR), UV, and “near” IR

Limitations include:

- Application usually limited to shops

• Powder suspensions in air may be explosive
• Difficulty in coating inside surfaces (Faraday “cage” effect; requires a tribo-gun)
• Occasional powder clumping
• Color changes may be time consuming/expensive

Surface Preparation

Parts to be coated should be exposed to a pretreatment operation to ensure that the surface is free of any contaminates. The pretreatment process normally takes place in a series of spray chambers where alkaline cleaners, iron or zinc conversion coatings, and rinses are applied.

For large areas, abrasive blast to SSPC-SP 5/ NACE 1 White Metal or SSPC SP 10/NACE 2 Near-White Metal, as recommended by the powder manufacturer, to achieve the profiles necessary for satisfactory bonding of the powder to the substrate.



Figure 3. Hot blast cleaned pipe goes through a water wash and then into another oven before entering the spray booth. The residual heat in the pipe will fuse and cure the epoxy powder coating within seconds of exiting the spray booth. Courtesy Dura Bond Coating, Inc.

Application Methods

Electrostatic Powder Spray

The electrostatic powder spray application system consists of five basic units: the powder supply unit, the spray gun, the power supply, the spray booth, and the powder recovery unit.

The powder delivery system consists of a powder storage container or feed hopper and a pumping device that transports a mixture of powder and air into hoses or feed tubes. These supply the



Figure 4. Electrostatic spray application of fusion-bonded epoxy powder onto a heated pipe. Courtesy Dura Bond Coating, Inc.



Figure 5. A worker monitors the temperature of the pipe as it exists the spray booth. The residual heat in the pipe will fuse and cure the epoxy powder coating within seconds of exiting the spray booth. Courtesy Dura Bond Coating, Inc.

powder to the applicator gun for electrostatic spraying. Pneumatic pumps driven by clean, dry compressed air are most often used to supply the powder, because they aid in dispersing the powder into individual particles for easier transport. Each powder pump supplies powder to one gun typically located several feet from the powder supply area. Delivery systems

are available in many sizes. Proper selection depends on the application, number of guns to be supplied, and volume of powder to be sprayed in a given time period. Recent improvements in powder delivery systems, coupled with better powder chemistries to minimize clumping, have improved particle flow to the gun. Some feed hoppers vibrate to help prevent clogging or clumping.

Manual and automatic electrostatic spray guns direct the flow of powder and control the pattern size, shape, and density of the spray as it is released from the gun. The gun also imparts the electrostatic charge to the powder and controls the deposition rate onto the electrically conductive, grounded item to be coated. There are two basic types of electrostatic powder spray guns, external (corona charging) guns and internal (tribo charging) guns.

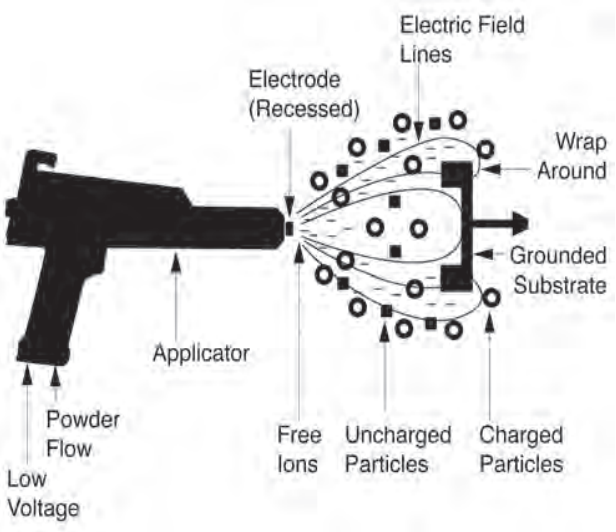


Figure 6. Spray gun principle.



Figure 7. Spray guns.

External charging guns have a charging electrode at the front of the gun that produces an electric field (corona) through which the powder particles pass and become charged. The charged particles are directed by the electrostatic field to deposit them onto the intended surface. The film thickness can be controlled by the application conditions or the properties of the powder. One drawback to the external charging gun is the relative difficulty of coating irregularly shaped parts in recessed areas or cavities.

Internal charging (tribo) guns have an internal electrode system that charges powder particles passing through the gun. These guns require more maintenance than external charging guns but do not create an actual electrostatic field and so are not so susceptible to the Faraday “cage” effect in recessed areas and cavities. The power supply must provide the necessary voltages for charging the powder during application. These voltages will vary with different applications.

The primary function of the powder spray booth is to safely contain the powder so that overspray cannot migrate into other areas. Several criteria must be met in selecting the appropriate spray booth for a given coating line. The entrance and exit openings must be properly sized to allow clearance of the largest product part. The air flow through the booth must be sufficient to channel all overspray to the recovery system, but not so forceful that it disrupts powder deposition and retention. This is usually accomplished by maintaining a minimum average face velocity of 100 ft/min across all end openings. The air flow must also prevent the accumulation of powder in the air from approaching the lower explosive limit. If one booth is to be used to apply multiple colors, the booth interior should be free of narrow crevices, seams, and irregular surfaces that would be difficult to clean. This is especially important if collected overspray is to be recycled. Because there is no solvent loading in the air exhausted from a powder coating booth, the air can be circulated back into the plant. This saves considerable energy during winter months. Color changes can be accomplished in a relatively short period of time if one independent booth is used to replace the one in need of cleaning.

Recovery and recycling systems are an integral part of the powder spray booth, allowing most overspray to be reused. The three commonly used

types of powder recovery systems are conventional (i.e., cyclone), filter belt, and cartridge (replaceable cartridge filters). The recovered powder is blended with virgin powder before reuse.

Fluidized Powder Bed

In this process, the item to be coated is heated to a temperature above the melting point of the powder and immersed in a fluidized bed where the powder fuses to it. The powder is fluidized by passing compressed air through a porous membrane at the bottom of the container in which the application is conducted. Coating thickness is determined by substrate temperature and time immersed in the fluidized bed. Attaining the proper cure of the deposited powder may require additional heating.



Figure 8. Powder is applied by flame spray to a small steel part. Courtesy KCC Thermocoat.

Electrostatic Fluidized Bed

The electrostatic fluidized bed process uses electrodes in the fluidized bed to charge the air and then the powder in the fluidized bed. This process is ideally suited to substrates that have a relatively small vertical dimension, such as flat sheets, expanded metal, wire mesh, screen, cable, and tubing. Preheating is not necessary. The electrical force will cause the powder to adhere to the cold or heated surface.

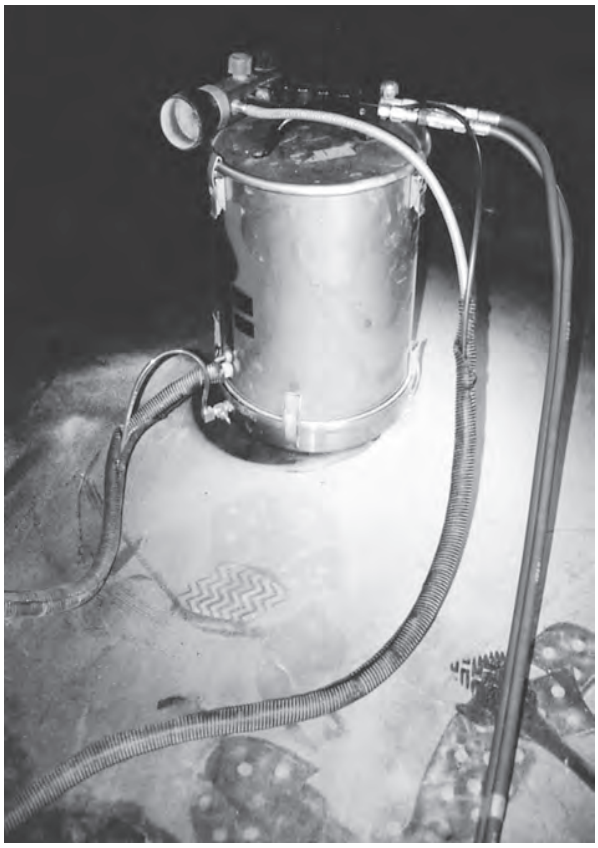


Figure 9. A flame spray gun connected to a fluidized bed. Courtesy KCC Thermocoat.

Thermal Spray of Thermoplastic Powders

In the thermal spray application of thermoplastic powder coatings, the atomized powder is melted in a propane or acetylene flame and deposited in a molten or semi-molten condition to form a continuous coating. To achieve optimum adhesion, the steel surface must be very clean (e.g., SSPC-SP 10). However, the steel is commonly cleaned by simply burning away any extraneous matter and condensation. Advantages of this method of application include:

- Good for field application (no oven required)
- Can coat non-conductive materials (wood, concrete, plastics, etc.)
- Can coat temperature sensitive materials

Limitations include:

- Performance affected by surface cleanliness
- Performance affected by quality of application
- Overheating powder may deteriorate resin
- Tight particle size distribution required



Figure 10. The container for the fluidized bed comes apart for easy cleanup. Courtesy KCC Thermocoat.

Oven Curing

Convection and infrared ovens or a combination of the two are used to cure powder coatings applied in shops. Air is heated and circulated inside gas or electric convection ovens to surround the powder-coated parts, which are heated to oven temperature for curing. Infrared (IR) ovens using either gas or electricity as their energy source emit radiated energy that is absorbed by the substrate to promote curing. Specially formulated thermosetting powders may be cured with ultra-violet (UV) light sources.

Combination ovens generally use IR in the first "zone" to melt the powder quickly. The substrate then passes into the convection zone, which uses high-velocity currents to permit faster heat transfer and a shorter cure time since there is no danger of disturbing the coating once it exits the IR zone. Most oven systems are positioned to be part of the conveyor line.

Cure temperature depends on the type of powder coating, the coating thickness, and the type of substrate. The average temperature usually ranges from 250°F to 350°F (121°C to 177°C).

Film Thickness

Powder coatings can be applied in a wide range of film thicknesses. Continuous thermosetting films as low as 0.5 mils (0.0005 inch) can be applied, as can specialized applications that require as much as 10 mils or more. Very thin films require special powder grinds. Extremely heavy films are generally achieved by coating the substrate while it is hot.

The normal thickness range for the majority of thermosetting powder applications is 1.0-4.0 mils with an average target value of 1.5 mils. The part's function and its expected environmental exposure will dictate the coating material and the desired film thickness.

Transfer Efficiency

Powder coating transfer efficiency is generally defined as the ratio of powder weight deposited on the part or parts to the total amount of powder weight sprayed. Recovered powder is not considered in this calculation. Many factors can affect transfer efficiency, including operator proficiency, shape of the part, booth design, condition of the spray equipment, part grounding, powder condition, and application technique.

Summary

Powder coatings are available in several compositions and have several methods of application and curing. These can be used to provide protective and decorative coatings to many industrial and domestic products.

Suggested Reading

Technical Brief 1; The Powder Coating Institute: Alexandria, VA.

Powder Finishing: http://www.pfonline.com (accessed April 2002).

Dow Plastics Form No. 296-940-1000 SMG.

User's Guide to Powder Coating; Association for Finishing Processes; Society of Manufacturing Engineers: Dearborn, MI.

Wicks, Jr., Zeno W.; Jones, Frank N.; Pappas, S. Peter. *Powder Coatings Educational Series—Part I: Binders for Thermosetting Powder Coatings,* pp 41-46; *Part II: Binders for Thermoplastic Powder Coatings,* pp 47-51; *Part III: Manufacturing Powder Coatings,* pp. 43-47; *Part IV: Application Methods: Advantages and Limitations,* pp 67-73 (May-August, 1999).

Powder Coating—The Complete Finisher's Handbook; Powder Coating Institute: Alexandria, VA.

Introductory Training Manual for Powder Coating Line Workers (English and Spanish); Powder Coating Institute: Alexandria, VA.

Jilek, Josef H. *Powder Coating;* Federation of

Societies for Coatings Technology: Blue Bell, PA.
Misev, T.A. *Powder Coatings: Chemistry and Technology;* John Wiley & Sons: Chichester, UK.
Panosky, Mark. Powder Coating of Large Ship Structures. In *Proceedings of SSPC '99,* pp 367-376.

Bibliography of ASTM Standards for Powder Coatings

B 859-95(2000) *Standard Practice for De-Agglomeration of Refractory Metal Powders and Their Compounds Prior to Particle Size Analysis.*
B 855-94(1999)e1 *Standard Test Method for Volumetric Flow Rate of Metal Powders Using Arnold Meter and Hall Funnel.*
B 895-99 *Standard Test Methods for Evaluating the Corrosion Resistance of Powder Metallurgy (P/M) Stainless Steel Parts/Specimens by Immersion in a Sodium Chloride Solution.*
C 1457-00 *Standard Test Method for the Determination of Total Hydrogen Content of Uranium Oxide Powders and Pellets by Carrier Gas Extraction (O/U) Atomic Ratio of Nuclear Grade Uranium Dioxide Powders and Pellets.*
C 1494-01 *Standard Test Methods for Determination of Mass Fraction of Carbon, Nitrogen, and Oxygen in Silicon Nitride Powder.*
D 2396-94(1999)e1 *Standard Test Methods for Powder-Mix Time of Polyvinyl Chloride (PVC) Resins Using a Torque Rheometer.*
D 2967-96 *Standard Test Method for Edge Coverage of Coating Powders.*
D 267-82(1999) *Standard Specification for Gold Bronze Powder.*
D 3214-96 *Standard Test Methods for Coating Powders and Their Coatings Used for Electrical Insulation.*
D 3451-01 *Standard Guide for Testing Coating Powders and Powder Coatings.*
D 4217-91(1995)e1 *Standard Test Method for Gel Time of Thermosetting Coating Powder.*
D 4242-91(1995)e1 *Standard Test Method for Glass Plate Flow for Thermosetting Coating Powders.*
D 4266-96 *Standard Test Methods for Precoat Capacity of Powdered Ion-Exchange Resins.*
D 480-88(1999) *Standard Test Methods for Sampling and Testing of Flaked Aluminum Powders and Pastes.*
D 4456-99 *Standard Test Methods for Physical and Chemical Properties of Powdered Ion Exchange Resins.*
D 521-90(1999) *Standard Test Methods for Chemical Analysis of Zinc Dust (Metallic Zinc Powder).*
D 5382-95 *Standard Guide to Evaluation of Optical Properties of Powder Coatings.*
D 5861-95 *Standard Guide for Significance of Particle Size Measurements of Coating Powders.*
D 5965-96 *Standard Test Methods for Specific Gravity of Coating Powders.*
D 6441-99ae1 *Standard Test Methods for Measuring the Hiding Power of Powder Coatings.*
D 731-95 (1999) *Standard Test Method for Molding Index of Thermosetting Molding Powder.*
D 962-81 (1999) *Standard Specification for Aluminum Powder and Paste Pigments for Paints.*
D 964-65 (1996)e1 *Standard Specification for Copper Powder for Use in Antifouling Paints.*
E 159-00 *Standard Test Method for Hydrogen Loss of Cobalt, Copper, Tungsten, and Iron Powders.*
E 194-99 *Standard Test Method for Acid-Insoluble Content of Copper and Iron Powders.*
E 1569-93 (1998) *Standard Test Method for Determination of Oxygen in Tantalum Powder.*
F 7-95 (2000) *Standard Specification for Aluminum Oxide Powder.*

Acknowledgements

The author and SSPC gratefully acknowledge Jeffery B. Palmer of the Powder Coatings Institute, Gloria J. Holder of Raytheon Service Corporation, and Elizabeth Haslbeck and Regis Conrad of the Naval Surface Warfare Center, Carderock Division for reviewing this chapter.

About the Author

Albert G. Holder

During his tenure as a chemist at the Naval Surface Warfare Center, Carderock Division, Albert G. Holder has been instrumental in introducing powder coatings for high-abrasion protection and polyurea snap-cure coatings for high-cavitation areas as a result of his laboratory and field evaluations of coatings for corrosion control on U.S. Navy ships. He has been a member for many years of the Federation of Societies for Coatings Technology and is active in the Baltimore Society for Coatings Technology. Also a member of SSPC and NACE, Mr. Holder has a B.Sc. in chemistry from Coppin State College.

Chapter 4.4
Thermal-Spray (Metallized) Coatings for Steel

Robert A. Sulit

Introduction

Thermal-spray coatings (TSCs) are used extensively for the corrosion protection of steel and iron in a wide range of environments. The corrosion tests carried out by the American Welding Society and the 34 and 44 year marine-atmosphere performance reports of the LaQue Center for Corrosion Technology confirm the effectiveness of flame-sprayed aluminum and zinc coatings over long periods of time in a wide range of hostile environments.[1, 2, 3] The British Standards Institution code of practice for the corrosion protection of steel specifies that only TSCs give protection greater than 20 years to first maintenance for the 19 industrial and marine environments considered and that only sealed, sprayed aluminum or zinc gives such protection in sea water immersion or splash zones.[4]

In Federal Highway Administration laboratory and field trials of low VOC coatings for the protection of steel bridges, 85/15 Zn/Al, 99.9 Zn, and 99.9 Al TSCs demonstrated the best corrosion performance among 34 coating systems. Metallized coatings have zero VOC. Conclusions are based on 6.5-yr. panel testing in a severe marine exposure site and 5-yr panel testing on three bridges in different but severe corrosion environments.[5] The 85/15 Zn/Al over SSPC 10/NACE 2 near-white metal blast is estimated to reach 5-15% degradation in a severe marine environment in 30 years.

The current industry standard for the application of TSCs is SSPC CS 23.00, *Specification for the Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc and Their Alloys and Composites for the Corrosion Protection of Steel*.[6] The qualifications for metallizing contractors are specified in the SSPC-QP series of qualification procedures for coating contractors.[7]

Thermal Spraying

Thermal spraying is a group of processes in which the thermal-spray feedstock material is heated, atomized, and propelled by a conveying gas stream and deposited to form a laminar TSC on a prepared substrate **(Figure 1a).**

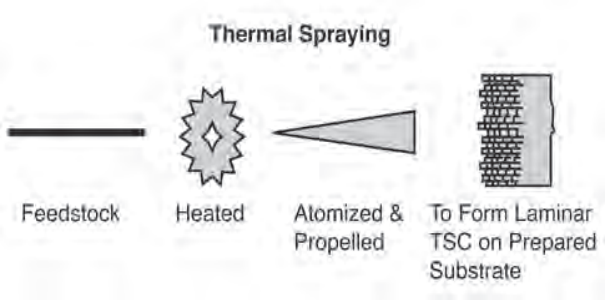


Figure 1a. Thermal spraying.



Fig. 1b. Arc spraying 85/15 on the interior of a 7 ft. diam. pipe over the Missouri River in Montana. Courtesy Montana Dept. of Natural Resources and Conservation

The material used may be in the form of a powder or wire. The thermal spray gun generates the necessary heat by using combustible gases or an electric arc. As the materials are heated, they are changed to a plastic or molten state, atomized, confined, and accelerated by a compressed gas stream to the substrate. The

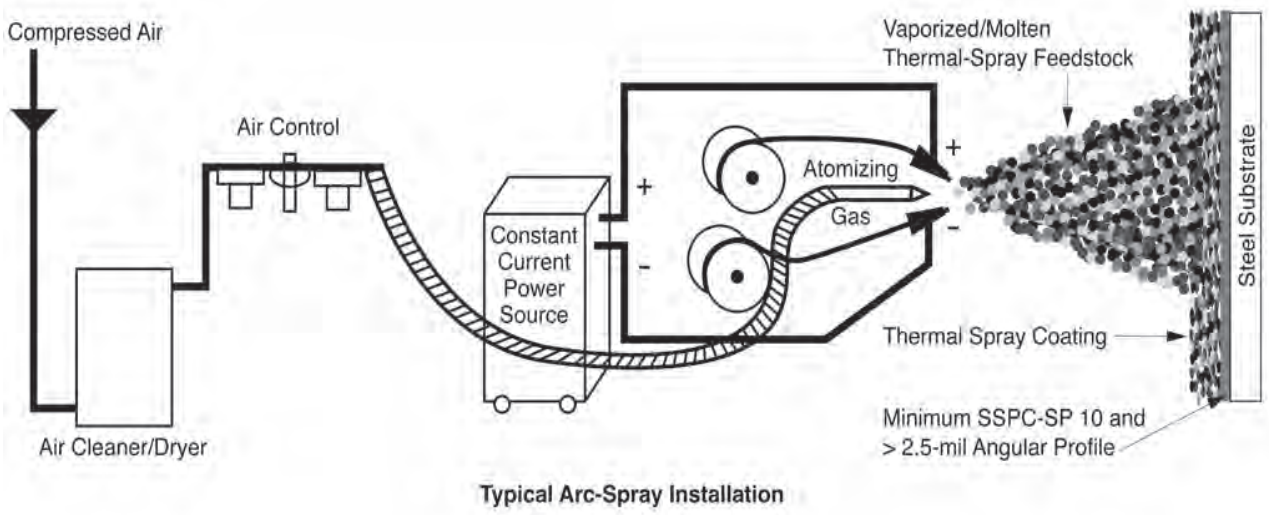


Figure 2. Typical arc-spray installation.

particles strike the substrate, flatten, and form thin platelets (splats) that conform and adhere to the irregularities of the prepared substrate and to each other.

Electric Arc Spraying

TSCs of zinc, aluminum, or their alloys, are used infrastructure corrosion-control applications, primarily applied by the electric arc thermal-spray process. Arc spraying production rates are 3 to 5 times faster than flame spraying concomitant with less energy cost.

In the arc-wire process, two consumable wire electrodes that are insulated from each other automatically advance to meet at a point in an atomizing gas stream. A potential difference of 18 to 40 volts applied across the wires starts an arc that melts the tips of the wire electrodes. An atomizing gas stream, usually compressed air, is directed the arc zone, shearing off molten droplets that form the atomized spray.

The arc spray system is shown in **Figure 2.** Wire electrodes are fed through wire guides and into the contact tips. The atomizing nozzle conducts the compressed air and directs it across the arc zone. Insulated power cables connect the gun to the DC power source. Arc guns also include mechanisms for feeding the wire at a controlled rate. Contact tips are sized for a particular wire diameter. A trigger switch on the gun controls the wire feed, compressed air supply, and electric power. During the melting cycle, the feed wire is super heated to the point where some volatilization may occur. The high particle temperatures produce metallurgical interactions and/or diffusion zones after impact with the substrate. These localized reactions form minute weld spots with good cohesive and adhesive strengths.

Safety

Potential thermal-spraying hazards include exposure to vapors, metal dust, fumes, gases, noise, and arc ultraviolet (UV) radiation. Uncontrolled metal dust is an explosion and inhalation hazard. Improperly used thermal-spray equipment can create potential fire and explosion hazards from the fuel gases and a potential electrical shock hazard from the electrical and electronic equipment and charged wire spools. Follow proper safety precautions to minimize hazards. Operators must comply with the procedures in the safety references, the manufacturer's technical information, and Material Safety Data Sheets. A summary of thermal-spray safety information may be found in SSPC CS 23.00A, Part B: Guide 8.

Thermal-Spray Coatings (TSCs) for the Corrosion Protection of Steel

Aluminum, zinc, and their alloys provide both barrier and galvanic protection; barrier protection when applied in non-through-porosity thickness, galvanic protection when applied in a through-porosity thickness. Zinc's greater chemical activity provides greater galvanic protection than aluminum. Aluminum's lower

Table 1. Estimated Service Life of Aluminum TSCs.

	Coating Thickness required for Service Life (μm) [mil]			
Environment	**5-10 yrs.**	**10-20 yrs.**	**20-40 yrs.**	**>40 yrs.**
Rural Atmosphere	—	—	50-200 [2-8]	—
Industrial Atmosphere	—	150-200 [6-8]	250-300 [10-12]	300 [12]
Marine Atmosphere	150-200 [6-8]	200-250 [8-10]	250-300 [10-12]	300 [12]
Sea Water Immersion	200-250 [8-10]	250-300 [8-10]	300-350 [12-14]	—
Fresh Water Atmosphere	150-200 [6-8]	200-250 [8-10]	250-300 [10-12]	—
High Temperature	200-250 [8-10]	250-300 [10-12]	—	—

Table 2. Estimated Service Life of Zinc and 85/15 Zn/Al-Alloy TSCs.

	Coating Thickness required for Service Life (μm) [mil]			
Environment	**5-10 yrs.**	**10-20 yrs.**	**20-40 yrs.**	**>40 yrs.**
Rural Atmosphere	—	75-125 [3-5]	150-200 [6-8]	250-300-[10-12]
Industrial Atmosphere	—	150-200 [6-8]	300-375 [12-15]	350-400 [14-16]
Marine Atmosphere	—	250-300 [10-12]	300-375 [12-15]	350-400 [14-16]
Fresh Water Atmosphere	150-200 [6-8]	250-300 [10-12]	300-375 [12-15]	—
Potable Water		250-300 [10-12]	300-375 [12-15]	—
Sea Water Immersion	250-300 [10-12]	350-400 [14-16]	—	—

Table 3a. Predicted Service Life for Selected Thermal Spray Applications[A].

Application	Paint System	Typical Paint Service Life	TSC System (minimum/ average TSC thickness)	Predicted Thermal Spray Service Life
Penstocks	Coal tar epoxy	20 - 30 years	360/400-µm (14/16-mil) 85/15 Zn/Al	30 - 40 years
Tainter gates	Vinyl zinc-rich	20 - 25 years	360/400-µm (14/16-mil) 85/15 Zn/Al	25 - 35 years
Tainter and roller gates (interior)	Vinyl	25 - 40 years	360/400-µm (14/16-mil) 85/15 Zn/Al	40 - 50 years
Tainter gates (very turbulent ice- and debris-laden water)	Vinyl zinc-rich	1 - 2 years	360/400-µm (14/16-mil) 85/15 Zn/Al	8 - 12 years
Roller gates	Vinyl zinc-rich	25 - 30 years	360/400-µm (14/16-mil) 85/15 Zn/Al	30 - 40 years
Service bridges	Alkyd/phenolic	10 - 15 years	250/300-µm (10/12-mil) 85/15 Zn/Al; or 250/300-µm (10/12-mil) Zn	50 - 60 years
Sector gates (seawater)	Epoxy zinc-rich/coal tar epoxy[5]	15 - 20 years	200/250-µm (8/10-mil) Al	20 - 40 years

A Adapted from EM 1110-2-3401.

chemical activity, adherent oxide film, and higher wear and temperature resistance as compared to zinc, provides longer term protection along with high-temperature and abrasion/wear resistance.

When zinc is alloyed with aluminum, the zinc-rich spray material forms an effective corrosion-resistant coating, having the attributes of both elemental components. 85/15 Zn/Al alloy and pseudo Al-Zn alloy, produced by arc spraying Al and Zn wires, can be used to maximize their alloy performance over their individual performance. In this case, the corrosion resistance of zinc is combined with the severe-environment and high-temperature resistance of aluminum. When cut to expose the substrate steel, or when applied in a through-porosity thickness, these TSCs will retard corrosion through cathodic protection.

Selecting TSCs

The selection of TSCs should be based on the service environment and the desired service life: **Table 1** illustrates the service life for aluminum TSCs and **Table 2** the service life for zinc and zinc/aluminum alloys.[9]

U.S. Army Corps of Engineers (USACE) has experience with 85-15 zinc-aluminum alloy coating (0.016 in. [400 mm]) providing 10 years of service in very turbulent ice- and debris-laden water.[10] **Table 3a** shows typical service lives of paint coatings and predicted service life of TSCs for selected USACE applications.

Sealing and Topcoating TSCs

TSCs of aluminum, zinc, and their alloys have porosity ranging up to 15%. Interconnected porosity will extend from the surface to the substrate when the TSC is applied at less than a non-through porosity thickness. Sealing fills the porosity extending the service life of the TSC. Sealing is accomplished by applying thin sealer coatings that will penetrate into and are absorbed into the pores of the TSC or naturally by the oxidation of the sprayed aluminum or zinc filling the pores with a tightly adherent oxide layer. The seal coat must be applied before significant natural oxidation occurs to be effective. The pigment particle size for colored sealers must be small enough to flow easily into the pores of the TSC, nominally a 5-fineness grind per ASTM D 1210.[11]

For service temperatures > 250°F [120°C], a high-temperature resistant coating such as an aluminum pigmented silicone sealer is required.

Sealed TSCs are preferable to topcoated TSCs. Sealed TSCs should be topcoated only when: (1) the environment is very acidic or very alkaline, i.e., when pH is outside the range of 5 to 12 for zinc and zinc alloy TSCs or 4 to 9 for aluminum and 90/10 MMC TSCs; (2) the metal is subject to direct attack by specific chemicals; (3) the required decorative finish

can be obtained only with a topcoat; and (4) when additional abrasion resistance is required. Topcoat materials must be compatible with the TSC material, sealer, and the intended service environment. Never topcoat an unsealed TSC.

Examples

There is a history of aluminum and zinc TSC corrosion protection for structural steel work: buildings, bridges, towers, radio and TV antenna masts, steel gantry structures, high-power search radar aerials, overhead walkways, railroad overhead line support columns, electrification masts, tower cranes, traffic island posts, and street and bridge railings.

Zinc TSCs complement hot-dip galvanizing and should be considered when fabrications are excessively large or otherwise cannot be hot-dip galvanized. Zinc TSC should also be considered for repairing galvanized coating damaged during the fabrication process (e.g., welding, cutting and joining areas) and for maintenance recoating. Here, a zinc TSC is particularly advantageous because it ensures the uniformity and reproducibility of the galvanized coating thickness.

Wellhead valve assemblies, for offshore use, have been thermal-spray coated for salt atmosphere protection since the 1950s. Aluminum TSCs are used for high-temperature corrosion protection of flare stacks. Aluminum and zinc TSCs have been used for external protection of oil and propane gas storage tanks. TSCs have been used to protect pipelines against many environments. Pile couplings, valves, sewer covers, industrial gas bottles, and other small industrial items are candidates for TSCs.
The interior of steel hopper rail cars for hauling coal have been sprayed with aluminum for sulfuric-acid corrosion protection and with aluminum composite for both corrosion and abrasion protection. Steel car exteriors have been sprayed with zinc for atmospheric-corrosion protection.

Zinc TSCs are used to protect potable water pipelines and storage tanks as specified in ANSI/AWWA D-102-78, *American Water Works Association Standard for Painting Water-Storage Tanks.*[12] Aluminum and zinc TSCs are used on sluice gates in irrigation systems and canal lock gates in shipping canals.

Sealed aluminum and zinc TSCs improve the corrosion resistance of steel bridgework and railings subjected to marine and de-icing salts. Reinforcing steel in concrete can be zinc sprayed to retard corrosion. Reinforced concrete bridges and highways, especially in those in marine and freezing environments where de-icing salts are used, commonly suffer from chloride intrusion into the concrete followed by reinforcing steel corrosion and concrete spalling. Zinc TSCs are used for reinforcing steel protection prior to pouring the concrete. Zinc TSCs are sprayed directly on bridge concrete substructures to provide a sacrificial protection coating or to be a secondary anode when electrically connected to an impressed current cathodic protection system.

In marine applications, ship structural areas and components are preserved with aluminum and zinc TSCs. The U.S. Navy uses aluminum TSCs in new ship construction and in the overhaul, repair, and maintenance of ship structures and for a wide range of shipboard components, especially those in topside and wet spaces.[13] The British, Australian, and New Zealand Navies use a duplex zinc (base) and aluminum (top) TSC system. Commercial shipping and barges have used TSCs to preserve ship superstructures and a range of topside and interior components.

TSC Cost

This section contrasts paint and TSCs based on cost and expected service life.[10] Both paint and TSCs may be used to provide corrosion protection. The use of TSCs is preferred on the basis of fitness-for-purpose for a few specific applications including corrosion protection in very turbulent ice- and debris-laden water, high-temperature applications, and zebra-mussel resistance. TSCs may also be selected because of restrictive air pollution regulations that do not allow the use of some paint with excessive VOC emissions. For all other applications the choice between thermal spray and paint coatings should be based on cost.

Whenever possible, coating selection should be based on life cycle cost. Because of their somewhat higher first cost, TSCs are often overlooked. To calculate life cycle costs the installed cost of the coating system and its expected service life must be known. Life-cycle costs for coating systems are readily compared by calculating the average equivalent annual cost (AEAC) for each system under consideration.

The basic installed cost of a TSC system is

Table 3b. Stepwise Procedure.

(1)	Calculate the surface area (SA).	SA = Length x Width
(2)	Calculate the volume (V) of coating material needed to coat the area.	V = SA x Coating Thickness
(3)	Calculate the weight (Wd) of the material to be deposited. The density (D) of the applied coating is less than that of the feedstock material. A good assumption is that the applied coating is about 90-percent of the density of the feedstock material.	Wd = V x 0.9D
(4)	Calculate the weight (W) of material used. Estimates of deposition efficiency (DE) for various materials and thermal spray processes are given in Table 4.	W = Wd/DE
(5)	Calculate the spray time (T). Spray rates (SR) for various materials and thermal spray processes are given in Table 5.	T = W/SR
(6)	Calculate electricity or oxygen and fuel gas consumption (C). Typical consumption rates (CR) for electricity, fuel gas, and oxygen are available from equipment manufacturers.	C = CR x T
(7)	Calculate cost of materials (CM).	CM = W x cost per unit weight
(8)	Calculate cost of application (CA).	CA = T x unit labor cost
(9)	Calculate cost of consumables (CC).	CC = T x unit cost of consumable
(10)	Calculate total cost (TC) of TSC.	TC = CM + CA + CC

calculated by adding the costs for surface preparation, materials, consumables, and thermal spray application. The cost of surface preparation is well known. The cost of time, materials, and consumables may be calculated using the "stepwise" procedure shown in **Table 3b.**

Table 4. Deposit Efficiency of Thermal Spray Processes.

Material	Wire Flame Spray	Powder Flame Spray	Arc Spray
Zinc	65-70%	85-90%	60-65%
Aluminum	80-85%	85-90%	70-75%
85-15 Zn-Al	85-90%	N/A	70-75%

Other factors that increase the cost of thermal-spray and other coating jobs include the costs of containment, inspection, rigging, mobilization, waste storage, and worker health and safety.

Design Guidance and Process Standards

Design Guidance

Applying TSCs for the protection of steel structures and components requires comparable design considerations as that for high-performance paint-coating systems, i.e., material selection, geometry and surface considerations in the structural design and during fabrication/assembly, accessibility for surface preparation, coating application, and in-service maintenance and repair. Design guidance documents suitable for thermal-spray systems are listed in the reference section.[4, 10, 14, 15]

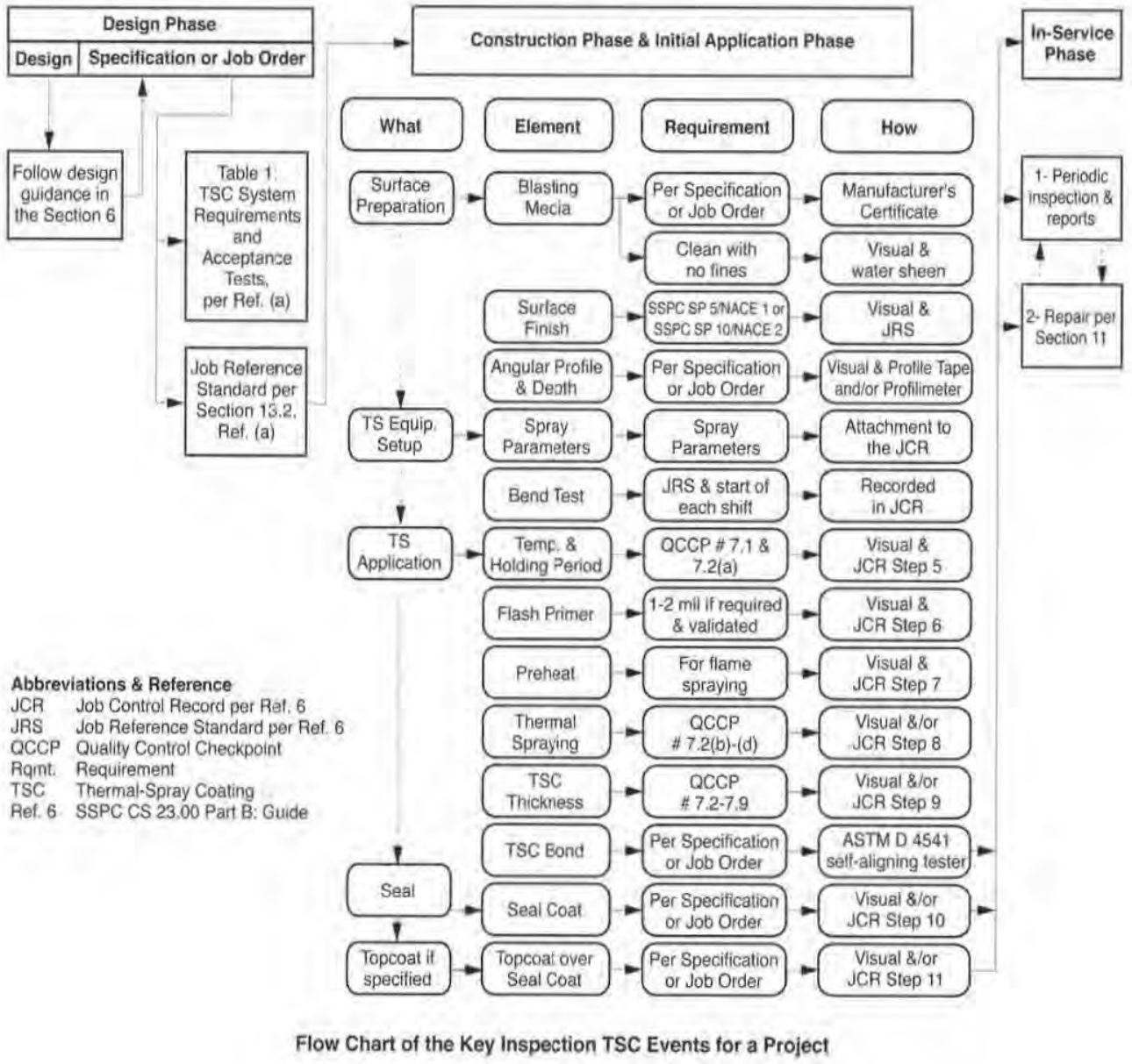
Process Standards

There are two thermal-spray process standards for the corrosion protection of steel in the U.S. and one ISO standard. These are also listed in the reference section.[6, 13, 16]

Inspecting Thermal-Spray Coatings

Inspection Requirements

The requirements and methods for inspection of thermal-spray coatings should be considered during the initial design and implemented/updated during the fabrication and assembly of steel structures and their components. The TSC system requirements for initial application and in-service performance should be established to parallel to other inspection requirements. Inspection should be based on inspecting and documenting the major planning, production, and maintenance and repair actions for the life-cycle support of the structural and components of the TSC system. The flow chart **(Figure 3)** shows the key thermal-spray inspection events for a project. The construction and initial application phase includes the



Flow Chart of the Key Inspection TSC Events for a Project

Figure 3. Flow chart of the key inspection TSC events for a project.

Table 5. Inspection Requirements.

Material	Wire Flame 2.4 mm wire	Wire Flame 3.2 mm wire	Wire Flame 4.8 mm wire	Powder Flame Spray	Arc Spray (per 100 A)
Zinc	9.1	20	30	14	18
Aluminum	2.5	5.4	7.3	6.8	2.7
85-15 Zn-Al	8.2	18	26	N/A	16

application process and quality-control checkpoints detailed in SSPC CS 23.00.[6]

It is important to note that the TSC procurement contract or the job order must specify the inspection requirements, i.e., the acceptable parameters and measurement methods per Table 1 of SSPC CS 23.00. If inspection requirements and methods are not specified, the inspection and corrective action for deficiencies cannot be contractually binding on the applicator.

Design Phase

Establish TSC system requirements and inspection acceptance tests comparable to Table 6 in SSPC CS 23.00. The design engineer, in the contract, should define the TSC specifications, application process, and inspection and acceptance requirements. The contract specifications should be based and balanced (traded off) with the project engineering requirements, and construction schedule on a life-cycle basis. The design should specify the key (mandatory) inspection items, acceptance values, and their sequence in the construction, overhaul, or repair schedule. The thermal-spray inspection actions should also be integrated into the overall project inspection schedule.

Construction Phase

During the construction phase, the key inspection events include surface preparation, thermal-spray equipment setup, TSC application, and sealing or sealing and topcoating. The in-process QC checkpoints are those cited in SSPC CS 23.00.[6]

In-Service

Establish the TSC in-service inspection actions and schedule to conform to the anticipated wear and degradation for the service environments and wear/abrasion duty cycles. The TSC inspection should be harmonized with other project inspection requirements to minimize inspection time and resources. Refer to SSPC-PA Guide No. 5, *Guide to Maintenance Painting Programs, for additional information.*[17] Repair TSCs per ANSI/AWS C2.18, *Guide for the Protection of Steel with Thermal Sprayed Coatings of Aluminum and Zinc and Their Alloys and Composites.*[8]

TSC System Requirements and Application Process

Proper surface preparation is mandatory to the successful application of a TSC. Accordingly, if separate contractors perform the surface preparation and thermal spraying, the suitability of the surface preparation should be approved by the TSC applicator. The procurement contract should account for this interaction among the owner's inspector and the surface-preparation and thermal-spraying contractors.

The major production and QC activities shown in **Figure 4** are taken from SSPC CS 23.00.[6] The applicable Section and Quality Control Checkpoint (QCCP) numbers are noted in the lower right-hand corner of each process action. A summary of the key production step follows.

Surface Preparation

The steel substrate should be prepared to (1) white metal finish, SSPC-SP 5/NACE 1, for marine and immersion service, or (2) the minimum of near-white metal finish, SSPC-SP 10/NACE 2, for other service applications.

The steel substrate shall have, at a minimum, an angular profile depth ≥ 63 mm (2.5 mils) with a sharp angular shape. There is currently no standard method for measuring the angularity of the blast profile. However, a "metallographic examination of a successful bend coupon" can be used to evaluate the angularity suitability of the blast.

The profile depth shall be measured according

Table 6. TSC System Requirements and Acceptance Tests.

Surface Preparation	TSC System Requirements		Acceptance Tests
	TSC	Sealer or Sealer and Topcoat	
SSPC-SP 10/NACE No. 2 minimum [A]	Smooth and uniform. No blisters, cracks, loose particles, or exposed steel.	Smooth and uniform. No runs, sags, lifting, pinholes, or overspray.	Visual according to SSPC-Vis 1
Angular-profile depth ≥ 63 µm [2.5 mils]	—	—	Profile tape or micrometer depth gauge according to ASTM D 4417
Specify blasting media	Specify feedstock	Specify paint(s)	Manufacturer's certificate [B] and MSDS
—	Coating Thickness [C] Minimum: ____µm [____mils] Maximum: ____µm [____mils]	Coating Thickness Minimum: ____µm [____mils] Maximum: ____µm [____mils]	SSPC-PA 2
—	Portable tensile bond (≥ Table 2 values) Minimum: ____MPa [____psi]	—	ASTM D 4541 [D]
Companion coupon bend test: [E]		—	Bend test
Condition of substrate surface preparation and TSC interface and morphology (structure) [F]		—	Metallographic examination of companion coupon
—	No peeling or delamination	—	TSC Cut Test [G]
	Other as specified by the Contract		Other as specified by the Contract

A For critical surfaces and marine and underwater service, clean to a white metal finish (SSPC-SP 5/NACE No. 1) with ≥ 63 µm [2.5 mils] angular profile. The owner should specify the minimum required blast quality and its validation according to Section 5, Job Reference Standard. The angularity of the blast profile can be determined by a metallographic analysis of a companion coupon.

B Verification that the manufacturers or suppliers provide a certificate or affidavit that
(1) the blasting media conforms to SSPC-AB 1 for mineral and slag abrasive or SSPC-AB 3 for newly manufactured or remanufactured steel abrasive;
(2) the TSC-feedstock chemical composition, obtained from a representative sample of each heat during the pouring or subsequent processing, conforms to Appendix C, SSPC CS 23.00; and
(3) the sealer and topcoat paints are formulated for the contract specified thermal-spray coating. The Material Safety Data Sheets (MSDS) provide supporting physical and chemical information.

C Measure the TSC thickness according to SSPC-PA 2. Calibrate the instrument using a calibration wedge near the contrac: specified thickness placed over a representative sample of the contract specified abrasive blasted steel, or a prepared bend coupon, or both.

D Specify the ASTM D 4514 self-adjusting portable tensile instrument to be used (Type III or Type IV) and its minimum acceptable value for the Job Reference Standard and the job work surfaces.

E The bend test is a macro system test for proper surface preparation, equipment set-up, and spraying parameters. Specify mandrel diameter to be used for the contract TSC thickness.

F Metallographic analysis of a companion coupon may be specified to establish the suitability of the surface preparation, TSC application, and/or porosity of the TSC.

G TSC cut test should be made by a tool cutting through the TSC to the steel surface. The TSC is defective if any part of the coating lifts off the surface.

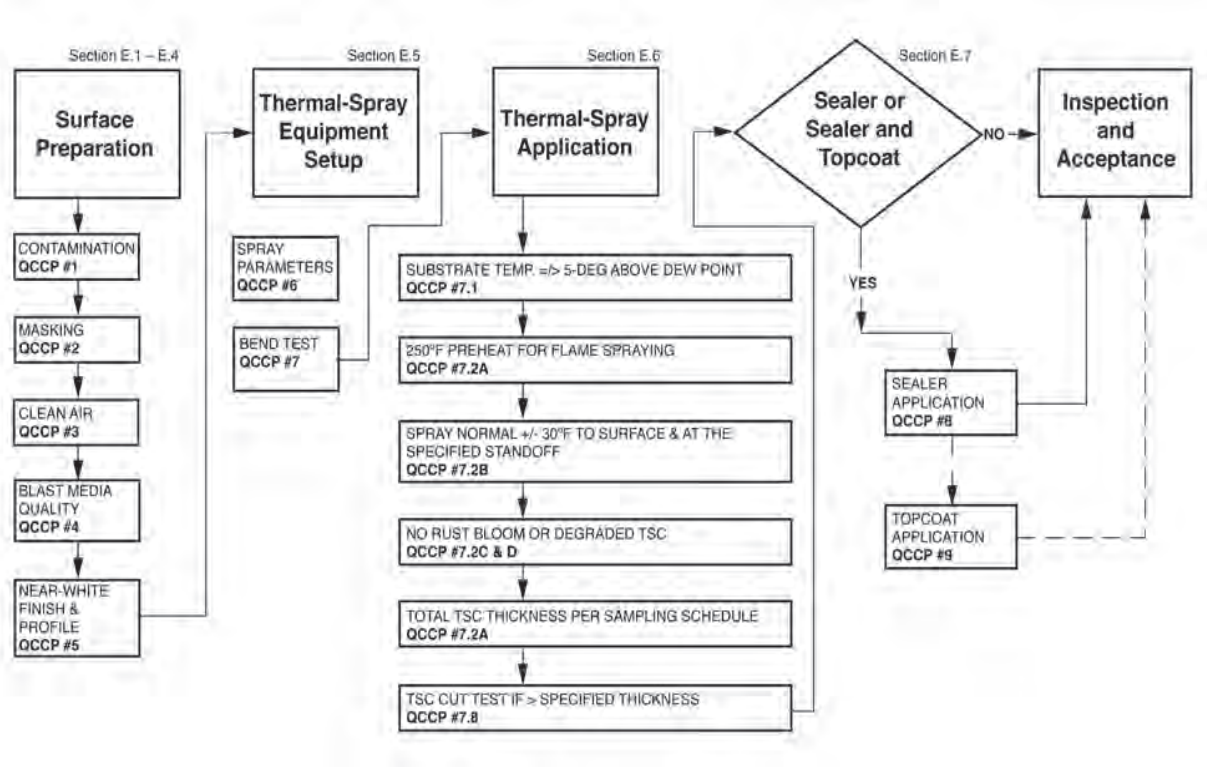


Figure 4. Key production and quality control checkpoints (QCCPs) for applying thermal-spray coatings.

to ASTM D 4417, Method C (replica tape, x-coarse, 38 to 113 mm [1.5 to 4.5 mils]), or Method B (profile depth gauge), or both.[18]

Use clean dry angular blasting media. Mineral and slag abrasives shall be selected and evaluated according to SSPC-AB 1, steel grit to SSPC AB-3.[19, 20] **Table 7** lists the blasting media and mesh size found suitable for TSCs on steel substrates.

TSC Requirements

Feedstock and TSC Thickness. The TSC feedstock material and thickness should be selected according to intended service environment and service life. The minimum and maximum TSC thickness shall be measured in accordance with SSPC-PA 2.[21]

(1) For flat surfaces a measurement line shall be used. The average value of five readings taken in line at 1.0-in. (2.5-cm) intervals shall be determined. The line measurement measures the peaks and valleys of the TSC.
(2) For complex geometries and geometry transitions a measurement spot shall be used. The measurement spot should have an area of approximately 10 cm^2 (1.6 $in.^2$). The spot measurement may not measure the peaks and valleys of the TSC.

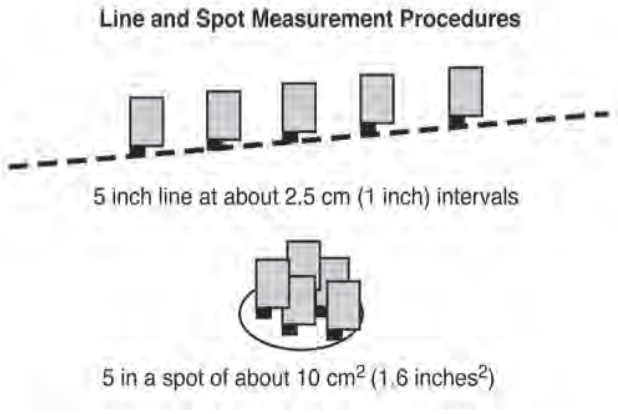


Figure 5. Line and spot measurement procedures.

Portable TSC Tensile Bond Instrument and Measurement. The TSC tensile bond shall be measured according to ASTM D 4541 using a self-aligning portable adhesion test instrument or equivalent. The minimum TSC tensile bond value may be specified according to **Table 8.** Higher values may be specified.

One portable tensile-bond measurement shall

Table 7. Blasting Media and Mesh Size Found Suitable for TSCs on Steel Substrates.

Thermal Spray Material	Process	Blasting Media [A]	Size [B]
Al, Zn, 85/15, 90/10 MMC	Flame wire and arc wire	Aluminum oxide	10-30 mesh
		Angular steel grit	G-16 to G-40
		Copper and nickel slag	G-16 to G-24
		Almandite garnet	G-16 to 30/40
		Chilled iron grit	G-16 to G-40
Al, Zn	Flame powder	Aluminum oxide	10-30 mesh
		Angular steel grit	G-16 to G-40
		Chilled iron grit	G-16 to G-40

A All blasting media should be dry and free of all oil/grease, fines, and materials not allowable in the blasting media material specification.
B Mesh size shall be selected as appropriate to the anchor-tooth depth requirement and the blasting equipment used.

be made about every 500 ft^2 (50 m^2). If the tensile bond is less than the contract specification, the degraded TSC shall be removed and reapplied.

For nondestructive measurement, tensile force shall be measured to the contract-specified tensile. The tensile force shall then be reduced and the tensile fixture removed without damaging the TSC.

Bend Test. The bend test (180° bend on a mandrel) is used as a qualitative "system test" for the proper surface preparation, equipment setup, and spray parameters. The bend test puts the TSC in tension. The mandrel diameter for the threshold of cracking depends on substrate thickness, coating thickness, and mandrel diameter.

Table 8. Minimum Tensile-Bond Requirements (per ASTM D 4514 using a self-aligning portable test instrument).

Feedstock	psi [MPa]
Zn	500 [3.45]
Al	1000 [6.9]
85/15	700 [4.8]
90/10 Al_2O_3 MMC	1000 [6.9]

Bend-Test Procedure for TSC Thickness Range 7-12 mils [175-350 mm].

(1) Spray five corrosion-control bend coupons and pass the following bend test:
   (a) Use a carbon steel coupons of approximate dimensions 2 x 4 to 8 x 0.05 in. [50 x 100 to 200 x 1.25 mm].
   (b) Surface preparation per contract specification.
   (c) Spray 7-12 mils [200-250 mm] thick TSC. The TSC should be sprayed in crossing passes laying down approximately 3-4 mils [75-100 mm] per pass.
   (d) Bend coupons 180°around a 0.5-in. [13-mm] diameter mandrel.

(2) Bend test passes if, on the bend-radius (see **Figure 6**), there is (a) no cracking or spalling or (b) only minor cracking that cannot be lifted from the substrate with a knife blade.

(3) Bend test fails if the coating cracks with lifting from the substrate.

Table 9. Bend-Test Cracking Threshold: Mandrel Diameter vs. Zn TSC Thickness.

TSC Thickness (mils)	≤ 12	≤ 15	≤ 25
Mandrel Diameter	1/2-inch	5/8-inch *	≤1-inch *

* Confirm diameter with JRS.

TSC Cut Test. The TSC cut test should consist of a single cut 1.5-in [40-mm] long through the TSC to the substrate without severely cutting into the substrate. All cuts should be made with sharp edge tools. The chisel cut should be made at a shallow angle. The bond should be considered unsatisfactory if any part of the TSC along the cut lifts from the substrate.

TSC Finish. The deposited TSC shall be uniform without blisters, cracks, loose particles, or exposed steel as examined with a 10x loupe.

TSC Porosity. If required by the purchaser, the

maximum allowable porosity and the metallographic measurement method to be used for the evaluation shall be specified. **Note:** Porosity measurements are not used for in-process quality control in metallizing for corrosion protection of steel. However, porosity measurements may be used to qualify thermal-spray application processes and spray parameters.

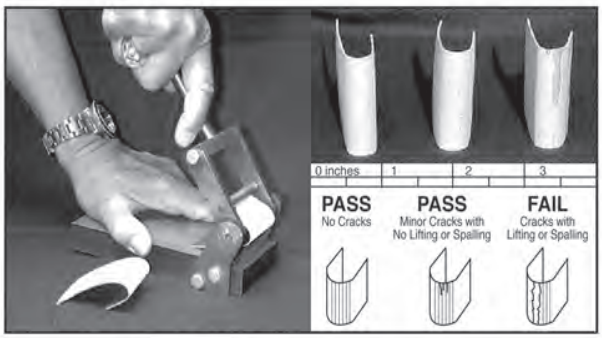


Figure 6. TSC bend test: pass and fail examples.

TSC QC Measurement Procedures and Instruments. The suitability of the TSC thickness, portable tensile bond, bend test, and cut-test measurement procedures and instruments shall be validated during the contract pre-award validation.

Job Reference Standard (JRS). The JRS is a job site pass/fail reference standard representative of the whole job or major sections of the job. The JRS is should be prepared by the TSCA at the pre-award job conference to demonstrate and validate the TSCA's surface-preparation and thermal-spray application processes. The JRS should be used as a "comparator" to evaluate the suitability of the application process. **Figure 7** illustrates the configuration of a JRS.

The JRS shall be made on a steel plate approximately 18 x 18 x 0.25 in. (46 x 46 x 0.60 cm). **Note:** For structural steel, the reference standard does not need to be more than 0.25 in. (0.60 cm) thick because steel does not thermally distort when TSC is applied. When the actual work is less than 0.25 in. (0.60 cm) thick, the JRS should be made from material of a thickness representative of the job.

(1) The JRS shall be made with the actual field equipment and the process parameters and procedures (surface preparation; thermal spraying; sealing or sealing and topcoating; and the in-process QC checkpoints) that shall be used for the contracted work.
(2) The JRS shall be made in representative environmental conditions spraying with or without enclosure as appropriate.
(3) Thickness and tensile-bond measurements shall be made according to **Figure 8.** The JRS is unsatisfactory if any measurements are less than the contract-specified value.
(4) The JRS is used as a pass/fail reference for the applicator's in-process QC and the purchaser's inspector.
(5) The preparation and the use of the JRS for in-process QC and the inspector's pass/fail reference standard should be agreeable to both the purchaser and TSCA.

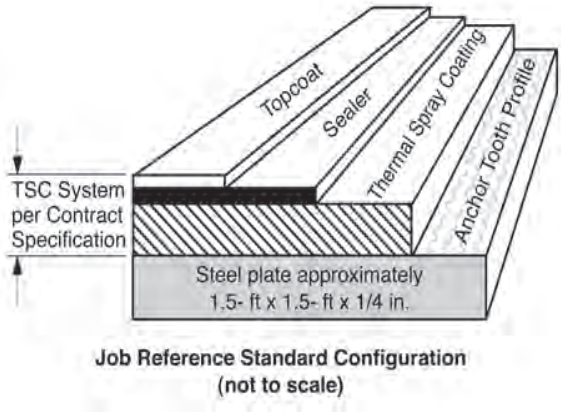


Figure 7. Job reference standard configuration (JRS).

Job Control Record (JCR). SSPC CS 23.00A, Part A: Specification, presents a JCR that covers the essential job information. The JCR lists information on the TSCA, the purchaser, TSC requirements, safety precautions, surface preparation and abrasive blasting media requirements, flame- and arc-spray equipment and spraying procedures and parameters. The JCR also lists the 11 production steps and their check-offs. The check-off list may be used as part of the inspection procedure.

Thermal-Spray Coating Applicator (TSCA) Qualification

There is one published and one standard in preparation for the qualification of TSCA:

(1) ASTM D 4228-95, *Standard Practice for Qualification of Coating Application of Coatings for Steel Surfaces* provides a standard qualifying method for coating applicators to verify their proficiency and ability to attain the required quality for

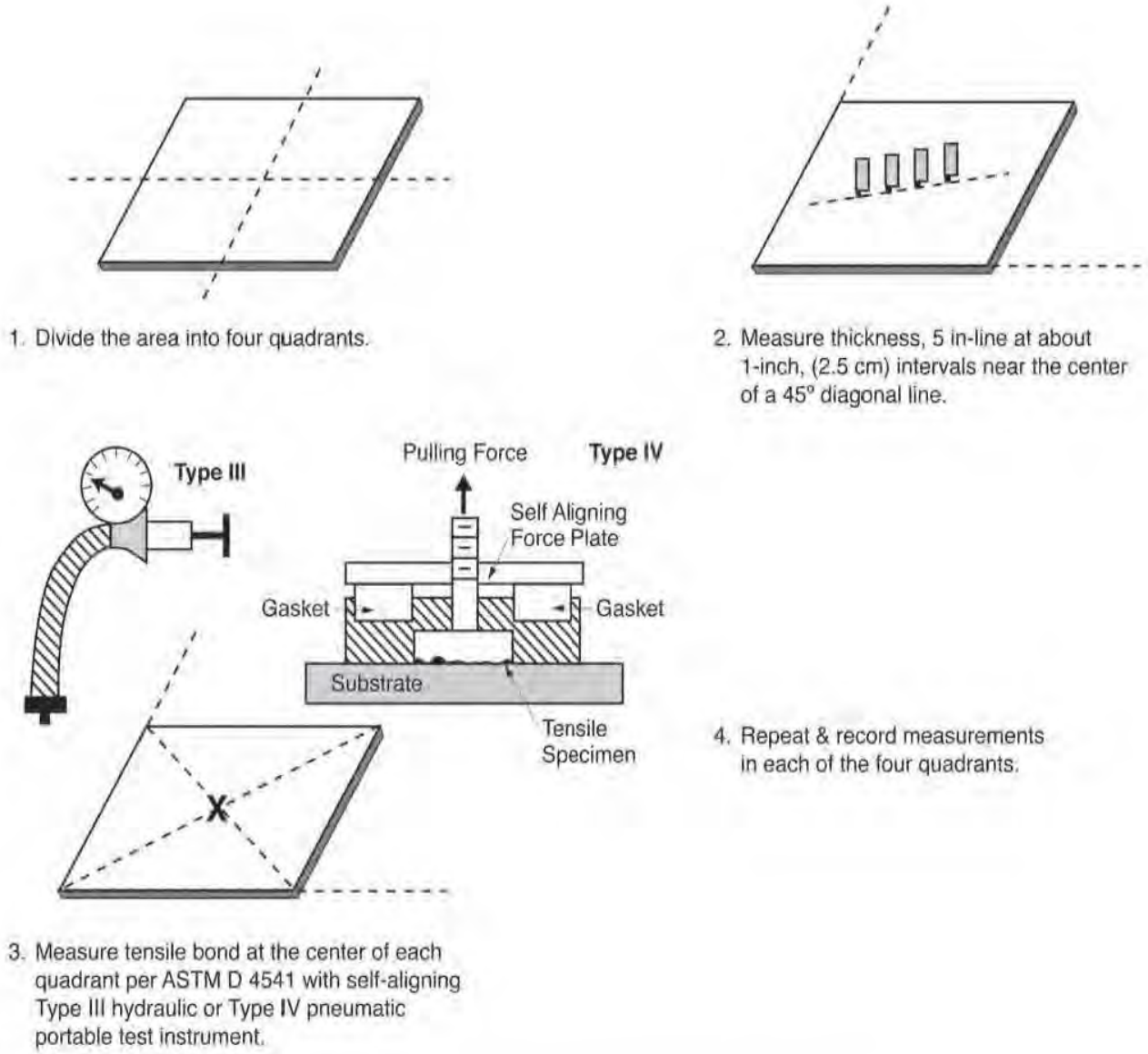


Figure 8. Thickness and tensile-bond measurements for JRS qualification.

Table 10. Recommended Personnel Qualification Requirements & Minimum Required Experience per SSPC-QP 6.

	Knowledge and Skill Requirements	Blaster	Arc Sprayer	Flame Sprayer	Blaster & Arc Sprayer	Blaster & Flame Sprayer	QC Technician
1	Qualified to prepare steel surfaces to SSPC-SP 5/NACE 1 and SSPC-SP 10/NACE 2.	X			X	X	
2	Qualified per AS-1, ANSI/AWS C2.16A-XX, Guide for Thermal-Spray Operator Qualification, CD #4, June 4, 2001.		X		X		
3	Trained and qualified to metallize per CS 23.00 (latest revision).		X	X	X	X	
4	Trained and qualified per FS-1, ANSI/AWS C2.16A-XX, Guide for Thermal-Spray Operator Qualification, CD #4, June 4, 2001.			X		X	
5	Trained and qualified to monitor the In-Process QC Checkpoints per SSPC CS 2300 (latest revision).						X

application of specified coatings to steel surfaces including those in a safety-related area in a nuclear facility.

(2) SSPC-QP 6, *Standard Procedure for Evaluating Qualifications of Thermal-Spray (Metallizing) Applicators,* (in preparation) describes a method for evaluating the qualification of thermal-spray (metallizing) applicators (or firms) to apply thermal-spray coatings in accordance with SSPC CS 23.00. Requirements and auditing criteria are included for the surface preparation, thermal spraying, and sealing or sealing and topcoating of components/assemblies in the shop and complex structures in the field. This procedure is applicable to a fabricating shop, shipyard, or other entity that applies coatings in the shop, even though providing coating application services is not the primary function. TSCA must have equipment, materials, and application and in-process QC procedures to meet SSPC CS 23.00. Table 10 lists the personnel qualification requirements and minimum required experience.

TSC Inspector Qualification

The TSC inspector is a person who is knowledgeable about the concepts and principles of TSC and skilled in observing and measuring conformance to SSPC CS 23. The TSC inspector, at a minimum, should:

(1) Meet the knowledge requirements of a qualified thermal-spray operator.

(2) Be skilled in observing and evaluating conformance of the application process to the contract specifications.

(3) Be knowledgeable of and skilled in using inspection equipment to measure and validate the TSCA's conformance to the purchasing contract.

(4) Submit timely oral and written reports to the purchaser.

More information is also found in SSPC's *The Inspection of Coatings and Linings: Handbook of Basic Practices for Inspectors, Owners, and Specifiers.*[22]

Summary

Thermal-spray coatings are used for the corrosion protection of steel and iron in a wide range of environments. TSCs of zinc, aluminum, or their alloys are used for infrastructure corrosion-control applications and are primarily applied by the electric arc thermal-spray process. The current industry standard for the application of TSCs is SSPC CS 23.00.[6] The qualifications for metallizing contractors are specified in the SSPC-QP series of qualification procedures for coating contractors.[7]

References

1. *Corrosion Tests of Flame-Sprayed Coated Steel:19-Year Report;* American Welding Society: Miami, FL.

2. Kain, R.M.; Baker, E.A. ASTM STP 947. *Marine Atmospheric Corrosion Museum Report on the Performance of Thermal-Spray Coatings on Steel;* ASTM: West Conshohocken, PA.

3. Pikul, S.J. *Appearance of Thermal-Sprayed Coatings After 44 Years Marine Atmospheric Exposure at Kure Beach, North Carolina;* LaQue Center for Corro-

sion Technology, Inc., February 1966.

4. B.S. 5493. *British Standard Code of Practice for Protective Coatings of Iron and Steel Structures Against Corrosion;* British Standards Institution/ASTM: New York, 1977.

5. Kogler, R.A; Ault, J.F.; Farachon, C.L. FHWA-RD-09-058. *Environmentally Acceptable Materials for the Corrosion Protection of Steel Bridges;* Federal Highway Administration: Washington, D.C., 1997.

6. SSPC CS 23.00. Specification for the Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc, and Their Alloys and Composites for the Corrosion Protection of Steel; SSPC: Pittsburgh.

7. Qualification Procedures. In *Steel Structures Painting Manual: Volume 2—Systems and Specifications;* SSPC: Pittsburgh.

8. AWS C2-18A, NACE RPX-2002, and SSPC CS 23.00A. *Application of Thermal-Spray Coatings (Metallizing) of Aluminum, Zinc, and Their Alloys and Composites for the Corrosion Protection of Steel—Part B: Guide, Draft #2, 2001-10-19.*

9. ANSI/AWS C2.18. *Guide for the Protection of Steel with Thermal Sprayed Coatings of Aluminum and Zinc and Their Alloys and Composites;* ANSI: New York.

10. U.S. Army Corps of Engineers (USACE) Engineering Manual EM 1110-2-3401 Engineering and Design. *Thermal Spraying: New Construction and Maintenance;* 29 January 1999.

11. ASTM D 1210. *Test Method for Fineness of Dispersion of Pigment-Vehicle Systems;* ASTM: West Conshohocken, PA.

12. ANSI/AWWA D-102-78. *American Water Works Association Standard for Painting Water-Storage Tanks.* AWWA/ANSI: New York.

13. MIL-STD-2138A(SH). *Metal Sprayed Coatings for Corrosion Protection Aboard Naval Ships.*

14. *Steel Structures Painting Manual: Volume 1—Good Painting Practice;* SSPC: Pittsburgh, 2002.

15. NACE Standard RP0187-89. *Standard Recommended Practice—Fabrication Details, Surface Finish Requirements, and Proper Design Considerations for Tank and Vessels to be Lined for Immersion Service;* NACE: Houston.

16. ISO 2063:1999. *Metallic and Other Organic Coatings—Thermal Spraying: Zinc, Aluminum, and Their Alloys.*

17. SSPC-PA Paint Application Guide No. 5. Guide to Maintenance Painting Programs; SSPC: Pittsburgh.

18. ASTM D 4417. *Standard Test Methods for Field Measurement of Surface Profile of Blast Cleaned Steel;* ASTM: West Conshohocken, PA.

19. SSPC-AB 1. *Mineral and Slag Abrasives;* SSPC: Pittsburgh.

20. SSPC-AB 3. *Newly Manufactured or Re-Manufactured Steel Abrasives;* SSPC: Pittsburgh.

22. *The Inspection of Coatings and Linings;* Bernard R. Appleman, ed.; SSPC: Pittsburgh, 1997.

About the Author

Robert A. Sulit

Robert A. Sulit has been involved with thermal-spray technology since 1977 in the areas of shipboard corrosion control, naval machinery repair, and the design/installation/operation of mobile/fixed corrosion control shops. Chair of SSPC's thermal-spray committee and the AWS/SSPC/NACE committee for corrosion protection of steel, he has authored or coauthored more than 110 technical papers and reports and one book, *Principles of Radiation and Contamination Control.* Mr. Sulit is a former recipient of the SSPC Technical Achievement Award (2000) and several other industry honors.

Chapter 5.1
Application of Industrial Coatings

Frank W. G. Palmer

Introduction

Proper application of coatings is as critical as their selection and surface preparation in producing long-term protective films. The new low-VOC products are especially difficult to apply. This chapter describes different recommended methods of applying industrial coatings. A detailed specification covering the general requirements for high-performance paint application is given in SSPC-PA 1.[1] Applicator Training Bulletins published in the *Journal of Protective Coatings and Linings* provide additional information on coating application.[2] Publications of spray equipment manufacturers were also used in preparing this chapter.[3-7] Application of coatings to concrete structures, not covered in this chapter, is described in SSPC's *The Fundamentals of Cleaning and Coating Concrete.*[8]

Preparing Coatings for Application

Mixing

During storage, the relatively heavy pigments in coatings tend to settle and cake at the bottom of cans. Coatings in this condition must be mixed thoroughly and uniformly so that they can be applied in an even, continuous film. Improper or inadequate mixing can result in inadequate or non-uniform film thickness, uneven color, limited adhesion, and checking or cracking of the film.

Mixing can be done manually or mechanically. Mechanical mixing is usually preferred because it is faster and more efficient, especially with large volumes and viscous materials. In both cases, it is necessary to first break up clumps with a wooden paddle by rubbing them against the interior can wall and then lift settled materials from the bottom of the can. Also, any surface skins must be removed.

When stirring mechanically:

- Use appropriately sized equipment (e.g., for a 55-gallon drum, a 1/2 hp motor that drives a three-bladed propeller, eight inches in diameter on a 36-inch shaft).
- Form a relative small vortex in the coating
- Use slow speed stirrer (never a mechanical shaker)

Entrapment of air bubbles (foaming) during mixing can result in bubbles, craters, and voids in cured films. Water-borne coatings are especially susceptible, because they contain wetting agents (dispersants). Also, some of the bubbles can escape if the mixed coating is allowed to sit for an extended period of time before use.

Thinning (Reducing) Mixed Coatings

Most coatings are formulated for application without thinning under normal conditions. Thinning may be required on cold days because viscosity is inversely related to temperature. Two-package coatings should be thinned only after combining and mixing the components. If thinning is necessary, the coating manufacturer's recommendations for the type and amount of thinner should be followed. Also, thinning must not cause the coating to exceed VOC limits. Overthinning can result in a runny consistency that may produce less than the desired film thickness. Use of the wrong thinner can cause the coating to gel or have other adverse effects.

Tinting

Adjacent coatings in a multiple-coat systems are sometimes tinted differently in order to more easily detect skips in the topcoat film. In such cases, the coating manufacturer's instructions should be followed, since not all tints are compatible with all coatings. It is safer to obtain adjacent coatings in different colors.

Straining

Paints should always be strained whenever it becomes apparent that lumps, skins, or other non-uniformities are present. Inorganic zinc-rich coatings should always be strained to remove coarse or agglomerated zinc particles. Straining is the last step before application. It should be done using a fine (e.g., 80-mesh) sieve or a commercial paint strainer.

Brush Application

Brushes are available with natural and synthetic fibers such as nylon or polyester. Typically, natural bristle brushes are used for applying solvent-based coatings, and synthetic fiber brushes are used for applying water-based coatings. Organic solvents will attack and degrade synthetic fibers, and water slowly degrades natural fibers.

Use of high-quality natural bristle brushes such as Chinese hog bristles will result in better quality work. The flagged (split) ends of these bristles hold more paint and thus increase greater productivity. Some tips for optimum brush application are:

- Before painting, shake loose any unattached fibers by spinning between the palms of the hands
- Remove any stray fibers with a putty knife
- Dip the brush in the paint to cover no more than one-half of the bristle length
- Remove excess paint by tapping the brush on the edge of the can
- Apply even strokes lightly with the bristle tips
- Hold the brush at a 75° angle, much like holding a pencil
- Apply paint from top to bottom always finishing in the same direction
- Start and finish at natural boundaries and always keep a wet edge to minimize lap marks

Typically, brush application is the slowest of all methods used for applying coatings, and has the potential to apply the coating with the most irregular mil thickness and the greatest amount of surface texture (e.g., brush marks). The brush application method has the advantage of being the cheapest equipment to purchase, requires the least amount of time and effort to clean up, and can be applied to surfaces in close contact to other surfaces without needing to tape or cover those surfaces. Brushes are used to apply stripe coats to edges and welds prior to spray application as paint will draw back from an edge or will not fill the voids found in welds applied by spray. The advantages and limitations are:

Advantages

- Good transfer efficiency
- No overspray
- Good for tight and irregular areas
- Inexpensive, light-weight equipment
- Used for striping

Limitations

- Low application rate
- Difficult to apply uniformly thick film
- Difficult to apply many high-performance coatings

Roller Application

Applying coatings with a roller is typically done when large, flat, or curved surfaces are to be coated and when spray application is prohibited or uneconomical. Roller application may be as much as four times faster than brush application. The finish obtained by a roller is not of even mil thickness, as may be obtained by spray application. Rollers, if used carefully, can also be effective when it is critical that the surrounding areas do not receive any of the applied coating in an overspray.

A paint roller consists of a cylindrical sleeve or cover that slips over a rotatable cage with an attached handle. Rollers vary in width from 1-18 inches (25-450 mm) in the nap of lambswool, nylon, polyester, Dynel, or Dacron fiber cover. The nap fiber length typically varies from 1/4 to 3/4 inch (6 to 18 mm). The core of the roller is usually made from either phenolic-reinforced fiberboard or metallic fiberboard.

Rollers can be dipped directly into a pail of coating and the surplus paint worked off on a grid or screen in the pail, or the coating can be taken from a tray that has a grid to remove surplus paint.

The use of rollers may be limited if the coating being applied contains extremely strong or fast-evaporating solvents, or if the loss of some of the roller fibers into the coating jeopardizes its integrity or performance.

Rollers also lack the ability to force the coating into the pores or profile of a surface and have the resins wet out on the surface. In addition, rollers have the potential to load air into the coating just as it is being deposited on the surface. If the air is unable to escape from the coating, it has the potential to form voids and cause a premature loss of coating or fail an inspection for holidays. The advantages and limitations of roller applications are:

Advantages

- Good transfer efficiency
- No overspray
- Better application rate that brush application on flat spaces
- Inexpensive, light-weight equipment

Limitations

- Slower application rates than spraying
- Difficult to apply uniform thicknesses and thick coatings
- Difficult to apply many high-performance coatings (mostly used for oil-based and water based paints)

Spray (General)

Spray application is the process by which coatings are atomized into fine particles and deposited upon a surface. It is considered to be the most effective method of applying coatings to produce continuous, smooth, aesthetically pleasing protective barriers. The two basic types of spray systems are air spray (conventional) and airless spray. All other spray systems are variations of these.

Spray application has inherent dangers to both humans and the environment. The worker must be aware of these dangers and take proper precautions during application using any type of spray system. There are also regulations that govern the use and operation of spray equipment in order to offer protection to the surrounding air, water, and soil. A worker skilled with the spray gun practices four basic principles:

- Keeping the gun at the distance from the surface recommended by the gun manufacturer (typically, 6-8 inches [15-20 cm] for conventional air and 12-14 inches [30-35 cm] for airless spray)
- Holding the gun perpendicular to the surface; arcing will result in varying film thicknesses
- Overlapping strokes 50% will result in a smooth film of uniform thickness
- Triggering the strokes (The trigger is pulled just before the gun reaches the edge of the work and is released just after the gun passes the other edge of the work.)

Conventional (Air) Spray

To understand conventional spraying, it is very important to understand the role of the compressed air used. Whichever power source is used (electricity or gasoline) to operate the compressor, it is nonetheless compressed air that operates the spray equipment. Compressed air is a very powerful source of energy. When used in conventional spraying, it moves material from the container to the gun and atomizes it at the spray gun head.

Applicators, when spraying with conventional systems, require compressed air to be maintained at a specific pressure. Not only is a specific air pressure required, but the ratio of air volume to spray coatings must be correctly set. Pressure is defined in pounds per square inch (psi) and volume is identified in cubic feet per minute (cfm). It is important to maintain both the correct volume and pressure at the spray gun head to ensure correct material application. Incorrect settings of either the volume or pressure will result in a faulty spray pattern.

The air cap at the gun head is the only component of the spray system that uses compressed air; therefore, the air cap must be matched to the size of the compressor output. All spray equipment manufacturers will identify the amount of air volume that each individual air cap requires. It is important that information be obtained from individual suppliers to establish the size of the compressor required for each individual air cap. The advantages and limitations of conventional air spray are:

Advantages

- Finer atomization and finish
- More operator control and versatility (use of air only for minor blow-down, easier change of fan width and amount of material for tight places, etc.)
- Lower initial investment
- Usually better with filled (e.g., textured) coatings
- Easier change of colors by changing suction cups

Limitations

- Lower transfer efficiency
- Lower application rate
- More overspray
- Viscous materials may be more difficult to spray

A conventional spray system consists of a spray gun, a material container, a compressor, fluid and air hoses, and air-controlling devices.

Spray Gun

The spray gun delivers specific amounts of paint and atomizing air to the gun nozzle, producing a controllable pattern of atomized coating. In external mixing guns (most commonly used) the compressed air and paint are mixed as they are sprayed from the air cap and fluid tip. In internal mixing guns, the air and paint are mixed inside the air cap as spraying occurs. Gun components are discussed next.

Air Cap

Air caps direct the jets of compressed air into the stream of material from the fluid tip to atomize the coating and form the spray pattern and are either an internal or an external mix type. The air cap fits over the fluid tip and is connected to the gun by a threaded ring. The air cap and fluid tip are selected according to the type of coating to be used and the desired application rate. The external mix air cap can be identified by the protruding sides, commonly called horns, that extend from the air cap. Air from the holes found on the face of the air cap partially atomizes the paint, and the air from the horn holes completes the atomization and shapes the spray pattern.

Fluid Tip and Needle

The fluid tip is a nozzle directly behind the air cap that meters and directs the material into the air streams. The fluid tip forms a seat for the fluid needle, which shuts off the flow of material. Fluid tips are available in a variety of nozzle sizes to properly handle materials of various types and to pass the required volume of material for different speeds of application.

When the trigger is pulled, the needle is drawn out of the fluid tip and the paint is allowed to flow to the air cap. When the trigger is released, the needle seats itself in the fluid tip, stopping the flow of the coating. Flow rate adjustments may be made by either increasing or decreasing the air pressure to the paint tank, or by changing to another size of fluid tip and needle. The fluid adjustment valve can be used when the operator needs to make minor adjustments to reduce or increase the paint flow.

Trigger

The trigger operates the air valve and the fluid needle. It acts as a switch to turn the atomizing air and fluid on and off.

Air Valve

The air valve controls the movement of air through the spray gun. It is the stem directly behind the trigger that is moved by the trigger. The air valve is the “on and off” control for the atomizing air.

Spreader Adjustment Valve

The spreader adjustment valve controls the air supply within the air cap and also controls the size and shape of the spray pattern. It controls the air flow to the holes in the horns of the air cap as well.

Air and Fluid Inlets

The air inlet on the gun handle connects the atomizing air hose to the air supply, which is either a compressor or a transformer. The fluid inlet connects the material supply container or hose to the fluid inlet behind the air cap on the spray gun.

Material Containers

The material for conventional spraying is supplied by a suction- or pressure-feed attached cup or pressure-feed remote pot. Suction-feed cups are used when colors must be changed frequently and when only small amounts of coating are needed.

Pressure-feed systems are assembled with zero, one, or two regulators and require two independent supplies of compressed air. One source of compressed air is used to pressurize the container to move the coating into and out of the gun. The other supply is used at the gun as the atomizing air source. With both regulators situated at the pot, the material is easier to control. For materials with heavy pigments (e.g., a zinc-rich coating), use a container equipped with an agitator.

Compressor

Compressors are needed to generate the energy used to move and atomize the coating. There are several different air compressor designs—diaphragm, piston, vane, screw, and turbine—all of which are effective for operating a conventional spray system. The most commonly used compressors are the piston, vane, and screw. Compressors must generate enough volume and pressure of clean, dry air to operate the system properly.

Fluid and Air Hoses

The fluid and air hoses carry specific volumes of atomizing air or coating. These hoses are specially constructed with liners that protect the hoses from attack by the strong solvents used in coatings and by any moisture or oil from a faulty compressor. Air hoses are usually red and material hoses are black.

Air-Controlling Devices

Regulators, transformers, separators, and filters are used in conventional spray systems between the compressor, the material container, and the gun.

Table 1a. Problems Encountered During Application of Coatings with a Conventional Spray System.

Problem	Cause	Correction
Fluid leaking from packing nut	Packing nut loose	Tighten, do not bind needle
	Packing worn or dry	Replace or lubricate
Air leaking from front of gun	Sticking air valve stem	Lubricate
	Foreign matter on air valve or seat	Clean
	Worn or damaged air valve or seat	Replace
	Broken air valve spring	Replace
	Bent valve stem	Replace
	Air valve gasket damaged or missing	Replace
	Packing nut too tight	Adjust
Fluid leaking or dripping from front of pressure-feed gun	Fluid tip or needle worn or damaged	Replace tip and needle with lapped sets
	Foreign matter in tip	Clean
	Fluid needle spring broken	Replace
	Wrong size needle or tip	Replace
	Dry packing	Lubricate
	Needle bound by misaligned sprayhead (MBC guns)	Tap sprayhead perimeter with a wooden mallet; retighten lock bolt
Jerky, fluttering spray	**Suction and Pressure-Feed**	
	Paint level too low	Refill
	Container tipped too far	Hold more upright
	Obstruction in fluid passage	Backflush with solvent
	Loose or broken fluid tube or fluid inlet nipple	Tighten or replace
	Loose or damaged fluid tip/seat	Adjust or replace
	Dry or loose fluic needle packing nut	Lubricate or tighten
	Suction and Pressure-Feed	
	Material too heavy	Thin or replace
	Container tipped too far	Hold more upright
	Air vent clogged	Clear vent passage
	Loose, damaged or dirty lid	Tighten, replace or clean coupling nut
	Dry or loose fluid needle packing	Lubricate or tighten packing nut
	Fluid tube resting on cup bottom	Tighten or shorten
	Damaged gasket behind fluid tip	Replace gasket
Top- or bottom-heavy spray pattern*	Horn holes plugged	Clean; ream with non-metallic point
	Obstruction on top or bottom of fluid tip	Clean
	Cap and/or tip seat dirty	Clean
Right- or left-heavy spray pattern*	Left or right side horn holes plugged	Clean; ream with non-metallic point
	Dirt on left or right side of fluid tip	Clean

Notes:
* Remedies for the top-, bottom-, right- and left-heavy patterns:
1. Determine if the obstruction is on the air cap or the fluid tip. Do this by making a solid test spray pattern. Then rotate the cap 1/2 turn and spray another pattern. If the defect is inverted, the obstruction is on the air cap. Clean the air cap as previously instructed.
2. If the defect is not inverted, it is on the fluid tip. Check for a fine burr on the edge of the fluid tip. Remove with #600 wet or dry sandpaper.
3. Check for dried paint just inside the opening. Remove paint by washing with solvent.

Source of table: Binks Manufacturing Company. 1992.

Table 1b. More Problems Encountered During Application of Coatings with a Conventional Spray System.

Problem	Cause	Correction
Centre-heavy spray pattern	Fluid pressure too high for atomization air (pressure-feed)	Balance air and fluid pressure; reduce spray pattern width with spreader adjustment valve
	Material flow exceeds air cap capacity	Thin or lower fluid flow
	Spreader adjustment valve set too low	Adjust
	Atomizing pressure too low	Increase pressure
	Material too thick	Thin to proper consistency
Split-spray pattern	Fluid adjusting knob turned in too far	Back out counter-clockwise to achieve proper flow
	Atomization air pressure too high	Reduce at transformer on gun
	Fluid pressure too low (pressure-feed only)	Increase fluid pressure (increases gun handling speed)
Starved spray pattern	Inadequate material flow	Back fluid adjusting screw out to first thread
	Low atomization air pressure (suction feed)	Increase air pressure and rebalance gun
Unable to form round spray pattern	Fan adjustment stem not seating properly	Clean or replace
Dry spray	Air pressure too high	Decrease air pressure
	Material not properly reduced (suction feed)	Reduce to proper consistency
	Gun tip too far from work surface	Adjust to proper distance
	Gun motion too fast	Slow down
	Gun out of adjustment	Adjust
Excessive overspray	Too much atomization air pressure	Reduce pressure
	Gun too far from work surface	Adjust to proper distance
	Improper stroking (arcing, gun motion too fast)	Move at moderate pace, parallel to work surface
Excessive fog	Too much thinner or too fast drying	Remix properly
	Too much atomization air pressure	Reduce pressure
Will not spray	No pressure at gun	Check air lines
	Fluid pressure too low (with internal mix cap and pressure tank)	Increase fluid pressure at tank
	Fluid tip not open enough	Open fluid adjusting screw
	Fluid too heavy (suction feed)	Reduce fluid or change to pressurized
	Internal mix cap used with suction feed	Change to external air cap

Notes:
* Remedies for the top-, bottom-, right- and left-heavy patterns:
1. Determine if the obstruction is on the air cap or the fluid tip. Do this by making a solid test spray pattern. Then rotate the cap 1/2 turn and spray another pattern. If the defect is inverted, the obstruction is on the air cap. Clean the air cap as previously instructed.
2. If the defect is not inverted, it is on the fluid tip. Check for a fine burr on the edge of the fluid tip. Remove with #600 wet or dry sandpaper.
3. Check for dried paint just inside the opening. Remove paint by washing with solvent.

Source of table: Binks Manufacturing Company, 1992.

Regulators and transformers are used to control air pressure and to allow for multiple compressor hook-ups. Separators and filters are used to clean oil and dirt from the air supply and to extract moisture in the air.

Airless Spray

Airless, or hydraulic, spray painting gets its name from the fact that no compressed air is used with the paint to form the spray. Instead, atomization occurs when the paint is pumped at high pressures (up to 7,400 psi [51,800 kPa]) through a small orifice in the gun nozzle. The pressure in airless spray painting is created by fluid pumps that are able to deliver between 28 oz. and 7 gallons of paint per minute. These pumps drive the paint through high-pressure hoses (typically 3/8-inch inside diameter) specifically designed for the airless system. The advantages and limitations of airless spray are:

Advantages
- High application rate
- Higher transfer efficiency (less overspray) than conventional air spray
- Easier than conventional air systems to use with high-viscosity materials

Limitations
- Hazardous spray pressures
- Reduced operator control
- Reduced quality of finish
- More expensive to maintain

The basic components of the airless spray system are an electric-, air-, or gasoline-powered fluid pump, high-pressure fluid (material) static-dissipating hose filters and screens, and the airless spray gun. Basic equipment designs of electric- and air-powered airless spray systems are very similar.

Airless Spray Fluid Pumps

Airless spray fluid pumps have gears, a diaphragm, or pistons to draw the paint from the container, and force it through the paint hoses and airless spray gun. Piston design pumps are more common than other pumps because they are better able to resist the abrasive and corrosive actions of the paint. The fluid pump may be mounted on a lid that can be attached to a paint drum; on a wheeled cart so that the pump head can be set inside a paint container; or the pump may use a siphon hose to draw the paint from the container.

Pump Classification

Airless spray pumps are identified by the ratio of paint pressure produced to that of the air pressure used. For example, a pump that delivers paint at a pressure of 4 psi (28 kPa) for each 1 psi (7 kPa) of air pressure would be identified as having a 4:1 ratio. Some fluid pumps in the painting industry will use 80 psi (560 kPa) of air pressure to generate a paint pressure of 2400 psi (16,800 kPa), resulting in a 30:1 pump ratio. Pumps are also classified by the volume of paint delivered per minute. A heavy-duty pump may be capable of delivering as much as 7 gallons of paint per minute. Paint pressure is regulated by adjusting the pressure regulator on the pump. The pressures on airless spray equipment cannot be regulated as precisely as that on conventional air spray equipment.

Electric Fluid Pump

An electrically driven pump motor can be plugged into a standard grounded outlet. The electric fluid pumps have adjustable paint pressure settings. In one type of electric pump, the motor moves a piston sunk in an oil chamber. The pressure thrust on the oil by the piston opens and closes a diaphragm that draws the paint into the paint chamber, where it is pressurized.

Spray Tip

The selection of a spray tip is based on the volume of fluid produced by the paint pump, i.e., there must be a match between the pump volume produced and the tip spraying rate. The pump must be capable of delivering more than the tip can use. This permits the pump to run slower than its maximum speed and thus reduce wear on its parts, while providing a reserve capacity of pressure in case a change is made to a larger spray tip or a longer hose. A reversible tip has a key than can turn 180° to blow out clogs.

The larger the spray tip orifice, the more speed and spray coverage that will be possible. Therefore, the airless spray painter chooses the spray tip according to the type of paint being used and the film thickness desired. An orifice that is too large used with a low viscosity paint, for example, would cause

the paint to flood the surface. Generally, the paint manufacturer will list recommended spray tip orifice sizes for use with specific coating materials. Each airless tip is defined by the three numbers located on it, such as 517:

• The first number (5) when doubled (10) indicates the approximate fan width in inches when spraying 12 inches (300 cm) from the surface.
• The second number indicates the tip has a flow rate in water equal to a 17 mil (0.43 mm) diameter hole. The coating flow rate through the tip will vary with the orifice size. It will also vary with the coating pressure and viscosity.

High-Pressure Fluid Hoses and Fittings

The paint hoses used in airless spray painting are specially constructed to withstand high-fluid pressure. The materials passing through airless hoses at high pressures and speeds build up static electricity through friction. For this reason, these hoses have a grounding wire located in the outer skin to dissipate the static electricity. The hose connections and couplings used for airless spray work are also designed for use on high-pressure equipment.

Filters and Screens

Airless spray systems require that the material sprayed is free of lumps of extra-heavy pigment. Because the orifice size of the spray tip is small, filters or screens are placed:

• At the base of the siphon hose
• Inside the surge tank
• In the material hose
• Sometimes behind the spray tip

It is important that the screens or filters are sized to the orifice in the spray tip.

Gun

The airless gun is not adjusted unless the tip is changed. The size and shape of the tip will determine the fan size and shape. There are two safety features on all guns: a tip guard to keep fingers away from the high-pressure spray and a trigger lock to prevent accidentally activating the trigger.

Airless Spray Techniques

Because the airless spray system produces a heavy application of coating, the airless spray painter must develop proper spraying techniques to avoid runs and sags. One such technique is to hold the spray gun farther from the surface than a conventional air spray gun, usually a distance of 12 to 14 inches.

Since the shape of the airless spray pattern is determined by the built-in angle of the fluid tip, the operator must change the spray tip in order to change the shape of the spray pattern. In general, airless spray patterns have cleaner, sharper edges than conventional air spray patterns, because all the paint particles in the airless spray system travel at the same speed while air spray paint particles tend to lose speed at the outside edges of spray patterns.

Insufficient application pressure will result in tails (fingers), an incomplete fan with coating concentrated at the top and bottom. Increasing the pressure will resolve this problem.



Figure 1. Air-assisted airless gun.

Air-Assisted Airless Spray

The air-assisted airless concept uses a combination of the air and airless methods. A pump is used to force material through a small orifice or tip at low hydrostatic pressure.

Air-assisted airless sprayers operate at pressures under 950 psi. However, most materials cannot attain quality atomization at these low spray pressures and fan patterns are usually incomplete, with “tails” formed at each end. To complete the atomization and eliminate the “tails,” low-pressure (10–30 psi [70–210 kPa]) compressed air is added to the airless spray through an air cap. The chief advantages of air-assisted airless spray are:

• Finer atomization and finish than airless spray

• Better operator control than airless spray
• Better transfer efficiency than conventional air spray
• Application rates comparable to airless spray

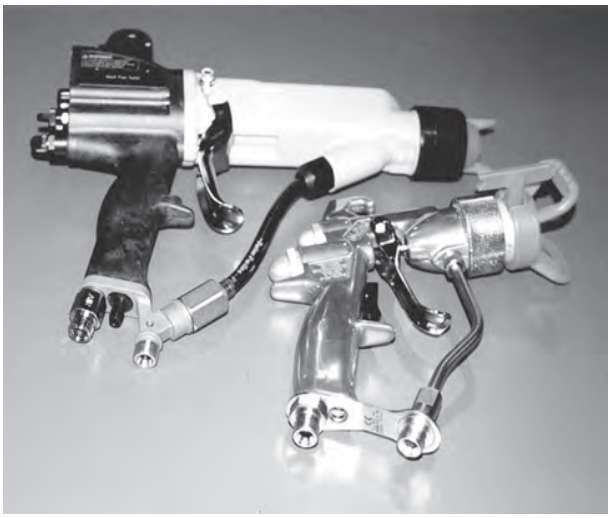


Figure 2. Air-assisted airless guns. Note tip guard, trigger lock, and reversible (switch) tip on bottom gun.

Parts of Air-Assisted Airless Gun

The basic parts of an air-assisted airless gun are:

• **Gun body—**Contains air and fluid passages
• **Trigger—**Opens air and material valves
• **Trigger safety lock—**Prevents discharge from gun not in use
• **Air inlet—**Connects to air supply
• **Air control valve—**Controls amount of air at air cap
• **Pattern-adjusting valve—**Controls spray pattern
• **Fluid inlet—**Connects to material supply
• **Fluid needle—**Forms seat with fluid valve seat
• **Fluid Tip—**Directs material into air stream
• **Air cap—**Forms the spray pattern
• **Air separator**—Filters and directs air

Gun Body

The gun body is made of forged aluminum and the fluid passages are stainless steel. Fluid and air inlet ports, the hanger hook, and the trigger safety lock are located on the gun body. The hanger hook provides for proper storage when the gun is not in use.

Trigger

The trigger has a two-finger design. It opens the air control valve, allowing air to flow into the gun and it unseats the fluid needle from the valve seat, allowing fluid to flow. The trigger assembly is designed to produce a “lead-and-lag” air flow. As the trigger is pulled, air is turned on before the fluid flow begins. As the trigger is released, air is turned off after the fluid stops flowing. The “lead and lag” can be felt when the trigger is pulled. This feature helps to keep the top of the tip free and the air horns cleaner.

Trigger Safety Lock

The trigger safety lock is permanently affixed to the gun handle. The trigger cannot be pulled when set in this position. To release, push the lever toward the trigger and to a vertical position.

Air Inlet

Air enters the gun body handle through a specially designed fitting.

Air Control Valve

The air control valve is located in the handle of the gun body, directly behind the trigger. A positive return spring on the stem keeps the valve closed until the trigger is pulled. When the trigger is pulled, the valve opens, allowing air to flow. The air control valve provides no air pressure regulation. When the valve is closed, no air enters the front portion of the gun. When the valve is opened, full air pressure is admitted. The air pressure is controlled entirely by a pressure regulator located between the compressor and the gun.

Pattern-Adjusting Valve

The maximum width of the spray pattern is typically determined by the pattern width specification of the fluid tip. The pattern-adjusting valve can decrease this dimension, but cannot increase the tip specification. This valve is located above the gun handle. The knurled adjusting knob is directly behind the hanger hook.

The stem of the pattern-adjusting valve seats in the air separator chamber in the front of the gun body. When the valve is turned counter-clockwise (closed), the pattern will be at maximum width. When it is turned clockwise (open), the pattern width will be reduced.

Fluid Inlet

Fluid enters the stainless steel fluid passages of the gun body through the specially designed fluid

inlet. The fluid is contained in the forward portion of the body by three pieces of packing, the ball of the needle, and the cone of the seat. Pressure of the needle spring against the packing assembly ensures proper seal of the fluid. Pulling the trigger engages the needle assembly and pulls the ball of the needle off the cone of the valve seat assembly, allowing the fluid to flow.

Table 2. Airless Spray Pattern Shape Problems.

Type and Description of Problem	Possible Cause(s) of Problem
Tails	Inadequate paint flow Paint not atomizing (too heavy or fibrous) Paint flowing too slowly Worn nozzle tip Low pump pressure
Heavy-centred pattern	Worn nozzle tip Paint will not atomize with airless sprayer
Distorted pattern	Plugged or worn spray tip
Pattern changes size	Pulsating paint flow Insufficient power to pump Leak in tubing or hose Paint too thick Pump not adequate in size

Table 3. Pump Delivery.

Spray Tip Size	May Deliver (gpm)
0.007	0.05
0.011	0.12
0.15	0.23
0.17	0.30
0.19	0.36
0.21	0.46
0.31	1.02

Fluid Needle

The fluid needle consists of four main parts:

- Needle stem and ball
- Spring
- Hex nut
- Air needle nut

The air needle nut fits over the hex nut and the stem of the air control valve. When the trigger is pulled, the air needle nut moves back.

Fluid Tips

The proper fluid tip is necessary to achieve the highest quality and efficiency with the air-assisted airless gun. Fluid delivery requirements (ounces/minimum) and fan pattern widths to accommodate production requirements are the basic criteria. Operating pressures are considerably lower than normal airless spray so material viscosity and fluid pressure will affect the delivery rates of the fluid tip.

Air Cap

The atomizing holes of the air cap are typically located in the horns of the cap, and the pattern-adjusting holes are typically located in the cap's face. The spray pattern can be adjusted to vertical or horizontal by loosening the safety-retaining ring and rotating the air cap 90°. The tip will rotate with the air cap.

Air Separator

An air separator divides the pattern air and atomizing air. It is made of a durable material and screws onto the front of the gun body. The air cap fits onto the separator, which has a snap ring seal.

Electrostatic Spray Systems

Electrostatic spraying permits the application of coatings to irregularly shaped, electrically conductive structures and components with a very high transfer efficiency. Non-conductive surfaces (e.g., wood, plastics, and composites) may receive a surface treatment or coating to render them conductive. Although all coatings may be electrostatically sprayed, some formulations must first be modified to improve their electrical properties. Electrostatic spray has these advantages and limitations:

Advantages

- Wrap-around of edges
- High transfer efficiency
- More uniform application
- Material savings

Limitations

- High initial/maintenance costs
- More suited for automation work
- Skilled operator required
- Safety precautions required
- Normally limited to one coat
- Limited to exterior surfaces
- Require conductive surface

Table 4. Airless Nozzle Selection Guide for Electrostatic Spraying.

	Large Targets	Small Targets	Tubular and Open Ware
Recommended Fan Angle	*65-80* A larger fan reduces the number of passes required.	*25-40* Select a smaller fan to reduce overspray that occurs when fan is wider than the parts; smaller fans penetrate recesses better.	*15-25* A fan should be 3 to 5 times the part width; for maximum wrap-around, about 2/3 of the paint should miss the front side of the part.
Recommended Nozzle Size			
Low Production	10-15 $ft.^2$/min Try 0.011-inch orifice	8-12 $ft.^2$/min Try 0.009-inch orifice	5-9 $ft.^2$/min Try 0.007-inch orifice
Medium Production	15-20 $ft.^2$/min Try 0.013-inch orifice	12-16 $ft.^2$/min Try 0.011-inch orifice	9-15 $ft.^2$/min Try 0.009-inch orifice
High Production	20 $ft.^2$ Try 0.015-inch orifice	16-21 $ft.^2$/min Try 0.013-inch orifice	15-21 $ft.^2$/min Try 0.011-inch orifice
Top Volume (with some drop in quality)	Try 0.018-inch orifice		

Electrostatic spray guns are available that apply the electrostatic charge by either one of these two processes:

- The paint is electrically atomized and charged as it leaves the edge of a spinning bell
- The electrical charge is applied to paint particles already atomized either by air spray or airless methods, or applied to the paint stream just prior to atomization

Spinning-Bell Method

Most solvent-based, free-flowing paints may be applied by the spinning-bell method. The flow of coating to the bell is provided by the usual regulated paint supply system. An electric motor in the gun rotates the atomizing bell so that the material flows uniformly to its outer edge. Atomization occurs under the influence of the electrostatic field as the paint flows from the edge of the bell, forming a spray pattern of electrically charged particles. These charged particles move at slow speeds and tend to deposit on the object at points of maximum electrostatic attraction. The paint applications will thus be thinner in cavities and depressions on the surface, and heavy on edges or protruding points. This represents a definite advantage when applying protective coatings. Non-electrostatic methods of painting application (brush or spray) tend to leave thin coatings on edges, where early coating failure usually occurs.

Paint application rates by the spinning bell method are too limited for most high production rate applications of maintenance paints and protective coatings. The bell with the largest capacity (6 inches) has an approximate maximum paint delivery rate of 6 oz/min. However, these rates are ample for painting open grills, chain link fences, etc.

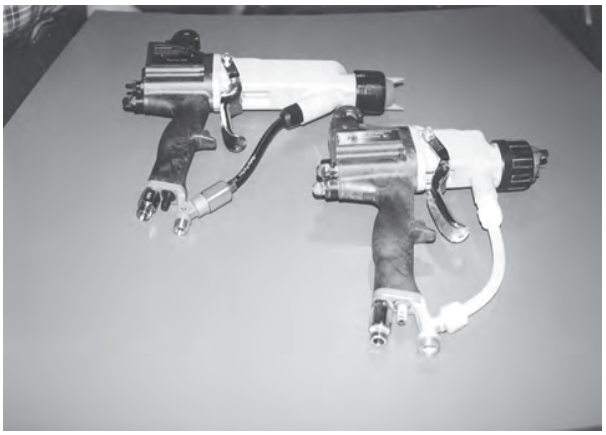


Figure 3. Electrostatic spray guns.

Air Atomizing and Airless Electrostatic Spray Methods

Air atomizing and airless electrostatic spray methods are more suitable for the field application of maintenance paints and coatings since higher deliveries are possible. The forces of electrostatic attraction result in a more uniform coverage over regular surfaces than is otherwise obtained, and furthermore, these guns may be used as ordinary spray guns whenever desired. Such electrostatic spray methods exhibit all the inherent advantages of the conventional

air and airless spray methods, with the added advantages of electrostatic attraction, paint savings, little if any fog and overspray, and less cleanup and protection of nearby objects.

The electrostatic charge is applied either by an electrode protruding in front of the gun and extending into the paint atomizing zone, or by an electrode extending into the paint stream in the gun just before atomization. Depending upon the manufacturer, ionizing voltages range from 30,000–90,000, with approximately 60,000 volts employed by several prominent manufacturers. These are usually fixed voltages that cannot be varied. Air spray and airless electrostatic guns may be fed by conventional paint pumps or pressure tanks. However, special electrostatically conductive hoses must be employed.

When electrostatic spray equipment is operating properly and the paint conductivity is within the range suitable for electrostatic spraying, a marked wrap-around effect occurs. If there is only a weak wrap-around or none at all, the paint conductivity may be too high, the power supply may not be operating, or there may be some electrical trouble with the high-voltage cable or gun.

Safety Features of Electrostatic Spray Systems

Although high voltages are used, the equipment, when property set up, is safe to operate. There is no voltage applied to the gun electrode when the trigger is not pulled. Upon pulling the trigger, high voltage is present, but with most equipment this decreases as the electrode approaches a grounded object until, when contact is made, the voltage difference becomes zero. Consequently, holding the gun in one hand and touching the electrode with the other will produce no shock. The fluid hose must contain a special grounding wire or the jacket must be conductive to electrostatic charges. In air-atomized spray, the fluid hose contains a conductive ground wire embedded in the carcass.

The painter is grounded when gripping the gun handle since the handle is connected to ground through the high-voltage cable as well as through the hose. Consequently, the painter cannot wear gloves, which would insulate hands from the gun handle, unless the palm of the glove is cut out to ensure contact with the handle.

There is very little paint fire hazard with modern electrostatic spray equipment that has been properly installed and is operated as recommended. Although gun voltages are high, only microamperes of current are required to charge the paint particles. It has been demonstrated that there is so little energy present in a spark from the gun electrode on some equipment that tests have failed to ignite hexane vapors.

However, the control of energy in the electrostatic equipment does not apply to nearby conductive objects that may be insulated from ground. These objects can develop high voltages with appreciable energy as they are contacted by charged air molecules and paint particles. A spark from such objects may easily contain sufficient energy to ignite solvent vapors. Consequently, it is essential that all electrically conductive objects, including personnel, be grounded when located within 10–15 feet of the gun operating area. In addition to grounding the power supply, it is recommended that the unit be located as far as possible from the spray area (at least 20 feet).

Metallic items must be removed from pockets (e.g., coins, keys, pencils, nail clips, etc.). There have been occasions where these overlooked items have acquired a sufficient charge to ignite solvent vapors as they sparked through the pocket when the painter moved close to the grounded paint bucket.

Application Procedure

Application techniques are, in many ways, simpler with electrostatic spraying than with straight air or airless spraying. Lapping is less critical in applying an even coat, and, for many applications, careful attention to triggering is not necessary. Overspray is essentially eliminated by the electrostatic attraction of the coatings.

With air electrostatic spraying, lower atomizing air pressures are required, both because of thinning and because the electrostatic charge aids in paint particle formation. Likewise, considerably lower fluid pressures are necessary with airless electrostatic spraying, and the degree of atomization is usually finer than without the electrostatic charge. Because the viscosity of most paints to be applied electrostatically has been adjusted to the desired range, only two or three spray nozzle setups satisfy most air electrostatic application requirements. A selection of airless spray nozzles is needed, however, depending upon the object shape and application rates desired.

The inclusion of an orifice spray insert is

helpful with paints that are difficult to atomize to a fine spray without using excessive fluid pressure. The insert tends to reduce the forward velocity of the paint through the nozzle, providing a “softer” spray with increased electrostatic efficiency. An insert may be useful for spraying tubular and open items. The spray insert orifice size should be equal to or slightly larger than the nozzle size, but never smaller.

When painting, it is recommended to hold the electrostatic gun at the manufacturer’s recommended distance from the surface (e.g., 6–10 inches with air spraying and when using the spinning bell gun, and 8–12 inches for airless atomization). The distance should never be much greater than 12 inches; otherwise, the sprayed paint particles may be attracted preferentially to the painter’s grounded hand rather than to the object being painted. This is one reason for the somewhat longer gun barrel on air and airless electrostatic spray guns.

Paints must be kept from accumulating on the electrode wire and on the face of the nozzle. Paint deposits may be removed with a bristle brush and solvent, but only after the high voltage has been turned off. For more extensive maintenance and service of electrostatic spray equipment, refer to the manufacturers’ service manuals.

Solvents Recommended for Coatings Applied by Electrostatic Spray Systems

The standard formulations of most solvent-based paints can be sprayed successfully by air and airless electrostatic spray methods, providing that the paint conductivity is not so high as to form a grounding path for the high voltage. Paints are conductive either because conductive (polar) solvents are used or metallic pigments are present.

Paints that have solvents too conductive for air and airless electrostatic spray application can seldom be successfully modified in the field by adding non-conductive (non-polar) solvents. The paint formulation must be revised by the supplier. All water-based paints and many paints with metallic pigments cannot be applied by electrostatic hand guns because of their conductivities.

In addition to considerations of paint conductivity, it has been found that optimum electrostatic attraction results when the paint viscosity is adjusted from 20–24 seconds with a No. 2 Zahn cup (or 14–22 seconds with a No. 4 Ford cup). This is lighter than the viscosity of most paints supplied for conventional spraying. Xylene, or other nonpolar or low-polar solvents compatible with the paint system, are recommended for thinning purposes.

Since lower spray pressures are generally used, the charged paint particles move more slowly to the surface being painted than when applied by conventional methods. Consequently, slower-drying solvents must be used in the paint formulation to ensure that a wet paint film is being applied. Furthermore, a paint particle that dries enroute to the surface quickly loses its charge and so will not be electrostatically attracted to the surface.



Figure 4. Plural-component proportioning system.

Plural-Component Spray

The plural component method of spraying coatings combines at the nozzle those components of thermosetting coatings that cure by chemical reaction. Each component is automatically proportioned as recommended by the manufacturer and combined in either a manifold/mixing chamber immediately before spraying or immediately after spraying with an airless

or conventional air spray gun. The basic components of plural-component spray systems are:

- Coating material feed system for each component
- High-performance proportioning pump
- Appropriately sized, chemically resistant hoses for unmixed components
- Mixer manifold assembly
- Whip hose
- Airless or conventional air spray gun
- Solvent-purge system
- Filters
- Heaters (optional)
- Off-ratio alarm/shut-down (optional)

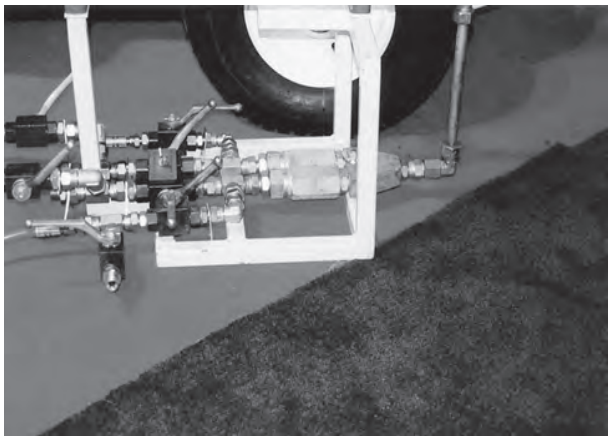


Figure 5. Manifold of plural-component system.

Fixed-ratio systems are used most often in production plants where the same operation is performed daily with no variance. Industrial coating contractors more commonly use a variable-ratio system because they apply, either in the shop or in the field, a variety of plural-component coatings with different mixing ratios. Typical plural-component materials applied include, but are not limited to, coatings with resins of epoxy, polyurethane, polysulfide, and silicone.

The spray system may be airless or conventional, or a combination of both. In many applications, the material is heated to reduce the viscosity. Use of this equipment requires special training and extra safety precautions.

Technology has made available control devices to monitor and control the mix ratio of the plural-component materials used in a variety of applications. These devices measure the positive displacement of the volume of solids flowing through the system, and automatically adjust the mix ratio to keep it within selected tolerances. If the desired mix ratio cannot be maintained, delivery of the material is stopped and an alarm message is issued.



Figure 6. HVLP spray gun.

High-Volume, Low-Pressure Spray

High-volume, low-pressure (HVLP) spray systems require a high volume of low pressure air to atomize the material being applied. The chief reason for developing HVLP spray was to produce a high transfer-efficiency system and thus reduce the amount of coating used and the amount of organic solvent entering the atmosphere.

In exterior appearance, HVLP spray equipment resembles a conventional air spray system, especially the actual spray gun. The air cap, fluid needle, fluid tip, fluid adjusting screw, spreader adjusting valve trigger, and gun body are similar. Spray application is slower, although some units (with the proper combination of air cap, fluid tip, and fluid needle) will deliver up to 18 oz/min. (0.5 L/min.). This delivery can be compared to using a 74:1 airless spray pump with a large orifice opening in the spray tip, which will deliver approximately 1.25 gal/min. (4.98 L/minute). Because of the high volume (at least 20 cfm) of air required with some industrial HVLP spray systems, a two-stage compressor is required if the system is to be productive.

In the process of applying industrial coatings to large areas, such as storage vessels, ships, etc.,

HVLP cannot accomplish the high application rate that is possible with high-volume airless equipment. However, HVLP is used extensively in the wood finishing, farm equipment manufacturing, and automotive industries, and for commercial and residential application, but will not achieve the production level of other spray systems. The advantages and limitations of HVLP are:

Advantages

- Good transfer efficiency
- Reduced overspray and bounceback
- Good with high-solids coatings
- Good gun control

Limitations

- Reduced application speed
- High initial/maintenance costs
- May require special training

References

1. SSPC PA 1. *Shop, Field, and Maintenance Painting of Steel;* SSPC: Pittsburgh.
2. Applicator Training Bulletins in the Journal of Protective Coatings and Linings; TPC: Pittsburgh.
3. *ABCs of Spray Finishing;* DeVilbiss: New York, 1999.
4. *Airless Spray Coating Technology, Including Air-Assisted Airless Spray Technology;* Graco, Minneapolis, 1995.
5. *Safety;* Graco: Minneapolis, 1995.
6. *Concept and Theory Training Module on Safety;* Graco: Minneapolis, 1995.
7. *Electrostatic Spray Finishing;* Graco: Minneapolis, 1995.
8. *The Fundamentals of Cleaning and Coating Concrete;* Randy Nixon and Richard W. Drisko, eds.; SSPC: Pittsburgh, 2001.

About the Author

Frank Palmer

This information has been prepared by Frank Palmer of Frank Palmer Consultants Limited and Cheryl McArthur of Perfect Words, both of Calgary, Alberta. Frank Palmer has specialized in designing training programs and seminars and writing specifications for more than 20 years. He has over 25 years of practical industry experience and was the first Canadian to obtain an SSPC protective coatings specialist (PCS) certification.

Chapter 5.2
Contractor Equipment: An Overview

Michael Damiano

Introduction

Industrial painting is a complex operation, especially when done in the field. Successful coating work in the field requires the quality-oriented contractor to use a large array of equipment in order to get the job done properly, on time, and in a safe and environmentally compliant manner.

This chapter provides an overview of the types of equipment typically used for successful industrial maintenance painting. It covers the major equipment needed to perform the primary functions of cleaning the surface and applying the coating and the various types of support equipment and tools used to complete each job successfully. It should be understood from the start that the types of equipment and tools actually used on a particular job would depend on site-specific conditions and contract requirements. For example, if dry abrasive blasting is normally the contractor's choice for surface preparation but use of this method is prohibited by the facility owner on a particular project, then the contractor will need to determine an alternate method that is acceptable to the facility owner to prepare the surfaces for coating.

More detailed descriptions about the operation of the equipment mentioned in this chapter can be found in other chapters of this book that key on a specific technology or process or in the suggested readings.

While this chapter focuses on maintenance painting in the field, specific equipment used in new construction or shop painting is briefly mentioned. With some exceptions, equipment mentioned for fieldwork is also used in new construction painting and shop painting.

Mobilization

Before a contractor can begin work on an industrial structure such as a tank, bridge, or structural steel at a power plant, the contractor's key management personnel in charge of the job must set up the job site. Setting up the job site often requires trucks and rigs to bring in site trailers that can be used for offices or lunch and break areas or meetings; material and equipment storage; and decontamination and change facilities.



Figure 1. Power plant with structural steel just coated.

Once these trailers are delivered to the site, additional equipment may be needed (e.g., phones and phone lines for Internet or fax connections; personal computers [PCs]; copiers and printers) as required. In many cases, PCs will require installation of special project management software or other software required for tracking work schedules, materials consumed, job costs, etc.

Protecting such equipment on-site may also require heavy-duty locks, security alarms, or fencing to prevent vandalism and theft. Security requirements are a function of the project's geography.

Prior to arriving on-site to actually start work, the contractor must survey the site to determine how employees will safely access the structure to be cleaned and painted. These surveys are often performed through use of snooper trucks, scissor lifts, manlifts, ladders, and scaffolds. Once access equipment needs are determined, the contractor must erect the needed scaffolding, platforms, ladders, containment structures, etc., so workers have reaching access to the actual work components. Access equipment will be discussed later in this chapter.

Once the workers arrive on-site, portable toilet and other hygiene facilities must be set up along with utility connections.



Figure 2. Portable toilet at job site.

Surface Preparation

The first key operation is erecting scaffolding, containment, and dust collection equipment as required. Prior to actually beginning paint removal, there is usually a hold-point to ensure that the appropriate equipment has been set up properly.

Prior to starting surface preparation, the surface condition should be evaluated and the appropriate precleaning method determined in accordance with SSPC SP 1. All SSPC dry abrasive blast cleaning surface preparation standards require precleaning prior to mechanical surface preparation. Such activities may include pressure-washing, steam cleaning, solvent cleaning, applying soluble salt removers, degreasing, etc.



Figure 3. Contractor equipment at job site.

Dry Compressed Air Abrasive Blast Cleaning

Once the job site is set up and the contractor has been given formal notice to proceed, surface preparation can begin. If the contractor is going to dry abrasive blast clean the surface, surface defects must first be repaired and detrimental contaminants removed. Blasting operations will likely include:

- Appropriately sized compressor and properly sized air hose
- Blast machine or blast pot, including metering valves
- After-coolers/air dryers
- Moisture separators
- Bulk abrasive storage facility
- Abrasive blast or "bull" hoses and related couplings and fittings
- Blast nozzles
- Breathing air filters
- "Deadman" controls (electric or pneumatic)
- Breathing air line hose
- CO alarms for breathing air lines when oil compressors are used
- Climate control valves for the breathing air line
- Two-way radio or other communication equipment
- Vacuum unit to clean up recyclable or spent abrasive
- Dehumidification units if work is being done inside a tank or confined space
- Portable ambient air heaters (propane, kerosene, electric, and diesel)

• Solvent recovery units, if solvents used for pre-cleaning
• Low pressure washing units (diesel or gasoline powered)
• Appropriate dust collection units
• Material (abrasive) handling equipment

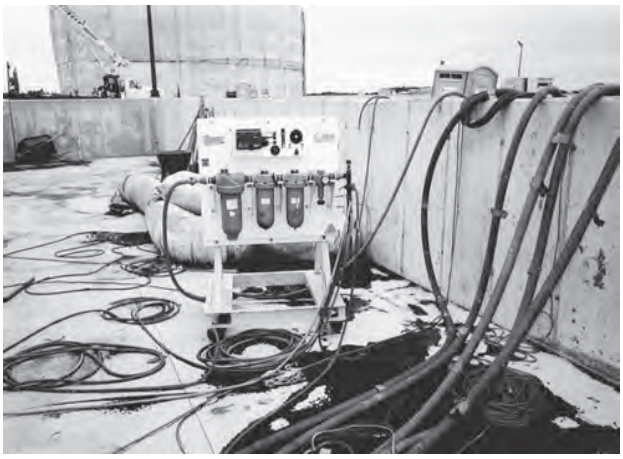


Figure 4. Breathing air filter unit with alarm.



Figure 5. Supersucker blast cleaning truck. Courtesy Eagle Industries.

Manual dry blast cleaning in the fabrication or paint shop is likely to take place in a blast room, or, if the pieces are small, in a hand-operated blast cabinet, both of which are specialized pieces of equipment manufactured for indoor blast cleaning. Dry blasting in the shop must be done in areas where fallout from abrasive blasting debris cannot contaminate previously painted or cleaned surfaces. If required to reduce dusting while blast cleaning in the field, the contractor may attach an abrasive water ring or similar attachment to the blast nozzle. Blast cleaning with some specialized soft media such as CO^2 (dry ice) or sponge will require customized equipment.

Centrifugal Blast Cleaning

Some surface preparation work is done using portable centrifugal blast cleaning units. Robotic, remote-controlled units are used to clean relatively flat surfaces such as those found on storage tanks or ship hulls. Portable shot blasting units are used to prepare concrete floors and other horizontal surfaces prior to coating.

In fabrication and blast and paint shops, large stationary centrifugal or wheel blasting equipment is used to clean fabricated items such as steel beams and piping using recyclable metallic abrasive. These units allow for good production rates, produce high quality cleaning, and eliminate the need for workers to do the blast cleaning manually.



Figure 6. Mobile machine and recycling unit. Courtesy Eagle Industries.



Figure 7. Sponge abrasive blast pot.

Wet Cleaning Methods

High and ultrahigh-pressure (HP & UHP) waterjetting units operating at nozzle pressures up to



Figure 8. Blast cleaning in paint shop. Courtesy Medford.

30–40K psi (207–280 Mpa) are often used to remove surface contaminants prior to coating application. Special wet abrasive blasting injector units are also used when a mix of abrasive, air and water, or just abrasive and water, are employed to prepare surfaces. Water cleaning produces less dust than would normally be found when using dry blast cleaning methods.



Figure 9. HP waterjetting machine.

Equipment needs for waterjetting are less intensive (although not necessarily less costly) than for dry blasting. A typical waterjetting system requires a water supply line and holding tanks, pump units to produce the pressurized water, hoses to get the water to the nozzle operator, and the appropriate wand and nozzle so the worker can control the water jet during cleaning. There are no controls on a manual waterjetting gun except the trigger and the dump valve. The dump valve is a safety device similar to the "deadman" control on a dry blasting unit that effectively shuts down or slows the pump or reduces nozzle pressure when activated.

Waterjetting equipment can be manually operated using a wand and nozzle, or can be remotely operated for cleaning tanks, ships, and other vertical surfaces. Hand operated or "walk-behind" units with vacuum attachments are also available for certain types of work, such as small vertical surfaces or floors and decks.

Specialty Blast Cleaning Methods

Special blast cleaning machines are available for specific surface preparation options using "specialty" abrasives such as sodium bicarbonate (i.e. baking soda), carbon dioxide (i.e. dry ice), and synthetic sponge. Because certain specialty media cannot be processed in a "traditional" blast machine, a specialized blast machine is required. Otherwise the equipment needs are essentially the same as for dry abrasive blast cleaning.



Figure 10. Electric-powered disc sander.

Hand and Power Tool Cleaning

When wet or dry blast cleaning or waterjetting methods are neither feasible nor practical or when spot repairs are needed in select areas of a surface, hand and power tools are typically used for surface preparation. The following are examples of the equipment and tools typically found on a painting project job site:

- Scrapers
- Putty knives
- Wire brushes
- Needle guns
- Disc sanders

• Grinders
• Rotary peens
• Chipping hammers
• Power chisels

Power tools used on industrial painting projects are most often pneumatic but electric-powered models may also be available.

Concrete Floors

A variety of equipment and tools are used to clean floors prior to coating. They include:
• Portable “walk-behind” or ride-on shot blasting machines
• Floor scalers, scabblers, or scarifiers
• Portable “walk-behind” or ride-on waterjetting units
• Traditional abrasive blast cleaning equipment
• Dehumidification equipment

Hazardous Paint Containment, Storage, and Disposal

If lead-based paint or other hazardous materials are to be removed during surface preparation, additional specialized equipment must be brought in, including:
• Hepa vacuums
• Hand washing units
• Shower and special “clean room/dirty room” change facilities
• Air monitoring equipment (for ambient air and personal breathing air)
• Biological monitoring and respiratory clearance equipment
• Lead and soil testing and associated equipment
• Metallic abrasive cleaning and recycling units
• Dust collection or bag house units, including appropriate ducting
• Containment materials (e.g., tarpaulins)
• Shrouds and vacuums attached to power tools to control dust emissions
• Storage drums or storage roll-offs for hazardous waste

Other Equipment

Industrial painting operations sometimes require special support equipment or accessories for non-routine circumstances. For example, working on structures such as a bridge over water or a lock and dam may require placing equipment on a barge.



Figure 11. HEPA vacuum.

Contractors working on offshore platforms or drilling rigs may require boats to transport equipment and supplies. Smaller offshore structures may require jack-up boats or barges to stage equipment. Helicopters and crew boats may also be required to transfer crews to the job site. In addition, living quarters may have to be set up for some projects. Diving equipment and accessories are required for underwater coating operations.

Night work or work in confined spaces or indoor spaces will require portable lighting. Lighting may be powered by compressor, portable generators, or plant electricity. In confined spaces, especially storage tanks, explosion-proof lighting is often required.

Working around or near vehicle traffic will require various traffic control devices for safety as well as for diversion of vehicles prior to beginning work.

Access

Having the proper equipment for coating operations is essential. However, most of the time additional support equipment is needed to provide workers with close access to the work surface to enhance the quality of work and for working safely.

The ladder is the most common and fundamental piece of access equipment. Step, extension, single and stationary ladders such as those found on the outside and interiors of storage tanks are common on industrial painting projects. More sophisticated access equipment such as aerial lifts, scissor lifts, and platform trucks are needed when ladders cannot provide adequate access.

Scaffolding is often used on industrial painting projects to provide worker access. Built-up, tubular, mobile, and swing scaffolds are typical. Scaffolds, particularly two-point suspension systems, are raised and lowered using powered hoists. Scaffolding systems also include guardrails, toeboards, canopies, and screens, as needed.

Associated rigging equipment such as transfer chains, scaffold platforms made of wood or aluminum, are also typical. A single worker sometimes uses a bosun chair and work cages for access.

Besides access equipment and accessories, working in high places (e.g.. 6 ft. off the ground or above a lower working surface) requires fall protection (i.e., fall arrest and fall restraint) equipment. Full body harnesses, shock absorbing lanyards, and deceleration, lifeline, and anchoring devices are among the critical components of a fall protection system. Work/containment “platforms” may be in the form of chain link fencing covered with tarpaulin, rolled steel decking, plywood, or other durable materials. Temporary ramps, runways, and stairways are sometimes required for access to the work platform.

Paint Shop Equipment

Most of the surface preparation equipment used in the field is also used in the fixed facility paint or fabrication shop. Some equipment farily unique to the shop (althought sometimes found in the field) includes:

- Fire extinguishers
- Fire sprinklers and alarm systems
- Solvent recovery equipment
- Permanent explosion-proof lighting in the paint storage area
- Materials handling equipment (e.g., cranes; forklifts)
- Atmospheric heaters
- Curing ovens
- Special dip tanks for pickling or phosphate treatment

Paint shops will usually have separate rooms or booths for blast cleaning and coating. Shops will also have a number of environmental controls such as filters and ventilation equipment. Often shops have pipe wrapping, powder coating, or metallizing equipment if these processes are used.

Application Equipment

Much of the support and access equipment used for surface preparation is the same needed for quality and safe coating application. Specific types of application equipment may include but are not limited to:

- Air compressors
- Moisture traps
- Air drying/cooling units
- Hoses, couplings, and fittings
- Conventional or air spray equipment
- Airless equipment
- Fluid pumps, pressure tanks, or pots
- Spray guns and tip accessories
- Powered portable or drill mixers
- Viscosity cups and straining equipment
- Siphon-fed spray equipment
- Electrostatic spray equipment
- Mechanical proportioning, plural-component spray equipment
- Ventilation fans for indoor and confined spaces
- Dehumidification equipment
- Forced-cure heater when applicable
- Power trowels, rakes, squeegees (for concrete surfaces)
- Materials handling equipment (paint cans)

Flame or arc spray guns and customized control units are used for specialized application processes such as thermal spray metallizing.

Fluidized beds for dry powder-coating application and other specialized powder coating equipment is usually found in the shop. More information on application equipment can be found in the chapters on paint application, thermal spray metallizing, and powder coatings.



Figure 12. Handwash unit.



Figure 14. Dust collector.



Figure 13. Containment tarps.



Figure 15. Equipment on barge.



Figure 16. Traffic control equipment.



Figure 17. Aerial lift.



Figure 19. Work containment platform.



Figure 20. Gas-operated 30-ton capacity rolling crane.



Figure 18. Scaffolding and containment on an AST (fuel tank) being cleaned and painted.

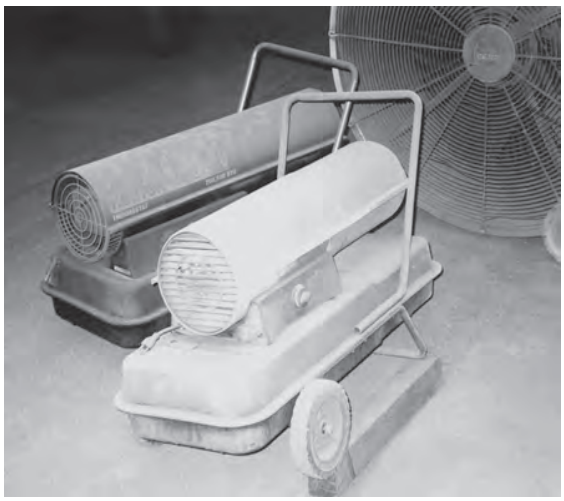


Figure 21. Portable heaters.



Figure 22. Airless spray gun.



Figure 23. Spray paint pump.

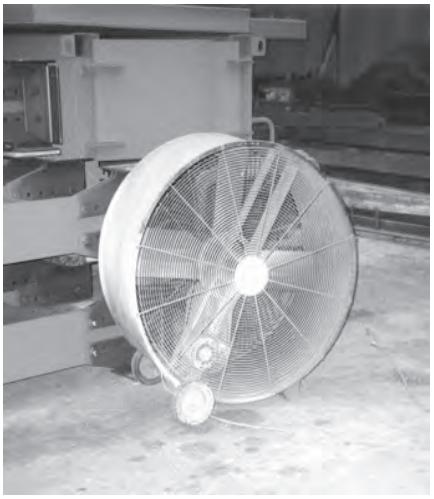


Figure 24. Ventilation fan.



Figure 25. Mixing zinc-rich painting material prior to coating.



Figure 26. Thermal spray metallizing.

Quality Control Equipment

The quality-conscious contractor will also bring to each job site the necessary quality control (QC) equipment to keep defects and rework to a minimum and thus increase production as well as to document the adherence to project specifications and normal good painting practices. The number and type of instruments brought to the job site will vary with the requirements of each contract and the size of the project. Examples of quality control equipment include but are not limited to:

Ambient Conditions

- Sling psychrometer (to obtain relative humidity and dewpoint)
- Surface temperature gauge (to measure working surface temperature)
- Psychrometric tables (used with psychrometer to obtain ambient readings)
- Moisture meter (to measure moisture in concrete)

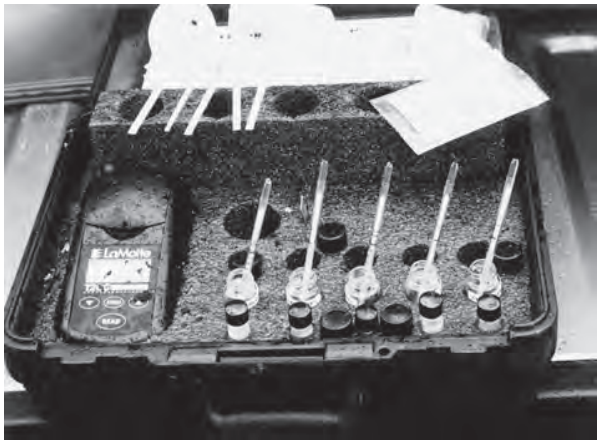


Figure 27. Soluble salts test kit.

Surface Preparation

- Hypodermic needle pressure gauge (to measure blast nozzle air pressure)
- Nozzle orifice gauge (to measure nozzle wear)
- Abrasive sieves (to measure abrasive size or separate recycled abrasive)
- Surface profile comparator (to measure surface profile using visual comparisons)
- Replica tape and micrometer (to measure surface profile per ASTM D 4417)
- Surface profile gauge
- Chloride ion and other soluble salts testing equipment
- Conductivity meter (to measure soluble salts)
- Camera (to document work)



Figure 28. Magnehelic gauge.



Figure 29. Anemometer.

Application

- Paint thermometer (to measure paint temperature)
- Wet film thickness gauge
- Dry film thickness gauge—magnetic pull-off or constant pressure (to measure paint film after it has dried)
- Tooke gauge (to measure coating thickness)
- Holiday or spark tester—low or high voltage (to measure discontinuties in the coated surface)
- Adhesion testers (to measure paint adhesion or

soundness of concrete)
• Camera
• Hardness pencils (to measure completeness of curing)

QC equipment kits may also contain visual standards such as SSPC-VIS 1, VIS 2, VIS 3, VIS 4, VIS 5, or ISO 8501, calibration instructions and plates as well as other written standards required for the job. These instruments and related inspection standards are covered in more detail in the chapters on inspection and quality control.

Safety
• Velometer (to measure air flow)
• Magnehelic gauge (to measure negative pressure)
• Anemometer (to measure air flow)
• Noise meter
• Heat-stress monitors
• Gas/Oxygen detector (for confined space work)



Figure 30. Worker wearing full PPE while changing dust collector.

Safety Equipment

Painting contractors are required by regulation to make available and utilize an array of safety-related equipment. Quality-oriented contractors also know that protected and safe workers are more productive and miss less work. They know, too, that safe operations reduce operating costs (lower insurance rates). See the chapter on safety for a more detailed discussion of safety equipment, which includes:

Personal Protective Equipment
• Dry blasting and water blasting suits
• Coveralls or disposable suits for paint application
• Protective gloves
• Eye protection (goggles, glasses, shields)
• Hard hat
• Ear protection (ear muffs, earplugs)
• Knee pads
• Protective footwear
• Specialized clothing for hazardous materials handling or nuclear work
• Special reflective vests for road or night work
• Approved buoyant vests and life rings for working over or near water



Figure 31. Ground fault circuit interrupter at job site.

Respiratory Protection
• Abrasive blast helmets appropriate for the hazard encountered
• Air purifying respirators and appropriate cartridges
• Powered air purifying respirators (PAPR)
• Supplied breathing air compressors

Confined Space
• SCBA – self-contained breathing apparatus
• Extraction equipment in case a rescue is required
• Two-way radio for ease of communication

Other

- First aid kits
- Eye wash units
- Fencing
- Electrical circuit breakers and GFCIs
- Safety and caution signage



Figure 32. Eye wash station.

Other Considerations

All equipment discussed in this chapter as well as other equipment used on the job must be checked for proper operation, preferably before it gets to the job site. Equipment should also be properly sized with the rest of the equipment on the site so the intended work gets done efficiently and cost-effectively. Common spare parts, fuel, and other accessories must be factored in to job planning.

Protecting equipment while on the job site is also a concern. Sometimes the contractor has access to storage areas or erects temporary storage facilities. Oftentimes storage areas are not available and the equipment is exposed to the environment. This is of particular concern in aggressive environments such as an offshore rig where the equipment is subject to salt air, splashing seawater, etc.

The contractor must also determine what utilities (e.g., water, electricity, compressed air) will be needed to operate powered equipment and whether the owner, painting contractor, or general contractor will supply the utility.

Training operators in the proper use and safe operation of all the equipment on coating projects is essential for quality work, safety, and good production



Figure 33. Fencing to protect hazardous materials.

rates. Often, contractor workers performing hazardous operations such as the removing lead-based paints, working in confined areas, working at heights, working with chemicals, etc., are required to have additional training on the hazards of the materials they are exposed to or handling.

Conclusion

This chapter has provided an overview of the equipment a contractor normally uses on an industrial painting project. This includes most of the more common equipment for surface preparation, application, access to work, quality control, hazardous paint removal, and other miscellaneous operations typically performed by the quality- and safety-oriented professional industrial painting contractor.

Suggested Reading

Wheels of Learning Craft Training—Trade: Industrial Painting, Prentice Hall/National Center for Construction Education and Research: New York, 1998.

Procedure Handbook: Surface Preparation and Painting of Tanks and Closed Areas, SSPC: Pittsburgh, 2000.

Technical Guideline No. 03732. *Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays;* International Concrete Repair Institute: Sterling Va., 1997.

The Collected SSPC Applicator Training Bulletins (1988-1992); SSPC: Pittsburgh, 1992.

The Inspection of Coatings and Linings: A Handbook of Basic Practice for Inspectors, Owners, and Specifiers; Bernard R. Appleman, ed.; SSPC: Pittsburgh, 1997.
The Fundamentals of Cleaning and Coating Concrete; Randy Nixon and Richard Drisko, eds.; SSPC: Pittsburgh, 2001.

Acknowledgements

The author and SSPC would like to thank Stephen Dobrosielski for his insight into the development of this chapter.

About the Author

Michael Damiano
Currently director of product development at SSPC, Michael Damiano joined the organization as manager of the painting contractor certification program (PCCP) in 1991. He also served as SSPC's technical services manager from 1994-1997.

Chapter 5.3
Shop Painting of Steel

Richard W. Drisko and Raymond E. F. Weaver

Introduction

Shop painting is by definition painting that is done in a shop environment protected from the weather. This chapter describes different types of industrial and light industrial/commercial paint shops, their methods of operation, and their advantages and limitations when compared to on-site field painting. The information was gathered from published literature and tours/surveys of a dozen painting shops.[1-3]

Types of Shops for Cleaning/Coating Operations

There are numerous different types of shop structures in which surface preparation and coating of metal objects are conducted. These include:

- **Enclosed Shop—**A permanent facility, enclosure, or building (four walls to grade and a roof)
- **Covered Shop—**A permanent facility, enclosure, or building having a roof
- **Open Shop—**A permanent area or facility with no roof or walls
- **Temporary Field Shop—**A facility, enclosure, or building set up for use at a field site while a specific construction job is being completed

Some painting shops are very small and do only custom work. Others serve a particular industry, such as off-shore petroleum production, or specialize in a particular product such as piping or rebar. Some painting shops are part of a larger fabrication shop and may build only one specific item (e.g., light rail cars) or structural steel.[4-5]

Probably the largest shop fabricating/painting work occurs in those ship yards where fabrication/coating is done indoors in part or in whole. Large ship yards may also have separate shops for automatic blast cleaning and application of pre-construction primer to steel sheet or beams, or metallizing, powder coating, or other specialized coating work. Powder coating and metallizing are usually accomplished in separately owned shops.

Advantages of Shop Painting Over Field Painting

The chief advantages of shop painting over field painting are:

- Better economics
- Ease of containing emissions produced in abrasive blast cleaning and recycling the abrasive
- Environmental control to meet surface preparation, coating application, and curing requirements
- Less opportunity for contamination of steel and undercoats
- Better access for surface preparation, coating application, and inspection as well as safer working conditions
- More choices of coating systems
- More constant labor force
- Less interference with personnel from other trades or from other activities (e.g., plant operations; highway traffic)
- Better storage of materials

Better Economics

Shop painting and fabricating shops have the opportunity for the more efficient use of automated or other more economic systems for cleaning and painting. Studies have reported significant economic advantages of shop painting over field painting.[6-7]

Ease of Containing Emissions Produced in Abrasive Blast Cleaning and Recycling

Shop abrasive blasting has environmental, as well as economic, advantages:

- Containment of emissions generated during blasting
- Abrasive can be cleaned and recycled to reduce waste
- Shipping to a shop is less expensive, and storage and handling of abrasive at a shop reduces field contamination

Environmental Control to Meet Surface Preparation and Coating Application Requirements

Environmental control in shop painting

operations has the following advantages:

- Operations can be conducted all year long
- Temperature and humidity control minimizes flash rusting
- Improved lighting permits greater production and quality of work
- No overspray caused by wind

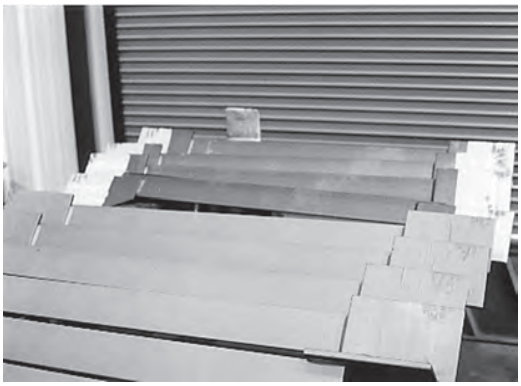


Figure 1. Ends of members coated with inorganic zinc-rich primer are masked off (background) before a coat is applied (foreground). Faying surfaces of bolted connections are often left unpainted or given a single coat of inorganic zinc. Courtesy Regal Industrial Corp.

Environmental restrictions for shop painting vary geographically. Overall, restrictions are more severe for shop than field painting because shop painting is more easily controlled.

Less Opportunity for Contamination

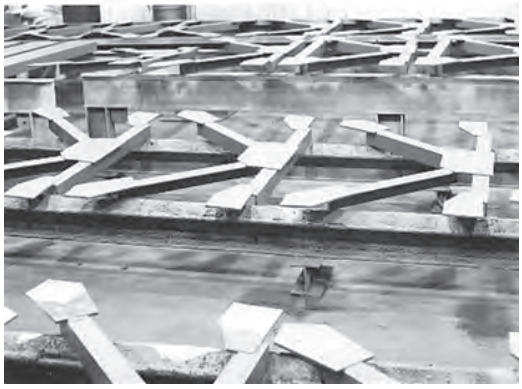
Steel cleaned in a shop is not likely to be exposed to salt or other undesirable wind-blown contaminants. Undercoats will similarly not be exposed to contaminants before topcoating.

Better Access for Surface Preparation, Coating Application, and Inspection

Better access to work minimizes the need for support equipment (ladders, scaffolds, lifts, etc.) and results in higher-quality, faster work and safer working conditions.

More Choices of Coating Systems

A controlled environment permits the use of surface preparation and systems that are easier to use, less expensive, or have greater field restrictions.





Figures 2a and 2b. Coated pieces occupy much floor space while curing. Courtesy Regal Industrial Corp. (2a) and Palmer Industrial Coatings (2b).

More Constant Labor Force in Shops

A more constant workforce is more skilled and content.

Less Interference with Personnel from Other Trades

In the field, it is common for blasters and painters to have interference problems with personnel from other trades, so that work must be deferred to a later time.

Better Storage of Materials

Shops have the ability to better protect materials, abrasives, and coatings from exterior weather conditions.

Disadvantages of Shop Painting Over Field Painting

The chief disadvantages of shop painting over field painting are:

- Damage to coatings during shipment from

shop to field
• Damage to coatings during field erection of structure, notably cutting and welding
• Inadequate space for curing and storing finished items in shop
• Special handling and erection techniques needed to minimize damage

Areas of shop-applied coatings damaged during shipment to a field site or the construction process and requiring touch-up is usually less than 5%.[8] During construction, cutting and welding coated steel probably causes the most damage to coatings. Thus, it is a common practice prior to abrasive blast cleaning and coating to tape areas to be welded later to prevent later burn-back of the coating **(Figure 1)**. Laser welding has been found to do less damage to coatings than conventional welding.

Most shops have limited storage areas for items to be coated and for those that have been coated **(Figures 2a and 2b)**. Thus, shops must arrange for a fast pick-up or delivery of finished items **(Figure 3).**



Figure 3. Hand rails with the full coating system rebundled for shipment. Courtesy Pittsburgh Coatings.

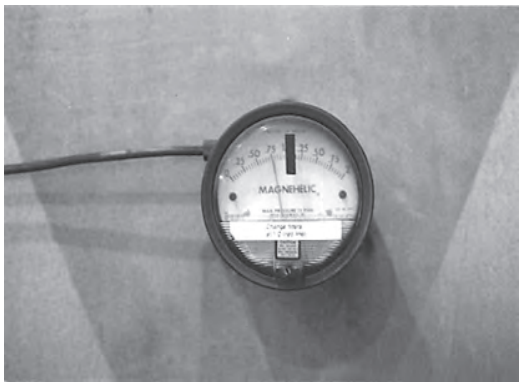
Environmental Control

A variety of environmental control systems are used in painting shops. All enclosed shops have ventilation and collections systems for dust and solvent vapors **(Figures 4a and b).** All utilize heaters on occasion, but many shops do not have expensive dehumidification systems. Higher temperatures have several effects on painting operations:

Advantages
• Less need for heating coatings
• Accelerated curing rate

Disadvantages
• Reduced shelf life
• Reduced pot life
• Reduced viscosity
• Reduced recoat interval





Figures 4a and 4b. A bank of filters on a ventilation duct in a large paint shop. A Pitot tube measures air speed. When the gauge indicates insufficient air flow (4b), the needle reaches the red line, and this bank of filters is replaced. Courtesy High Steel Structures, Inc.

Surface Preparation in Shops

Cleaning Methods

Dry abrasive blast cleaning is virtually always the preferred method of cleaning and profiling steel for surface preparation **(Figures 5a and b)**. SSPC-SP 10/ NACE 2, *Near White Blast Cleaning* is the most commonly used level of blast cleaning. SSPC-SP 6/ NACE 3, *Commercial Blast Cleaning*, is satisfactory





Figures 5a and 5b. A) A large beam supported by an overhead crane is carried through a centrifugal wheel blast unit. The roof of the blast unit is split to allow passage of the support cables. B) As the cleaned beam exists the blast unit, workers sweep abrasive off the piece. Courtesy High Steel Structures, Inc.

when applying alkyd coatings. Shop abrasive blast cleaning has the following advantages/limitations:

Advantages

- More efficient cleaning
- Particulates more easily contained in blast cleaning area
- More consistent surface profile produced
- Less tendency to flash rust
- Can apply coating immediately after cleaning

Limitations

- Special containment system needed for particulates generated
- More difficult to handle large or awkwardly shaped pieces

Waterjetting steel does not produce a surface profile. Thus, waterjetting is more suited for maintenance painting where a steel surface profile already exists.

Steel grit, a mixture of grit and shot, and garnet were found to be the most commonly used abrasives in the SSPC survey. All of these abrasives are recycled, but garnet was found to break down much quicker than metallic abrasives. Staurolite, coal slag, and aluminum oxide abrasives are used occasionally, but are not recycled.

Inspecting Surface Preparation

Inspection of steel surface preparation is addressed in Reference 9. Surface cleanliness and profile are the two chief surface preparation concerns.



Figure 6. An electrostatic air-assisted airless gun (top) and a conventional air-assisted airless gun (bottom). SSPC file photo.

Coating Application in Shops

SSPC-PA 1, *Shop, Field, and Maintenance Painting of Steel*, is a commonly used specification for shop (as well as field and maintenance) painting. It covers both general and specific requirements for the application of paint.

Coating Application Methods

Airless spray is the most commonly used coating application system because of its high application rate and relatively good transfer efficiency **(Figure 6)**. Since high fluid pressures are a hazard, airless guns have safety guards and trigger locks.

High-volume low-pressure (HVLP) spray guns are used in California and elsewhere where restrictions on transfer efficiency exist **(Figure 7)** .

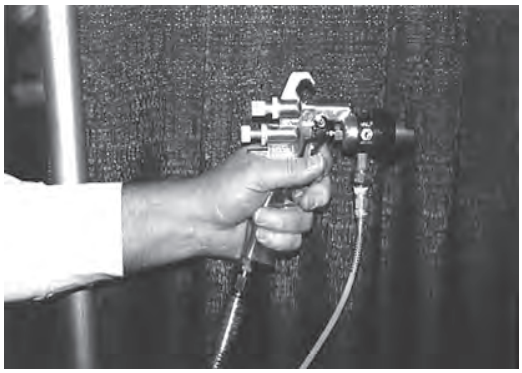


Figure 7. A typical high-volume low pressure (HVLP) gun. This type of gun is used extensively in California to reduce VOC emissions. Production rates are significantly less than airless guns. SSPC file photo.

Inspecting Coating Application

Coating dry film thickness, holidays, completeness of cure, adhesion, and application defects are of major concern.

Coatings Used

Specific Coating Systems

Thin temporary coatings are seldom shop-applied because they must be removed and replaced with a high-performance system after construction.

Pre-construction primers (PCP) are commonly used today in some large fabrication shops. Wash primer, epoxy, and alkyd PCPs have been successful. However, the most commonly used PCP today is a thin film (0.5-1.0 mil dry [12-25 µm] film thickness) zinc-rich inorganic coating (e.g., SSPC Paint 30). After construction, the PCP is given a secondary surface preparation, usually sweep blast cleaning, to clean damaged or contaminated spots, and then coated with an epoxy or other appropriate coating system.[10]

The American Society of State Highway and Transportation Officials and the National Steel Bridge Alliance prepared AASHTO/NSBA Collaboration S 8.1-200 to define three shop coating systems with inorganic zinc-rich shop primers.[11] All three have 3-5 mils (75-125 µm) of inorganic zinc-rich primer applied to near-white blast cleaned (SSPC-SP 10/NACE 2) steel and two organic topcoats:

- **shop/shop/shop—**All three coats are applied in a shop, so that only repair of damaged coating is required in the field
- **shop/shop/field—**The primer and the intermediate coat are applied in the shop, and the finish coat is applied in the field.
- **shop/field/field—**Only the primer is applied in the shop; the rest are applied after field construction.

The most commonly used generic shop coatings are epoxies. When intended for exterior service, they are usually topcoated with an aliphatic polyurethane or an acrylic topcoat to provide weather resistance.

Alkyd coating systems are sometimes used on steel in mild environments. They require a lower level of surface cleaning than higher performance coatings.

References

1. Drisko, Richard W.; Weaver, Raymond E. F. *Shop Painting of Steel;* SSPC: Pittsburgh, 2002.
2. *Shop Cleaning and Painting of Steel;* SSPC: Pittsburgh, 1990.
3. Leland, Huntley R. A Review of Shop Coating Failures. *Journal of Protective Coatings and Linings*, June 1999, pp 34-38.
4. Buesing, K.; Edwardson, W. Coatings in the Fabricating Shop, In *Proceedings of SSPC '01*.
5. Griffin, Dan. Coating Work in the Fabricating Shop. *Journal of Protective Coatings and Linings*, September 1986, pp 34-37.
6. Castler, L. Brian. *Why Shop Paint?* World Bridge Symposium: Chicago, 2001.
7. Problem Solving Forum: The Value of Total Shop Painting. *Journal of Protective Coatings and Linings,* September 1986, pp 20-21.
8. Problem Solving Forum: Bidding Field Touch-Up of Shop-Applied Coatings. *Journal of Protective Coatings and Linings*, February 1992, pp 9, 11-12.
9. *The Inspection of Coatings and Linings;* Appleman, Bernard R. ed.; SSPC: Pittsburgh, 1997.
10. Fultz, B.S. Retaining Pre-Construction Primers Under Standard Lining Systems. *Journal of Protective Coatings and Linings,* February 1999, pp 30-44.
11. American Association of State Highway and Transportation Officials/National Steel Bridge Alliance S 8.1-2001. *Guide Specification for Coating Systems with Inorganic Zinc-Rich Primer*, 2001.

About the Authors

Dr. Richard W. Drisko

Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society for Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy's center of expertise on coatings for shore structures. He is a professional corrosion engineer in the state of California, an SSPC certified protective coatings specialist (PCS), and a NACE International certificated corrosion specialist. Dr. Drisko received his BS, MS, and PhD degrees from Stanford.

Raymond E. F. Weaver

Raymond E. F. Weaver has been employed by SSPC since 1972—first as the coordinator of SSPC research projects and coauthor of many technical reports and publications stemming from these projects—and more recently in the area of standards development. He has also been involved in preparing and grading the protective coatings specialist (PCS) examinations. Mr. Weaver is currently a mathematics professor and chair of the mathematics department at the Community College of Allegheny County–Boyce Campus where he also taught physics from 1972 until 1984. He received his BS degree in physics from the College of the Holy Cross and his MS in physics from Carnegie-Mellon University.

Chapter 6.1
Painting Highway Bridges and Structures

Robert Kogler

Introduction

This chapter covers present practice in painting of highway bridges and related structures. It emphasizes painting done in the field. Shop painting is covered in a separate chapter.

Coatings provide the primary corrosion protection system for steel highway bridges. There are currently approximately 587,000 highway bridges in the U.S. with approximately 220,000 of these constructed from steel. Although steel bridges are still being built, the vast majority of steel bridges were constructed between 1920 and 1970. In recent years, the construction of new highway mileage has slowed and the use of concrete for construction of new bridges has increased. These factors indicate that the primary issue in steel bridge coatings is maintenance of the existing and aging inventory of steel bridges. The median age of the existing inventory now exceeds 30 years, and a large percentage of coating systems protecting steel bridges have met or exceeded their useful service lives. Thus there is an increasing demand for maintenance and replacement of coating systems on steel bridge structures.

Bridge painting practices have changed dramatically over the past two decades. Typical, evolutionary changes in surface preparation and coatings materials technology have been accelerated by environmental, health, and safety regulations. Specifically, the requirements to build controlled containment structures around surface preparation and coating removal operations and dramatically reduce the solvent content of industrial coatings have forced significant changes in painting practices that have not only created cost increases of 200 to 500% but have also made innovation a key driver for success in the bridge painting arena.

Types of Bridge Structures

Steel bridges can be simple rolled or plate girder constructions with all of the steel located below the level of the roadway deck or constructed of a combination of steel trusses located below and above the deck. They can have unique, challenging structures, such as main and suspender cables on a suspension bridge, or they can be highly complex with moving parts such as a Bascule or liftspan bridge. Steel highway bridges can range from 20 to thousands of feet in length. From the perspective of corrosion protection and coatings, the following variables are considered important in that they may impact coating materials or methods chosen:

• **Complexity—**Bridges with high levels of surface complexity can be significantly more difficult to clean and repaint. Complex details include box beams, riveted construction, lacing bars, and small clearances between steel members.



Figure 1. The complexity, size, and limited access to large structures can have a large impact on the cost of a bridge painting project.

• **Height and access—**Rigging for access to steel surfaces is often an important factor in the cost and schedule of a bridge coating project. By their very function, bridges cross difficult to access areas. Often, access to a structure is also heavily impacted by local traffic patterns. Sometimes viaducts and overpasses may be accessed from below; however, truss, suspension, and bridges over water require at least

some closure of the bridge deck for access and equipment placement.

• **Large and unique structures—**Cable-stayed and suspension bridges have unusual features that require a special approach during maintenance painting. There may be separate specifications and contracts for painting towers, cables, anchorage areas, and fixed-approach and suspended-truss spans. In addition, moveable bridges have obvious special requirements associated with their moving mechanical parts.

• **Utilities—**Many bridges serve as a "piggy back" for local utility crossings. The existence of live utilities attached to bridge steel can impact the maintenance painting operation.

• **Rail sharing—**Some bridges share their capacity between automotive and rail traffic. This presents the unique challenge of operating with deference to the rail schedule for access. The proximity of high-voltage third rails can also restrict the use of certain surface preparation methods.



Figure 2. Most highway bridges are relatively simple structures, but the need to keep lanes open to traffice complicates bridge painting projects.

Since many bridges cross a body of water, there is obviously a source of local moisture to promote corrosion and coating deterioration. This is especially true when salt or brackish water is crossed. For highway bridges, the other primary source of corrosivity is the large quantity of deicing salt spread on the roadway during the winter months. This is only a factor in areas that experience freezing temperatures and frequent winter storms. However, where salt is applied, it tends to drain from the bridge deck through expansion joints and other specially designed drainage areas onto the painted structural steel below, collecting onto horizontal surfaces and continuing to damage the coated steel for months. There are several areas on each structure that should be examined separately from the standpoint of localized corrosivity.



Figure 3. Drainage of water containing deicing salts onto steel below the bridge deck makes these areas particularly susceptible to coating breakdown and corrosion.

• **Drainage areas—**Various areas of the steel structure below the roadway surface will see the majority of drainage and runoff from the deck above. These areas will be wetter longer than the rest of the steel structure. They will also receive an increased level of dirt and debris from the roadway. This is particularly critical in areas that receive significant amounts of salt to melt road ice in the winter. Designed, directed drainage is often inadequate and deck-mounted expansion joints often leak as well.

• **Splash zones—**Splash zones exist in the lower parts of bridges over any body of water and also in areas that receive significant splash and spray from traffic. These areas include the lower parts of towers and pilings, parapets, curbs and guardrails, and lower portions of overhead truss structures and overpasses.

• **Facia beams and other outboard members—**These areas can receive increased damage from salt and moisture carried by prevailing coastal winds and by increased ultraviolet exposure (sunlight).



Figure 4. The "splash zone" in the area above a body of water or above traffic can be a harsh "micro-environment" on a bridge.

• **Bottom flanges—**Lower portions of flanged structures can often show paint breakdown early due to higher and longer degrees of wetness relative to the rest of the bridge.

Exposure Environments

The local environment of the metal on a structure substantially influences the rate of corrosion of the exposed steel and the deterioration of the protective coating. For highway bridges these environments are most relevant:

• **Mild:** Low pollution in the form of sulfur dioxide, low relative humidity, absence of chemical fumes, or accumulation of deicing salts, usually an interior (inland) location

• **Humid, Interior**: High humidity, low sulfur dioxide, little deicing salt

• **Industrial:** High sulfur dioxide, moderate or high humidity

• **Marine:** High salt content from proximity to seacoast or from deicing salt, high humidity and moisture

These definitions are, by necessity, arbitrary. Many bridges will not fall distinctly into any of the categories. Some bridges may have intermediate climates with moderate sulfur dioxide and moderate humidity, while others may suffer from high humidity, high sulfur dioxide, and salt. Frequently, there is a large variation in the environment within a very small geographic area due to local effects. Sulfur dioxide levels may vary substantially from one end of a structure to the other. The direction of sun and wind and the degree of sheltering strongly influence the highly critical time of wetness of structural members

Identifying the corrosion environment is important because the suitability and durability of the coating are directly affected by the type of environment. Thus, in some locales, a relatively inexpensive, easily applied oil-alkyd may last 15 years, whereas in more severe locations, that system may show significant deterioration in 2–3 years.

The environment can be determined from the geography (proximity of seacoast, industry, cities) and climate (acidity and quantity of rainfall, relative humidity, pollution levels). However, the decision about painting normally requires inspecting the structure to determine its actual condition. In particular, the inspector must note the performance of the coating system used previously and the pattern of corrosion in order to select the most suitable coating for repainting.

Coating Systems For Field Application

Surface preparation, paint application, and coating materials are important factors in achieving satisfactory protection.

Surface Preparation

Bridge painting surface preparation involves either abrasive blast cleaning to bare metal (i.e., SSPC SP 10/NACE 2 or SSPC SP 6/NACE 3) and application of a full, new, multiple-coat paint system or water washing (SSPC SP 1) and power tool cleaning (SSPC SP 3) in areas showing visible deterioration, followed by application of a spot prime and full topcoat paint system.

These two approaches are both valid depending on the particular circumstances of the structure in question. Costs for full abrasive blast removal and paint system replacement are currently between \$4 and \$20/ft.^{2}, with most jobs falling in the \$6 to \$10/ft.^{2} range. With this approach, the bridge is expected to perform for 15 to 25 years, depending on the environment, with little to no maintenance. The alternative approach, commonly referred to as "overcoating," currently costs between \$1.25 and \$5.00/ft.^{2}, with an expected performance of 5 to 15 years.

Sometime a hybrid of these methods, termed "zone painting," is employed. Areas demonstrating a higher tendency to corrode and deteriorate are locally

abrasive blast cleaned while all other areas are overcoated. This has been a highly successful in providing overall cost savings, but can only be practically applied to structures with discrete, easily defined corrosive areas. It is particularly effective on simple beam and girder bridges located in mildly corrosive areas where deicing salt is regularly applied. The splash and drainage areas (e.g., under expansion joints) are blast cleaned and fully repainted while the remainder of the structure is overcoated.

Abrasive Blast Cleaning. Abrasive blast cleaning has been, and continues to be, the predominant method for surface preparation of bridges prior to repainting. Blast cleaning is accomplished with either recycleable steel grit or with expendable slag abrasive. Specification requirements differ among bridge agencies, with some requiring steel grit in an effort to minimize the volume of waste generated during surface preparation. Other agencies allow the contractor to choose the method of blast cleaning based on the particular economics of the bridge.



Figure 5. Regulations protecting the environment and workers have created the need for large amount of complex equipment and containment on bridge abrasive blast cleaning jobs.

Historically, existing bridges were specified to be cleaned to SSPC SP 6/NACE 3, commercial blast. In recent years, the trend has been toward specifying SSPC SP 10/NACE 2, near-white metal. There are several reasons for this. First, as the cost of work has increased, greater attention has been given to the resultant quality of maintenance painting. It is generally acknowledged that since SSPC SP 10/NACE 2 provides a higher degree of cleanliness than SP 6/NACE 3, a higher level of performance will be achieved. In addition, many of the structures being repainted today were originally constructed leaving intact millscale coated with lead-based alkyds. For the majority of structures, a blast cleaning job that sufficiently removes millscale tends to leave a final surface closer in appearance to SSPC SP 10/NACE 2. This phenomenon has led to several disputes between owners and contractors. Hence, the trend had been to specify SSPC SP 10/NACE 2 up front to avoid potential confusion.

Abrasive blast cleaning is still considered the most productive method available to provide a clean surface ready for high-performance coatings (e.g., zinc-rich primers). Typical production rates on bridge painting jobs range from 50 to 250 ft.^{2}/hr, depending on the particulars of the job, the abrasive, and the equipment. Production rates for recycleable steel grit are around 200 ft.^{2}/hr.[1]

Hand and Power Tool Cleaning. About half of the bridges painted on an annual basis are overcoated.[2] This method of maintenance painitng requires washing the steel with water and using power tools to clean loose paint and rust from the surface. The predominent specification calls for SSPC SP 3, power tool cleaning, in areas where deteriorated paint or rust are visible. A smaller number of specifications call for the use of SSPC SP 11, power tool cleaning to bare metal. This specification calls for manually removing all visible paint and rust and provides for a visually cleaner surface than SP 3.

Power tool cleaning is labor intensive, with slow production rates. It is only suitable for surface preparation without extensive deterioration. Once a structure shows rusting and coating breakdown that exceeds 10-15% of the surface area, power tool cleaning generally becomes economically unattractive; however, it can be a useful method for cleaning and repairing small areas in an otherwise intact existing coating. In addition, power tool cleaning generally requires much less stringent containment and produces less waste than abrasive blast cleaning.

Alternative Surface Preparation Methods. In recent years, the bridge painting industry has seen an influx of new technology, particularly in the area of surface preparation. Cleaning methods using high-pressure

water have gained a foothold in the market and are often attractive due to the improved productivity of newer equipment. Low dust and the added benefit of a reduction in surface chemical contaminents (e.g., chlorides) when compared to other [dry] surface preparation technologies are advantages. SSPC SP 12/NACE 5 provides guidance for the specification of pressurized water paint removal methods.

One limiting factor in the use of water for surface preparation of bridge steel is the fact that the vast majority of bridges were constructed with adherent millscale beneath the original paint systems. Since water alone, regardless of pressure, will not remove mill scale, this technology is excluded whenever a fully cleaned and profiled surface is specified for a bridge with intact mill scale. Newer bridges that did receive initial blasting in a shop or bridges that have been previously blast cleaned and painted may benefit from water-based surface preparation. Local environmental regulations regarding waste water disposal pose another factor to consider in choosing water-based surface preparation methods.

In certain situations, chemical strippers and electrical current are used to remove existing coatings. Neither are widely used, but may play a larger role in future years. Chemical strippers have already been used on some structures that are in sensitive areas where the potential release of lead dust from abrasive blast cleaning is a concern.

Coating Materials

In the past, bridge steel was painted in a low-cost manner to achieve steel throughput from the shop and a marginal level of corrosion protection and aesthetics. Until the 1960s, steel was shop and/or field painted with alkyd coatings that contained high amounts of lead. These coatings were applied directly over intact millscale with little to no significant surface preparation. In addition, alkyds with aluminum pigments were used by several states as standard topcoats. Typically, any maintenance painting was completed with coatings similar to the original to avoid compatibility problems.

During the 1960s and 1970s, bridge agencies began to specify shop blasting to remove all millscale and provide a clean, profiled surface for painting. This led to the extensive use of zinc-rich primer systems that have provided a consistent performance of 25 years or more for many original applications.

Today, the use of lead-based paints has been eliminated, and new laws governing paint solvent VOC content have essentially forced a change in the formulations for industrial maintenance paints. Presently, coating materials used to protect steel bridges fall into one of two categories: coating systems for new and blast-cleaned steel and coatings for maintenance painting without abrasive blast cleaning.

Coatings for Blasted Steel. The majority of state highway departments currently specify the use of some type of zinc-rich primer based coating system. For new steel, the predominant approach is to blast and prime in the shop and apply topcoats following erection of the structure. In this scenario, ethyl silicate inorganic zinc is the primer used most often. In field painting, when abrasive blasting is employed, there is a split between the use of inorganic and organic zinc-rich primers. A 1996 survey by the Transportation Research Board found that 42 of 54 bridge agencies specify zinc-rich primers for new construction. Fewer states specify zinc-rich primer systems for maintenance painting of existing structures; however, the majority of bridge owners choose some form of zinc-rich coating when abrasive blast cleaning the surface of an existing highway bridge.

Topcoats for zinc-rich systems vary widely. Initial applications in the 1970s used vinyl topcoats. With recent regulations limiting the amount of solvent in coatings, vinyls have become passe. The predominant topcoating system used now for zinc-rich primers is an epoxy midcoat with a polyurethane topcoat. In addition, three-coat urethane systems have become very popular with bridge owners and bridge painting contractors. These systems are predominantly two-coats of moisture-cured urethane with a more weatherable two-component aliphatic polyurethane as the topcoat. Other agencies specify systems in which water-borne acrylic is substituted for the obsolete vinyl topcoat previously used over inorganic zinc.

A small but growing number of bridges have been metallized. Metallizing requires at least an SSPC SP 10/NACE 2 abrasive blast cleaning and application of 8 to12 mils of thermal- sprayed metal (either zinc or zinc/aluminum alloy). This system has many years of demonstrated durability, and recent improvements in application equipment have made metallizing more attractive for both shop and field applications to bridge steel.

Coatings for "Overcoating" Applications. In maintenance painting applications where the existing coating system is not completely removed, there is a lot of diversity in the materials specified by various agencies. In this instance, the zinc-rich systems do not play a role, due to a lack of appropriate surface cleanliness. Instead, there is a mixture of barrier and inhibited coating systems marketed as surface-tolerant. Among the most popular are generic high-build epoxies, moisture-cured urethanes, calcium-sulfonate modified alkyds, and other reformulated low-VOC alkyds.

Several variables have been identified as critical to the success of overcoating applications. These include the adhesion of the existing coating that remains after surface preparation to the steel substrate; the compatibility of the remaining existing coating with the new overcoating; the amount and severity of the exposed rust that must be coated over; and the thickness of the remaining existing coating. All of these variables are discussed in detail in the SSPC TU-3: Overcoating and in guidelines published by FHWA.[3, 4]

High-Performance Coating Materials for Bridges. Due to the increased cost of repainting bridge structures, there is a significant interest among owner agencies to move toward higher performance (i.e., longer lasting) bridge coatings. This movement has been slow, in part because there is a high degree of satisfaction with the current generation of zinc-rich coating systems; however, there is a growing use of coating systems such as zinc and zinc-alloy metallizing. Thermal-spray metal coatings are not new, but the cost and low productivity of metallizing application equipment has inhibited the specification of this coating in the bridge market. With new equipment and standards, prices for metallizing have become more competitive.

Other types of coatings technologies, such as 100% solids (epoxy, polyurea, etc), fluoropolymers, and powder coatings have all been discussed and even demonstrated for the bridge market, but have yet to make a significant impact.

Application Techniques

Bridge coatings can be sprayed, brushed, or rolled onto the steel, depending upon the requirements of the particular job. The majority of coatings are applied using airless spray. However, in many cases where nearby traffic or facilities may be impacted by overspray, the agency may restrict the use of spray equipment, and brushing or rolling will be required. With the use of containment on all blast cleaning jobs, often the specification will call for the containment to remain in place for spraying the primer. The containment can then be moved and the final coats brushed or rolled.

There has been a renewed emphasis on stripe painting techniques for complex bridge surfaces. Most striping is specified as hand striping using only a brush. Stripe painting is considered good painting practice for slower drying coatings. These coatings tend to "thin" at edges and acute angles due to the surface tension of the wet-applied paint film. Often, this phenomenon has caused paints to fail prematurely on edges of flanges and fasteners. Stripe coating these areas will ensure proper paint film build and should alleviate this potential problem.

Table 1. Regulations Impacting the Bridge Painting Industry.

Impacting Regulation	Effect on Coating Operations
OSHA; CFR 29 1926.62, Lead in Construction	Establishes guidelines for protection and monitoring of workers removing lead paint from bridges. Requires lead training and monitoring for workers.
EPA; Resource Conservation and Recovery Act (RCRA)	Regulates the handling, storage, and disposal of lead (and other heavy metal) containing waste. Can increase the cost of disposal of waste from bridge paint removal by 10X.
EPA; Title X, Residential Lead-Based Paint Reduction Act of 1992	Mandates training and supervision requirements for workers associated with lead containing paint removal.
EPA; Comprehensive Environmental Response Compensation and Liability Act (CERCLA or Superfund)	Assigns ownership of and responsibility for hazardous waste to the generator "into perpetuity."
EPA; Clean Water Act	Regulates discharge of materials into waterways.
EPA; Clean Air Act Amendments	Mandates restrictions on allowable volatile organic compound (VOC) content of paints and coatings. Regulates discharge of dust into air from bridge painting operations.

Impact of Regulations

Federal and local regulations have effectively eliminated the use of traditional lead-based alkyd and high-solvent paints. Specific environmental and worker health and safety regulations have been established to limit generating, handling, and disposing of waste containing toxic heavy metals (e.g., lead and



Figure 6. Containment and environmental monitoring are essential components in today's bridge painting operations.

chromium). Likewise, air pollution regulations continue to reduce the allowable solvents in coatings. **Table 1** provides an outline of the critical regulations and their direct impact on the bridge painting industry.

Industry has responded to these regulatory drivers by providing a broader spectrum of coating materials that are compliant with new regulations. Many of these materials actually offer significant performance improvements over older formulations; however, there are also many new materials that provide disappointing performance, and many that have more highly constrained use parameters (e.g., mixing, application technique, etc.) than traditional paints. These factors have combined to make the selection and specification of coating materials for steel structures a more complex practice requiring a significant knowledge of the performance and application properties of a wide range of coating materials.

Additionally, compliance with environmental, health, and safety regulations has created significant change in the methods used for bridge maintenance painting. "Open" abrasive blast cleaning—the dominant method of surface preparation until the 1980s—is a thing of the past. Specifications and regulations requiring containment of surface preparation activities vary, and continue to evolve, but the time, labor, skill, oversight, and equipment needs for steel surface preparation have all increased dramatically over the past 15 years. In fact, a "typical" simple overpass repainting job that may have required less than $100,000 in capital equipment to accomplish can now require nearly $1 million in specialized gear at the job site. Figure 1 shows a typical layout of required equipment at a bridge abrasive blast cleaning job site. These new methods have produced a general increase in maintenance painting costs of 200 to 500% over the past decade. Although these cost increases caused a significant reduction in the number of bridges being painted during the 1990s, this trend is reversing. The costs are coming down somewhat, and the new protocols (and their associated costs) have placed a higher premium on work quality in maintenance painting operations.



Figure 7. Panels exposed at a marine test site for five years. The panel on the left uses a zinc-rich primer, while the panel on the right uses a non-zinc barrier coating system.

Performance of Modern Bridge Coatings

On the whole, industrial maintenance coating materials supplied to the bridge industry perform better today than in years past. Due to the influence of regulations limiting the VOC content of industrial maintenance coatings, coatings used today contain far less solvent than coatings used 20 or 30 years ago. In essence, all of the coatings applied today are "new" materials with track records less than 10 to 15 years. Testing to determine the relative performance of new "environmentally acceptable" formulations versus older, higher solvent and lead-based formulations has

produced mixed results. The new generation of bridge coatings shows better performance at the high end, but a wider overall distribution in performance. This wide performance distribution can be seen even among separate formulations within a specific generic coating. Because there is a wider variety of bridge coating formulations available today, and because there is a wide variation in performance among these paint formulae, the specification of coatings for bridges has become a more difficult and important task.

With new coating formulations, performance is also affected by the relative practicality of each coating. Many of the newer formulations contain very small amounts of solvent and high amounts of solids. When applied properly, these systems usually perform as advertised; however, application has been made more difficult with reduced solvents and defects can be more prevalent. In addition, higher solids coatings requiring specialized application equipment are now specified more frequently. The use of the newer coating formulations makes the judicious use of formal quality control and quality assurance even more essential than in the past.

Specific performance expectations of bridge owners vary widely; however, as a general rule, bridge owners expect 20 to 30 years of performance from a new coating system applied to a abrasive blast cleaned surface (i.e., SSPC SP 10/NACE 2). There is significant evidence that the three-coat inorganic zinc primer systems will meet this level of performanc in all but the most severe marine applications. Since several state DOTs began using zinc-rich primers in the 1970s, and many of these bridges are still performing quite well, there is highly confident evidence to support theses assumptions.

Expectations for overcoating are less well defined, but most owners are looking for at least 10 years of performance from maintenance overcoating applications. The ultimate performance of an overcoating application is highly dependent on the existing conditions of the paint and steel. Specifically, is there is a significant amount of existing, active rust on the bridge, or are the physical properties of the existing coating (e.g., adhesion, plasticity, thickness, etc.) good enough to accept and support the new overcoat for a ten year period? Because of the highly variable and often poor surface preparation involved in the past, overcoating can be considered a high-risk proposition that may lead to early failure within 1-2 years. In other instances, where the surface can be cleaned of rust and other contamination in a reasonable manner, and the existing coating has some remaining protective characteristics, overcoating can be a very economical approach to bridge maintenance painting.

The trend is for bridge owners to expect greater and greater performance from coating applications. This expectation is driven by the increased cost of performing bridge maintence coating work. Owners are currently attempting to achieve longer term performance by moving toward higher performance coatings such as thermal-spray metallizing with its expectations of at least 40 years of performance.

Because all of the existing coating systems available for bridges are essentially “new” products, the performance database for service of these coatings on actual structures is very limited. The experience and performance history associated with each generic type of coating (e.g., epoxies, polyurethanes, inorganic zinc primers, etc.) is still quite valuable and should be used to define the appropriateness of any particular coating selection in a generic or general sense; however, the choice of a specific coating product has become much more difficult due to the ever changing fomulations in the product lines of coating manufacturers.

These factors have led to a high degree of activity and reliance upon accelerated coating tests for materials selection. Manufacturers have leaned heavily on accelerated tests in the past to produce screening results for new foumulations. In recent years, bridge owners have also turned to these tests to develop independent data for bridge coating material selection.

The particular tests used vary and are the source of some debate. Traditional salt fog testing (ASTM B 117) has been used the most, and is still used extensively to characterize the relative performance of zinc-rich coatings.

In recent years, salt fog testing has yielded to the use of cyclic salt fog testing (i.e., wet/dry, hot/cold cycles). The most common testing specified is ASTM 5894. This test provides a less severe salt exposure, introduces the concept of wet/dry cycling and small amounts of ammonium salts (to model acid rain conditions), and exposes test samples to UV light to test for chalking and color loss. There are many other

tests preferred by various specifiers, most of which are customized to suit assumptions regarding the specific conditions encountered by that agency. Over the past ten years, bridge agencies have worked cooperatively to leverage resources and data associated with bridge coatings qualification testing.

The North East Protective Coatings Committee (NEPCOAT) has developed a standard test protocol and maintains a qualified products list that is shared by eight transporation departments in the Northeast. The American Association of State Highway and Transportation Officials (AASHTO) has recently taken this approach on the national level through their National Transportation Product Evaluation Program (NTPEP), which provides a nationwide shared database for bridge coatings test data.

Planned and Preventive Maintenance

The appropriate method for determining maintenance painting strategies is an examination of the life cycle cost of each available alternative. This concept is well understood by bridge owners and decisionmakers; however, it requires longer term planning, prioritization, and budgeting than is reflected in current practice.

Planning and prioritization require quality condition assessment data, and longer term budgeting requires a change in current funding mechanisms that apply to bridge maintenance painting. The programs throughout the country that are showing the greatest degree of overall success exhibit these characteristics. In addition, a few states have budgeted specifically for bridge maintenance painting over a multi-year plan.

When proper planning is applied to a maintenance painting program for a system of bridges, an agency can assess the corrosion protection needs of each structure and apply various levels of cleaning and painting to different bridges (or portions of bridges) based on the existing condition of the bridge, the anticipated costs of maintenance painting using various approaches, the traffic control demands, and the remaining expected life of the particular structure.

Maintenance painting of existing bridges can cost anywhere from $1.50 to $4/ft.^{2} for overcoating to $8 to $15/ft.^{2} for full removal and repainting. These costs are a significant investment into the life cycle cost of ownership of the structure and should be minimized through life cycle maintenance planning. Because of the large range of costs for the various maintenance painting approaches and because there are now highly durable coating systems available to bridge owners for nominal premium costs, the planning of life cycle corrosion protection for the bridge is critical to minimizing the cost of ownership for the structure.

Quality Challenges

Increasing costs coupled with the burgeoning number of bridges that require maintenance painting has brought focus to the issue of quality in bridge painting. New coating materials are being used that promise increased performance but at increased cost and often increased demands of application and surface preparation.

The driving factors in bridge painting demand an increased emphasis on quality; however, this is a significant challenge, given the typical results of low-bidder driven contractor procurement. For this reason, bridge owners have turned in several directions for relief. First, they have employed expert third-party inspection firms to serve as their oversight representatives. These firms supply expertise that, in general, does not exist within the transporation departments. Often, these firms also provide resources to cover the technical and compliance aspects of environmental, health, and safety issues.

The bridge painting contracting community has stepped forward with the Painting Contractor Certification Program (PCCP), a self-regulating qualification program administered by SSPC, that ensures a professional level of corporate quality and competence in surface preparation, paint application, and removing and handling hazardous coating materials. This program is gaining significant popularity among bridge agencies. Contracting mechanisms such as warranties that hold a specific party, most often the contractor, responsible for any defects and failures of coating systems are also being used more frequently in the bridge painting industry.

References

1. FHWA Surface Preparation Study. FHWA: Washington, D.C.
2. NCHRP Synthesis 251: Lead-Paint Removal.
3. SSPC TU 3. *Overcoating;* SSPC: Pittsburgh.
4. FHWA-RD-97-092. Guidelines for Repair and Maintenance of Bridge Coatings: Overcoating; FHWA: Washington, D.C.

Acknowledgements

The author and SSPC gratefully acknowledge Brian Castler's peer review of this document.

About the Author

Robert Kogler

Robert Kogler is currently team leader for corrosion and coatings research for the Federal Highway Administration. In this capacity he is responsible for development and oversight of FHWA's research and technology transfer efforts in the area of corrosion protection for structures. Mr. Kogler has been with FHWA for 6 years, during which time he has headed the corrosion protective technology program for steel bridges. Prior to coming to FHWA, Mr. Kogler spent seven years in the consulting engineering field focusing on corrosion engineering. He has extensive experience in corrosion protection applications in the marine industry. including significant coating and cathodic protection design work for the U.S. Navy. Mr. Kogler holds a degree in materials science and engineering from the University of California, Berkeley.

Chapter 6.2
Corrosion Protection of Water and Fuel Tanks

Joseph H. Brandon

Introduction

This chapter provides an overview of the industry guidance concerning corrosion protection of tanks for storage of water and fuel, and practical experience in applying this guidance. The scope includes coating and cathodic protection of steel and concrete tanks for storage of water, oil, and gasoline, although the guidance may also apply to tanks for storage of other commercial liquids. The primary focus is aboveground storage tanks (ASTs), field-constructed, welded steel tanks for fuel and water, and concrete tanks for water storage. The very specialized area of tank lining is covered in detail in a separate chapter. Ancillary subjects such as surface preparation, safety, and application techniques are also covered in separate chapters.



Figure 1. Unpainted steel tank.

This guidance is provided by the American Concrete Institute International (ACI), American Waterworks Association (AWWA), American Petroleum Institute (API), National Fire Protection Association (NFPA), National Sanitation Foundation (NSF), National Association of Corrosion Engineers International (NACE), and SSPC: The Society for Protective Coatings (SSPC), and work by individual authors considered experts in the field of tanks.[1-6]



Figure 2. Painted steel tank.

Overview

The standards referenced in this chapter are typical of consensus standards that are developed and maintained by technical organizations, and are intended to describe products, processes, or services that have proven satisfactory for the prescribed usage. The use of these standards is voluntary, and frequently requires additional inspection, evaluation, or engineering, as well as detailed specifications, to provide a complete and usable facility.

While the standards are voluntary, they provide the best-judgment of a consensus of the particular industry involved, and should be followed until modified by engineering evaluation or re-engineering.

Tables 1a and 1b. Applicable Guidance for Tanks.

Type/Area	Applicable Guidance/Standards						
		Interior			Exterior		
	Design and Construction	Coating	Cathodic protection	Disinfection	Coating	Cathodic protection	Maintenance
Steel Potable Water tanks	AWWA D100 [i]	AWWA D102 [ii] NSF 61 [iii]	AWWA D104 [iv] NACE RP0196 [v] NACE RP0388 [vi]	AWWA C652 [vii]	AWWA D102	NACE RPO193 [viii]	AWWA M42 [ix]
Concrete Potable Water tanks	AWWA D110 [x] AWWA D115 [xi] Other	NSF 61 AWWA D102 NACE RPO892 [xii]	NACE RP0187	AWWA C652	NACE RPO591 [xiii] AWWA D102 ACI 515.1R [xiv]	NACE RPO290 [xv] (not for prestressed structures) NACE RP0187	
Fire Protection Water tanks – welded steel	NFPA 22 [xvi]	AWWA D102	AWWA D104 NACE RP0196 NACE RP0388	ACI 515.1R AWWA D102	NACE RP0193	NFPA 25 [xvii]	
Fuel Tank AST	API 650 [xviii]	API 652 [xix] API 1631 [xx]	NACE RP0575 [xxi]			API 651 [xxii] NACE RP0193	API 653 [xxiii]

i AWWA D100. *Welded Steel Tanks for Water Storage*; AWWA: Denver, CO
ii AWWA D102. *Coating Steel Water Storage Tanks*; AWWA: Denver, CO
iii NSF 61. *Drinking Water System Components - Health Effects*; NSF: Ann Arbor, MI
iv AWWA D104. *Automatically Controlled, Impressed-Current Cathodic Protection For The Interior Of Steel Water Tanks*; AWWA: Denver, CO
v NACE RP0196. *Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks*; NACE: Houston, TX
vi NACE RP0388. *Impressed Current Cathodic Protection of Internal Submerged Surfaces of Carbon Steel Water Tanks*; NACE: Houston, TX
vii AWWA C652. *Disinfection of Water Storage Facilities*; AWWA: Denver, CO
viii NACE RP0193. *External Cathodic Protection of On-Grade Metallic Storage Tank Bottoms*; NACE International, Houston, TX
ix AWWA Manual M42. *Steel Water-Storage Tanks*; AWWA: Denver, CO
x AWWA D110. *Wire- and Strand-Wound, Circular, Prestressed Concrete Water Tanks*; AWWA: Denver, CO
xi AWWA D115. *Circular Prestressed Concrete Water Tanks With Circumferential Tendons*; AWWA: Denver, CO
xii NACE RPO892. *Coatings and Linings over Concrete for Chemical Immersion and Containment Service*, NACE International, Houston, TX
xiii NACE RPO591. *Coatings for Concrete Surfaces in Non-Immersion and Atmospheric Service*; NACE International, Houston, TX
xiv ACI 515.1R. *Guide to the Use of Waterproofing, Dampproofing, Protective, and Decorative Barrier Systems for Concrete*; ACI: Farmington Hills, MI
xv NACE RPO290. *Impressed Current Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures*; NACE International, Houston, TX
xvi NFPA 22. *Standard for Water Tanks for Private Fire Protection*; NFPA: Quincy, MA
xvii NFPA 25. *Inspection, Testing and Maintenance of Water-Based Fire Protection Systems*; NFPA: Quincy, MA
xviii API 650. *Welded Steel Tanks for Oil Storage*; API: Washington, DC
xix API 652. *Lining Of Aboveground Petroleum Storage Tank Bottoms*; API: Washington, DC
xx API 1631. *Interior Lining Of Underground Storage Tanks*; API: Washington, DC
xxi NACE RP0575. *Internal Cathodic Protection Systems in Oil Treating Vessels*, NACE International, Houston, TX
xxii API RP 651. *Cathodic Protection of Aboveground Storage Tanks*; API: Washington, DC
xxiii API 653. *Tank Inspection, Repair, Alteration, and Reconstruction*; API: Washington, DC

Design Considerations for Corrosion Protection	NACE RPO178 [xxiv]
Contractor Certification Program	SSPC QP 1 [xxv]
Coating Inspection Company Certification	SSPC QP 5 [xxvi]
Coating Inspection Manual	SSPC Coating and Lining Inspection Manual [xxvii]
Coating Inspection Guide – Steel Substrates	ASTM D3276 [xxviii]
Coating Inspection Guide – Concrete Substrates	ASTM D6237 [xxix]
Tank Lining Inspection Guide – Steel and Concrete Substrates	NACE RPO288 [xxx]
Coating Maintenance Program	SSPC PA Guide 5 [xxxi]

xxiv NACE RP0178. *Fabrication Details, Surface Finish Requirements, and Proper Design Considerations for Tanks and Vessels to Be Lined for Immersion Service*; NACE: Houston, TX
xxv SSPC QP 1. Standard Procedure for Evaluating Painting Contractors (Field Application to Complex Industrial Structures); SSPC: Pittsburgh, PA
xxvi SSPC-QP 5, *Standard Procedure for Evaluating Qualifications of Coating and Lining Inspection Companies*; SSPC: Pittsburgh, PA
xxvii *Coating and Lining Inspection Manual*, Drisko, Richard W., ed., SSPC: Pittsburgh, 1991, publication 91-12
xxviii ASTM D3276. *Standard Guide for Painting Inspectors (Metal Substrates)*; ASTM: West Conshohocken, PA
xxix ASTM D6237. *Standard Guide for Painting Inspectors (Concrete and Masonry Substrates)*; ASTM: West Conshohocken, PA
xxx NACE RPO288. *Inspection of Linings on Steel and Concrete*; NACE: Houston, TX
xxxi SSPC PA Guide 5. *Guide to Maintenance Painting Programs*; SSPC: Pittsburgh, PA

Applicable Guidance

Tables 1a and b provide a listing of technical standards that are applicable to the specific utilization or type of construction.

Tank Interior Surfaces

Water Tank Interiors—Potable and Fire Protection

Paint systems for water tank interiors must conform to regulations issued by various agencies, depending on the type of contents to be stored. The NSF, the Environmental Protection Agency (EPA), the Food and Drug Administration (FDA), the NFPA, and other regulatory bodies at all levels of government are a few of these agencies. The potable water system requirements of AWWA, EPA, and the states are aimed at ensuring sanitation of the water supply system. NFPA water requirements are aimed at providing a sufficient quantity of suitable water for fire protection.

For potable water systems, states are generally responsible for administering the EPA water quality regulations, and each state has developed criteria for selecting coatings. The NSF evolved through the collective efforts of numerous agencies and organizations, including the EPA and AWWA, to develop appropriate protocols for testing potable water system components and additives, including interior coatings. The testing procedure for coatings, included in NSF 61, covers biological, toxicological, and volatile products that may leach out from the coating when in contact with potable water, but performance and longevity are not included. Interior coatings that pass the testing protocol are certified in accordance with NSF 61.

Most of the coatings that have NSF 61 certification are epoxies, but there are some polyurethanes, and a few other types. Having NSF 61 certification for a coating, however, does not indicate that it meets AWWA D102 or state criteria. The coating system specified should meet all applicable criteria, or be subjected to appropriate engineering evaluation.

According to December 2000 NSF survey, all 50 states responded that they intend to make use of NSF 61, 38 have regulations and eight have policies, and two more have actions planned to make use of NSF 61.

AWWA D102, which does not involve biological, toxicological, and volatile products testing, lists six paint systems for tank interiors:

- ICS-1 2 coat system – epoxy/epoxy
- ICS-2 3 coat system – epoxy/epoxy/epoxy
- ICS-3 3 coat system – zinc-rich epoxy/epoxy/epoxy (for non-immersed surfaces only)
- ICS-4 4 coat system – vinyl/vinyl/vinyl/vinyl
- ICS-5 Coal tar enamel (hot applied)
- ICS-6 2 or 3 coat – cold-applied coal-tar (3 coats where primer is shop-applied)

The two most common systems are the two-coat and three-coat epoxy systems. Other systems have been developed in recent years and their incorporation into the latest revision of AWWA D102 is pending review. Some of those coating systems being considered for incorporation into AWWA D102 are polyurethanes, zinc-rich primers for submerged surfaces followed by two coats of epoxy, and metallic-sprayed zinc. Very few vinyls are used in water tanks today, due to VOC restrictions on manufacturing.

It should be understood that NSF 61, and associated testing protocol, are concerned about health aspects only, and do not measure or evaluate performance in any way. It is, therefore, incumbent upon owners to keep abreast of current technology so as to be able to specify coatings that comply with all applicable requirements and suit their needs. It should be understood that there is potentially a significant difference in performance and cost among the approved systems. For instance, force-cure systems will generally outperform ambient cures products, and galvanizing will frequently outperform liquid-applied coatings.

On tanks to be used exclusively for fire protection, especially where the stored water is pumped through sprinkler heads, water cleanliness is of prime importance. Particulate matter entering the pipe can clog the sprinkler head system. Most municipal water storage facilities are combination potable water supply and fire protection water supply. Such facilities, when coated in accordance with AWWA D102, meet the cleanliness requirements for fire protection water. Where the requirement for additional fire protection water is required, such as in factories, plants, refineries, etc., the NFPA recommends that these tanks be designed and coated in accordance with NFPA 22, which, with a few exceptions, specifies coatings from AWWA D102. This provides for compat-

ibility with requirements of potable water systems, where necessary. NFPA allows all AWWA D102 coating systems, both interior and exterior, except ICS 5 Coal Tar Enamel.

Some tank owners are coating interior surfaces of concrete tanks. This is done for several reasons, such as better protection of the reinforcing steel from chlorine, and to provide an approved contact surface for potable water. Even though most state regulations that require the use of NSF 61 do not exempt concrete surfaces, administration of the regulations remains with the states, and some do not require concrete testing. Although NSF started certifying cement in 1995, concrete is generally batched with local aggregates and water. It follows then, that certification of concrete requires additional evaluation of materials proposed for a specific project, but this will involve additional costs. NSF recommends that, as a minimum, NSF certified cements be specified for construction of concrete structures or appurtenances for potable water contact.

If an interior potable water tank coating is desired, or required by state or local regulations to separate the concrete from the water, such coatings should comply with AWWA D102, be certified in accordance with NSF 61, and be compatible with concrete in immersion.

Fuel Tank Interiors

Coatings for AST linings are not specifically prescribed by API, except for the floor (water-contact area), and this area is recommended to be coated in accordance with API 652. API recommends that underground steel tanks (USTs) for fuel storage (primarily intended for the underground "service station" tanks) be lined in accordance with API 1631.

Fuel tanks are coated for one of or a combination of two reasons: 1) to protect the tank from corrosion; and 2) to protect the product from the tank. Fuel is organic and generally contains free sulfur, which can support numerous forms of bacteria, including sulfate-reducing bacteria (SRB). Delahunt reports that corrosion from SRB in these tanks is usually nominal.[7] Free sulfur can also react with ballast water or condensation to form sulfuric acid that will accelerate breakdown of coatings and corrosion.

Coatings are also used to prevent contamination of fuel from both corrosion products and the steel itself, although bare steel does not contaminate fuel for most purposes. Aviation fuel is frequently pre-heated on military aircraft, and even low concentrations of metallic contamination can catalyze one or more reactions that render the fuel like jelly, commonly called "apple jelly." Aluminum and stainless steel are not contaminants. Only minimal separation between the steel surface and the fuel is required, and most fuel resistant, thin-film coatings will provide this; however, the coating needs to be designed so that it can withstand the chemical and corrosion stresses that it will encounter.

API 1631 recommends complete coating of all surfaces in USTs, while API 652 recommends only bottom coating for ASTs. The Naval Facilities Engineering Command (NAVFAC) has found that significant corrosion can occur in the ceiling (interior surfaces above the fuel level) as a result of frequent condensation, and recommends in Military Handbook 1022 that the ceiling be treated the same as the floor area.[8] The findings of Delahunt and Wallace support this.[7, 9]

Although API does not prescribe interior lining materials for ASTs, the coating requirements of API 1631 include a rigorous testing and evaluation process that can be used to select coatings for fuel storage tanks. While this document prescribes the resin system for coatings in certain USTs, it also provides a series of tests that should be performed to prove the ability of a proposed coating to withstand immersion in fuel and water and to remain bonded to the steel substrate.

Zinc is a fuel contaminant, which makes all zinc-rich paints, galvanizing, and thermal-spray zinc unsatisfactory for corrosion protection in aviation fuel tanks. SSPC PS 12.00 indicates that some zinc-rich primers may be usable in solvent, salt water, and fresh water, all of which are found in fuel tanks; however, zinc-rich primers are not normally recommended for this service.[10] Wallace reports that the free sulfur generally found in fuel can react with the zinc to form zinc-sulfide, which may adversely affect both the paint and the stored product.[9]

Some agencies, especially outside the U.S., use conductive coatings to assist in dissipation of static electricity that is generated during fuel movement. Much research has been done in this area, and the U.S. military services have concluded that conductive coatings do not materially affect the static dissipation rate, therefore, such coatings are not used in bulk

storage facilities. In operational and ready-issue tanks systems, especially where high-flow rates are experienced and in-line filters are used, relaxation tanks are employed to allow time for static to dissipate, generally seconds to minutes. The addition of graphite to a coating is a common method of making a coating conductive.

Interior Cathodic Protection

Where cathodic protection (CP) is acceptable and usable, it can be complementary to the coating system, in that the CP reduces corrosion pressures, especially at holidays, and the coating reduces the power requirement from what would be required to protect an uncoated structure. Working in tandem, this combination can provide long-term, cost-effective corrosion protection of immersed surfaces. A detailed discussion of cathodic protection, including the mechanism, the beneficial relationship with protective coatings, the various types available, and use and operation of each is contained in a separate chapter of this book.

Pure hydrocarobon fluids are usually not electrically conductive, and therefore not corrosive, but corrosion can occur where the fluids are contaminated with water, sediments, or other electrically conductive contaminants. Since CP is only effective on surfaces submerged in an electrolyte (electrically conductive medium), this generally limits its use in fuel tank interiors to the area where water collects in the floor. Even then, CP in fuel tank interiors is difficult to apply unless sufficient water is allowed to collect to completely immerse the anodes, which must be mounted some distance from the surface being protected to ensure good CP current distribution. As with zinc-rich coatings, potential effects of contaminating the fuel with zinc, magnesium, or other corrosion products from the anodes must be considered. For reasons mentioned above, CP for the interior surfaces of fuel storage tanks has not had widespread use, but it can be effective under certain conditions.

Cathodic protection is often used to protect both potable and fire protection water tanks. AWWA has addressed both the “submerged area” limitation of CP and the potential problems with zinc-rich primers in immersion, by providing ICS 3, a three-coat epoxy system with a zinc-rich primer for non-immersed surfaces in a tank. When combined with a two- or three-coat epoxy system and CP to protect immersed surfaces, long-term, cost-effective protection of internal tank surfaces can be achieved. Impressed current CP systems are normally provided for larger tanks, or poorly coated and uncoated tanks. Galvanic systems are usually more appropriate for smaller, well-coated tanks. In the case of pre-manufactured, shop-coated, bolted or riveted tanks, electrical continuity between steel plates must exist for CP to be effective.



Figure 3. Scaffolding on a tank.

Tank Exterior Surfaces–Water and Fuel Tanks

Coatings

While tank interiors are designed with respect to service conditions and special requirements of the material being contained, tank exteriors are designed for the service conditions of exterior exposure, irrespective of the tank contents. Weathering, most notably due to ultraviolet radiation (UV) from sunlight, as well as moisture and daily and seasonal temperature variations, must be considered if a successful coating system is to be designed.

Seldom is it economically prudent to leave a carbon steel structure uncoated. The coating system should be designed to address both the desired service life and the anticipated service conditions of the structure. Since the service life of a steel structure can easily surpass 100 years, such structures are generally considered permanent, and only under

special conditions is a structure designed to have a temporary or fixed service life.



Figure 4. Fuel tank in containment for maintenance painting.

A wide variety of coatings has been used on fuel and water tanks, however, the exterior of a tank is coated to resist the environmental conditions rather than the conditions of the stored material. In this way, fuel and water tanks are similar, and most exterior coating systems will work equally well on either.

In addition to the topcoat providing functional protection for the underlying corrosion protection coats, the color of the paint topcoat is functional. Heat adversely affects the contents of both fuel and water tanks, therefore, the ideal topcoat is one that is highly reflective, such as white, aluminum, or similar. Heat contributes to increased volitization and to early degradation of fuel, especially where degradation is from biological growth, and it adversely affects chlorine retention and promotes biological growth in both potable and fire protection water tanks. The primer and intermediate coats should be designed according to the service conditions, and to be compatible with the desired topcoat.

API does not provide guidance on exterior coatings for fuel storage tanks. AWWA D102-97 recommends six paint systems for exterior surfaces:

- OCS-1 3 coat system – alkyd/alkyd/alkyd
- OCS-2 4 coat system – alkyd/alkyd/alkyd/alkyd
- OCS-3 3 coat system – alkyd/alkyd/silicone alkyd
- OCS-4 3 coat system – vinyl/vinyl/vinyl
- OCS-5 3 coat system – epoxy/epoxy/polyurethane
- OCS-6 3 coat system – zinc-rich epoxy/epoxy/polyurethane

The systems range from the simple three-coat alkyd to the sophisticated zinc-urethane, including fluorourethane, and a significant number of combinations. In addition to the systems shown in AWWA D102, there is a wide variety of proprietary paint systems, all of which have some merit and all of which have their limitations. Coating systems containing polyurethanes, including zinc-rich urethane primers and fluoropolyurethane topcoats, are being used. Acrylic coatings have been developed that have nearly similar color and gloss retention as polyurethanes, but have much better dry-fall characteristics and are more environmentally acceptable due to lower VOCs.

Fuel tanks and fire protection water storage tanks are generally located in industrial areas, whereas water storage tanks, including elevated tanks, are frequently found adjacent to highways, and residential and commercial areas. This requires particular consideration in choosing surface preparation methods, coating materials, and application methods.

AWWA D110 and D115 reference ACI 515.1R for dampproofing on buried portions of concrete tanks. Coating the exterior surfaces of concrete tanks is done primarily for aesthetics and weather resistance. Uncoated concrete tends to have a mottled appearance and coating the exterior of a concrete tank will provide a more aesthetically pleasing tank. Exterior coatings also protect the concrete and reinforcing steel from the elements by keeping moisture and salts from penetrating the concrete, as well as potentially slowing the effects of carbonation. Many exterior concrete coatings allow the concrete to “breathe,” that is to allow moisture vapor to dissipate. Acrylic coatings are the most commonly used coatings for the exterior surfaces of concrete tanks.

Exterior Cathodic Protection

Cathodic protection (CP) is routinely installed to protect the exterior bottoms of on-grade fuel storage tanks. Evolving federal or state environmental laws may require the installation of CP to protect the exterior tank bottom of fuel or hazardous materials storage tanks. Several types of systems are available depending on the design and configuration of the storage tank bottom itself.

Environmental laws require CP and coatings for corrosion protection of the external surfaces of underground fuel or hazardous materials storage tank

(UST) systems. Note that a UST, as defined in environmental laws, includes associated piping systems. In one extreme case, a small on-grade fuel storage tank was deemed to be a UST because of the volume of the buried piping system connected to the tank.

Design Considerations

Efficient design does not always ensure suitability for coating. For instance, sharp edges are common to steel fabrication, as are lap joints, both skip-welded and non-welded, and other components formed in such a way that areas are protected from surface preparation and coating application. Such areas have the potential for collecting water or moisture, and corroding components at a rate that is different from properly coated components. Uncoated components also allow for unsightly corrosion stains to form on coated areas below. Some of this corrosion is inconsequential, but some is highly detrimental and will shorten the useful life of the structure or require extensive repair or rebuilding. NACE RP0178 provides guidance in designing and fabricating steel structures for immersion service and for non-immersion service when appropriately adapted. Examples of areas that cannot be fully protected with field-applied coatings are:

- Roof plate lap joints (typical in cone roofs)
- Roof plate to rafter lap joints (cone and other roofs that have internal support)
- Edges of I-beams and channels
- Back-to-back tack or skip-welded components
- Column plate to floor (typical in fuel tanks—column cannot be welded to floor)

When specifying a coating system, the specifier should realize that the cost of the paint materials is a small percentage of the overall cost of painting or repainting. Labor, especially for surface preparation, accounts for a large portion of the costs of a tank repainting project. If existing lead-based paints are to be removed, this will increase the total cost of exterior repainting, and the percentage of paint material costs is reduced further. Coating systems that maximize the time between maintenance, and between complete removal and repainting, are becoming more desired, especially as both government and private owners are looking more to one-time contracts than in-house forces for coating work. Where in-house forces are available, coatings that require more frequent but less extensive maintenance are desired.

Selecting a coating system based on first-cost is not necessarily cost-effective, especially when considering such costs as downtime, mobilization, demobilization, etc. The costs of obtaining access to the interior of a water or fuel tank, or for access to an elevated tank, seem to dictate choosing the package that provides the most longevity at the least risk. An elevated water tank in a densely populated residential area may seem to justify a high-performance coating system for longevity. To justify the costs of this system, and especially one that includes a fluoropolyurethane topcoat for extended longevity, generally requires a good specification, a qualified contractor, and qualified inspection.

When designing a high-performance coating system, consideration should be given to follow-on inspection and development of a maintenance program. A separate section of this chapter discusses the development of a maintenance program; however, a part of the design decision should involve maintenance. For instance, it may not make financial sense to prepare the surfaces to SSPC SP 6/NACE 3 or SSPC SP 10/NACE 2 for a high-performance coating system if the system will be allowed to weather without maintenance. A lesser system might provide more cost-effective coatings.

A common technique for specifying coating material is to list one or more acceptable products, and include the “or equal” clause. This clause may save the specifier effort in identifying the acceptable range of competitive products; however, it does little to protect the owner or the integrity of the coating system design. The fact remains that the coating industry has not developed standards for evaluating materials from laboratory tests to correlate with coating longevity, therefore, the likelihood of being able to equate products based on laboratory testing is very low, and engineers that approve products on this basis are taking on significant liability.

Where CP systems are being used in combination with protective coatings, it is imperative for the coating designer to communicate with the CP designer. Miscommunication can result in inadequately designed CP systems.

Specifications

It is quite common to find owners taking shortcuts in developing specifications for a project. A

tired cliché, “You get what you pay for” needs some adaptation to be descriptive of the specification writing process: “You get what you specify, at best.” Assume for a moment that a project goes unusually smooth and you get exactly what you specified. If your specification was incomplete, your project will probably be incomplete. The first rule of contracting is “don’t expect more quality or completeness than you specified.” A separate chapter provides additional details and guidance in specification writing.

CP systems should be designed by qualified personnel such as a Registered Corrosion Engineer or NACE Certified Corrosion or Cathodic Protection Specialist. The designer should also be experienced in the design of storage tank CP systems. Environmental laws mandate the use of such qualified personnel. Coatings should be designed by qualified personnel, such as SSPC or NACE protective coatings specialists.

Contractors

Selecting a competent contractor is a most important aspect of obtaining a quality coating, either in initial application or maintenance. The use of a program such as SSPC QP 1 as a prerequisite for bidding will greatly reduce the owner’s efforts required to qualify the apparent low bidder, or otherwise chosen contractor.[11] The objective of this procedure is to determine if a painting contractor has the personnel, organization, qualifications, procedures, knowledge, and capability to perform surface preparation and coating application of the required quality under the conditions and restrictions specified by the owner for complex structures. Using such a program adds leverage to the owner in that a certified contractor will generally try to protect its certification status by performing according to the specification, or to minimum industry practice.

Inspection

Inspection, as referred to in this section, is inspection of any operations of surface preparation, coating application, and repair. Today’s high-performance coatings require that continuous, competent inspection be provided for the entire project. The idea that constant inspection is not required is a holdover from the days when coating systems consisted of red-lead primers and alkyd topcoats, in which case, the condition of the steel surface was often only solvent cleaned to remove dirt and oils, and the costs and risks of failure were much less significant than they are today. The large number of variables and problem-prone areas dictates continuous, competent inspection if the risks of premature failure are to be reduced to a manageable level. Two prominent programs for providing competent inspection are SSPC QP 5 and the NACE Coating Inspector Certification Program.[12]

There are numerous guides for inspecting coatings, and a chapter of this book discusses coating inspection in detail and provides guidance in developing an inspection program. A few notable guides are SSPC’s *Inspection of Coatings and Linings,* ASTM D 3276 for steel substrates, D 6237 for concrete substrates, and NACE RPO288 for steel and concrete substrates.[13, 14, 15, 16]

Maintenance

Once a tank is constructed, the job of maintaining it begins. Water and fuel tanks get painted many times during their service lives, and maintenance painting often represents a greater expenditure than the original construction and painting. It is then in the owner’s best interest to monitor the condition of these structures, and to be prepared to react to the needs of both the structure and the components protecting the structure from corrosion.

API recommends that aboveground welded steel fuel storage tanks be inspected and maintained in accordance with API 653. Exterior operator inspections (non-qualified to API 653) are recommended at least monthly, and inspections by API 653 qualified inspectors are recommended for no less than every five years. Interior inspections are recommended on a basis of either tank history, or corrosion estimation, but in no case less than every 10 years. These inspections, when executed in accordance with API guidance, give highly variable results on coating condition, as the inspectors are not required to be trained in coating inspection. It is desirable to obtain a competent coating inspection at least as often as an API 653 inspection is accomplished. In the absence of other guidance in performing this inspection, the general principles of SSPC PA Guide 5 may be used.

AWWA M42 recommends that all tanks be inspected on every three years for both structural and coating maintenance needs.[17] This is a change from the older AWWA D101 standard that previously 115.

recommended a five-year cycle based on the need for increased scrutiny on sanitation. This document also outlines the areas that should be inspected.

NFPA outlines a complete tank inspection schedule, including monthly and annual inspection requirements for specific appurtenances, no more than three years for a tank not protected by cathodic protection and no more than five years for a tank protected by cathodic protection. It is a good practice to inspect fire protection water tanks once a year, if for no other reason than to remove stagnant water. If the tank cannot be inspected frequently, or the stored water cannot be "turned-over" regularly, then additional measures may be required to control algae growth. If the use of a paint fungicide is required, this must be preceded by actions to prevent water from such tanks from entering the drinking water system.

SSPC PA Guide 5 outlines procedures for evaluating the coating needs of a structure or structures, and the process outlined in this document can be applied to other components, such as cathodic protection, structural integrity, etc.[18] When used in conjunction with AWWA M42, a comprehensive inspection program can be designed to address all of the needs of a tank in a fashion that allows for identifying most problems in time to plan and design corrective action.

A separate chapter on maintenance details the processes involved and provides guidance in developing a maintenance program. It is good, sound practice to inspect any industrial coating application within the first year after painting has been completed. A large percentage of premature coating failures occur within the first year, and the standard contractor's warranty extends for 12 months after beneficial occupancy. AWWA D102 recommends that any cathodic protection system not be energized during the first year, and that the tank be emptied and readied for inspection within the first year. If replacement of a defective coating is required, it is generally easier to get the work accomplished as part of the 12-month warranty; however, this rework should not be considered in lieu of rework required as a result of latent defects. In most states, facility owners are protected for an indefinite period against latent defects, although such defects become more difficult to prove as time progresses.

Summary

Tank painting can be relatively simple, environmentally acceptable, and still comply with government regulations and appropriate industry standards. Recommendations for coating systems for both interior and exterior surfaces, as well as CP for buried or immersed surfaces, are provided by numerous industry organizations in appropriate standards.

Although steel is relatively inexpensive as a building material, the costs of design, fabrication, labor, erection, and repair add up to a sizeable investment, yet often little attention is given to the components that must be in place to protect the structure.

References

1. American Concrete Institute International (ACI). P.O. Box 9094, Farmington Hills, MI 48333, www.aci-int.org.
2. American Waterworks Association (AWWA). 6666 West Quincy Ave., Denver, CO 80235, www.awwa.org.
3. American Petroleum Institute (API) American Petroleum Institute. 1220 L Street, NW, Washington, D.C. 20005-4070, www.api.org.
4. National Fire Protection Association (NFPA). 1 Batterymarch Park, P.O. Box 9101, Quincy, MA 02269-9101, www.nfpa.org
5. National Sanitation Foundation (NSF). 789 Dixboro Road, P.O. Box 130140, Ann Arbor, MI 48113-0140, www.nsf.org.
6. National Association of Corrosion Engineers International (NACE). P.O. Box 201009, Houston, TX. 77216-1009, www.nace.org.
7. Delahunt, John F. Coating and Lining Applications to Control Storage Tank Corrosion. *Journal of Protective Coatings and Linings,* February 1987.
8. Military Handbook 1022. *Petroleum Fuel Facilities;* Naval Facilities Engineering Command.
9. Wallace, W.J. Painting Steel Tanks. In *Good Painting Practice – Steel Structures Painting Manual: Volume 1;* SSPC: Pittsburgh, 1994, pp 315-319.
10. SSPC PS Guide 12.00. *Guide to Zinc-Rich Coating Systems;* SSPC: Pittsburgh.
11. SSPC QP 1. *Standard Procedure for Evaluating Painting Contractors (Field Application to Complex Industrial Structures);* SSPC: Pittsburgh.
12. SSPC-QP 5. *Standard Procedure for Evaluating Qualifications of Coating and Lining Inspection Companies;* SSPC: Pittsburgh.
13. *The Inspection of Coatings and Linings;* Bernard

R. Appleman, ed.; SSPC: Pittsburgh, 1997.
14. ASTM D3276. *Standard Guide for Painting Inspectors (Metal Substrates);* ASTM: West Conshohocken, PA.
15. ASTM D6237. *Standard Guide for Painting Inspectors (Concrete and Masonry Substrates);* ASTM: West Conshohocken, PA.
16. NACE RPO288. *Inspection of Linings on Steel and Concrete;* NACE: Houston.
17. AWWA M42. *Standard for Inspecting and Repairing Steel Water Tanks, Standpipes, Reservoirs, and Elevated Tanks For Water Storage;* AWWA: Denver, CO.
18. SSPC PA Guide 5. *Guide to Maintenance Painting Programs;* SSPC: Pittsburgh.

Acknowledgements

The author and SSPC gratefully acknowledge Jack Delahunt, Walt Harris, and Tom Tehada for their peer reviews of this document.

About the Author

Joseph H. Brandon
Joseph H. Brandon, a protective coating specialist with the Naval Facilities Engineering Service Center (NFESC), specializes in industrial coatings for both steel and concrete. A member of the International Concrete Repair Institute (ICRI) and several SSPC and NACE committees, he holds protective coatings specialist certifications from both SSPC and NACE and is a NACE certified coating inspector. He has a BS degree in structural engineering.

Chapter 6.3
Linings for Vessels and Tanks

Wallace P. Cathcart and Albert L. Hendricks (original chapter)
Joseph H. Brandon (2002 revision)

Introduction

This chapter describes accepted practices for selecting and applying protective coatings to the interior surfaces of steel tanks. These coatings used as linings protect tank interiors from corrosive and/or erosive products and often prevent contamination of the product by the steel substrate. The tank may be used for processing, transporting, or storing chemicals or food products.

The requirements necessary to obtain economical service life with a lining include safety, design/fabrication, and proper coating materials, surface preparation, application techniques, curing, inspection, and maintenance. In this chapter, a protective coating used as a lining is defined as materials applied in one or more coats by conventional air spray or airless spray methods to a total dry film thickness no greater than 50 mils. Flame spraying, sheet-applied linings, metallizing, and hand lay-ups are not covered.



Figure 1. Worker wearing protective gear while spraying the inside of small food processing tank. Courtesy Tank Lining Corp.

The success of a coating system depends upon satisfactory completion of all aspects of planning, design, and execution. These factors make it essential to seek advice from competent suppliers of coating materials, knowledgeable and experienced applicators, and consultants.

Safety

Assuring the safety of workers in tank lining is of utmost importance. Working in confined areas with dust and toxic and/or flammable materials can create hazardous conditions. Regulatory bodies, such as OSHA, have guidelines that must be followed. In addition, training programs should be established to educate all individuals who apply coatings to steel tanks. The safety chapter of this book provides detailed requirements about safety issues.

Design and Fabrication to Receive Lining

Whether a tank is being lined to prevent contamination of a product or to provide protection from corrosion, the coating must act as a continuous barrier between the product and the steel tank. More commonly though, coatings are used as linings to prevent iron or oxide contamination of the product.

The essentials of good tank design, from a corrosion protection perspective, are provided in NACE RPO178.[1] This document focuses on reducing sharp edges, skip welds, rough welds and weld splatter, and other areas that are difficult or impossible to coat properly.

When applying a coating by spray, excessive coating tends to accumulate in areas where crevices, pits, and acute angles exist. If such areas cannot be avoided in the design, they should be eliminated by fillet welding. The contour should be smooth enough for the lining material to be applied uniformly **(Figure 2).**

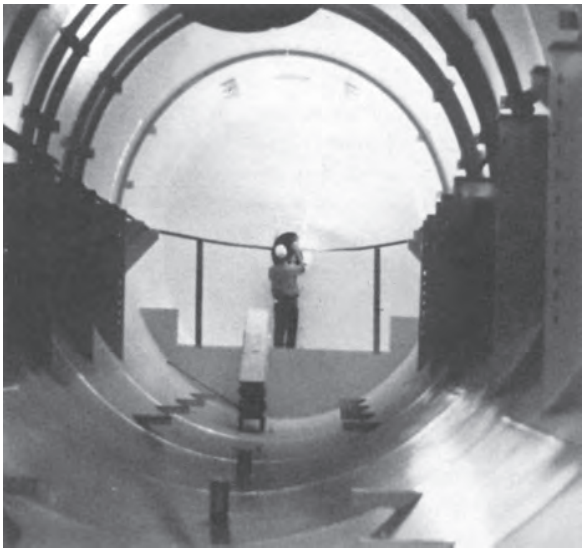


Figure 2. Lining baked phenolic over carbon and stainless steel for high pressure and temperature chemical separator. Courtesy Tank Lining Corp.

Selecting Material

The three most criticial factors in coating selection for tank lining are: resistance to the reagent or the product to be stored; resistance to undercutting or underfilm attack at points of minor breaks, discontinuities, or permeations; and proper physical properties, such as flexibility, adhesion, and elongation. A thick brittle lining might work well in a fixed, rigid storage tank yet fail prematurely if used in a railroad tank car or a thin-walled storage silo. Other factors to consider include resistance to water and oxygen passage, abrasion, and aging. The coating selected should also feature application and curing characteristics feasible for the specific vessel to be lined.

As an example, baking phenolic coatings that are final cured at 400°F (204°C) cannot easily be applied in extremely large tanks due to the difficulty in obtaining a uniform temperature. Final cure temperature is limited to the temperature resistance of the insulation on the vessels that have been permanently insulated. Double-skinned barges, as now designed, cannot be baked above approximately 300°F (149°C) because the inner tank expands and distorts or even splits the outer shell.

When selecting the proper coating system, it is necessary to understand all of the conditions to which the lining will be subjected, such as product type, exposure time, temperature variations, temperature source, vapor area, pressure, cleaning procedures, agitation, wet and dry conditions, versatility, degree of abrasion or erosion, thermal shock, trace chemicals present and possible physical impact on the lining or the reverse side. **Figure 3** shows a typical failure that occurred, in part, because all of these conditions were not taken into account.

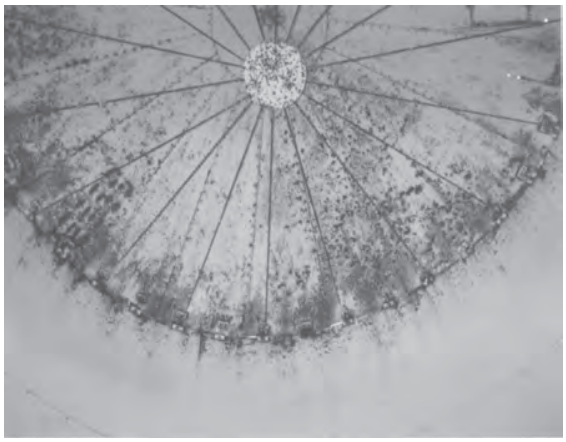


Figure 3. Failure of water tank lining from poor design, fabrication, materials selection, and application. SSPC file photo.

Gathering information is simplified if a field history exists. Some materials suppliers and some application companies keep extensive records of the successes and failures of each coating system used. This information is often available, but it must be used judiciously. If actual experience is not available, it is necessary to conduct field or laboratory tests. Field testing in the actual environment is most effective because it takes into consideration all of the variables that exist; however, the tendency is to utilize accelerated laboratory testing for cost and convenience even though it may not correlate with actual field results.

If substrate testing in the field is not feasible, it is then advisable to suspend or attach a steel coupon within the tank. Dissimilar metals should be insulated from the sample to prevent a galvanic differential between the sample and the vessel itself.

Laboratory tests are normally conducted on steel coupons prepared by individuals well-versed in the application of coatings to test samples. Coated coupons are exposed to the product intended for storage or transportation by submerging in a container or using an Atlas Test Cell.[2] The samples are normally observed at various intervals from 24 hours to one year, or until failure occurs.

The Atlas Test Cell consists of an open pipe to which test panels are bolted on each end to form a double-end flange. The center piping has openings where heating elements, condensers, thermometers, and/or agitators can be inserted. The body of the cell is constructed of glass, resistant alloy, or coated steel. This test can simulate many of the conditions experienced in actual service, such as agitation, temperature differential across the surface, and temperature sources from inside or out. In evaluating a protective coating for immersion, the test should be conducted for a minimum of six months and ideally for one year or more.

Any changes in the appearance of the coating should be recorded. Failure is normally indicated if blistering, severe softening, swelling, or severe discoloration has been noted. With regard to softening and discoloration, the difference between "severe" and "less severe" or "inconsequential" requires considerable experience. Likewise, failure of the panel is indicated if the liquid is affected by the exposure in any significant manner.

Several different generic coating systems are used as protective barriers for vessels in immersion service. The resistance of each type varies with the individual formulation. Resistance tables can be obtained from coating manufacturers or organizations such as SSPC and NACE. These tables should be used with discretion since slight variations in formulations could decrease the resistance of a specific generic type. Interpretation is also important. Good alkali resistance does not mean the system is resistant to 73% caustic soda but possibly resistant to pH slightly in excess of 7. Similarly, good solvent resistance does not normally mean the coating system can resist immersion in methylene chloride. This section contains brief descriptions of the major generic coatings used as linings.

Phenolic

A high-bake unplasticized pure phenolic based on a phenol formaldehyde resin is often referred to as a straight phenolic. Polymerization is accomplished by heat curing at metal temperatures ranging between 350°F to 450°F (177° to 242°C). Phenolics are spray-applied in a number of coats to a total dry film thickness ranging between 4–8 mils. The pigmentation used in formulations affects the end color, adhesion, permeability, and spray characteristics. The chemical and physical properties of bake phenolic systems are excellent. They are unaffected by most solvents and resistant to concentrated sulphuric acid but due to the limitation on total dry film thickness cannot be used in dilute acids where the corrosion rate on the underlying steel would be excessive. They exhibit poor resistance to alkalies, alkali salts, and strong oxidants. This system normally meets all the requirements of the FDA and USDA for protecting substrates exposed to products intended for human consumption Because of the limitation on film thickness, this system normally is not specified as a pinhole-free lining.

Phenolic/Epoxy Baking Type

These formulations are based on a phenol formaldehyde resin crosslinked with a Bisphenol A Epichlorohydrin. Polymerization is accomplished by heat curing at metal temperatures of 350° to 450°F (177° to 242°C). Phenolic/epoxy baking formulations are normally applied by spray in a number of coats to a total dry film thickness ranging between 4 and 8 mils. Pigmentation varies to enhance adhesion, permeability, spray characteristics, and color. Chemical and physical properties are excellent, although when compared to the unmodified or straight phenolic coatings, the resistance to solvents and concentrated acids is lower. Some modifications can result in an increase in resistance to alkalies and strong oxidants. Due to the limitation on film thickness, this system should not be used in highly corrosive areas and is not pinhole free.

Similar, but generally less resistant formulations are available that, while still thermosetting, can be polymerized at lower temperatures. Optimum cure is obtained at approximately 200°F (93°C) metal temperature. Much of the disparity in resistance can be overcome by this material's ability to be applied at much heavier films (8–12 mils).

Epoxy

Epoxy formulations are based on Bisphenol A Epichlorohydrin resins utilizing either amines, amine adducts, or polyamide curing agents for polymerization. Heat, while not always necessary to cure, does optimize resistance. This type of system can also be modified with phenol formaldehyde resins, coal tar, or other resinous materials. It is possible to formulate systems with no volatile solvent, various solvent

combinations, or with water. Pigment is added to the formulation to obtain color, workability, adhesion, or abrasion resistance. Resistance varies substantially with formulation, but, generally, resistance to various chemicals with a pH range from 4 to 12 is excellent. Solvent resistance will be fair. Exposures in severely corrosive environments is limited by normal film thicknesses ranges of 8 to 30 mils when applied by spray. Heavier films can be formulated with flaking or fibrous fillers and applied by spray, trowel, or hand lay-up.

Polyester-Vinyl Ester

Formulations based on either a polyester or vinyl ester resin contain styrene or a similar monomer at a varying percentage up to 55%. The styrene monomer enters into the cross-linking but also evaporates; therefore, it is difficult to determine coverage by normal volume/solids methods. Polymerization is accomplished with peroxide catalysts and promoters. Pot life can vary from 15 minutes to 8 hours, depending on the reactivity of the formulation. The pigmentation varies with the intended use and the manufacturer's recommendations. Formulations containing chopped glass, glass flake, or inert oxide flake pigment are used for lining vessels. Film thickness varies with the formulation, but for immersion application ranges from 30 to 60 mil as applied by spray. Heavier films from 40 to 120 mils may be applied by trowel or hand lay-up. Resistance to various acid and alkali environments is excellent. Solvent resistance is generally fair. A pinhole free film can be obtained.

Neoprene

Neoprene includes synthetic elastomers that may be dissolved in solvents or latex dispersed in water. Common curing agents are zinc or magnesium oxide. Solvent materials are spray-applied in thicknesses of 20 or more mils and have excellent resistance to both alkalies and acids. Latex is sprayed in thicknesses of 10–25 mils and is widely successful in strong alkali immersion (50-73% caustic soda) but not in acids.

Inorganic Zinc

Formulations are based on either alkali or alkyl silicates with a varying percentage of zinc pigment. The alkali formulations are water-based and the alkyl are solvent-based. The amount of zinc loading will determine the degree of galvanic protection offered. This kind of system may be self-curing, may rely on moisture in the air, or may be post-cured by applying an acid solution. Its chemical resistance is excellent in solvents and petroleum products that are relatively free of water and with a near neutral pH. It prevents corrosion of steel substrates by sacrificial or preferential action, while providing barrier protection. Topcoating may be advantageous to prevent rapid zinc deterioration in some service conditions. Possible contamination of the stored product may result when zinc coatings alone are used for immersion service. SSPC PS Guide 12 provides guidance in using and selecting zinc rich primers.[3]

Vinyl

Vinyl solutions consist of vinyl chloride/vinyl acetate copolymers in ketone/aromatic solvents. Low-volume solids normally necessitate the application of several coats to achieve the recommended film thickness of 5–12 mils. Special high-build formulations are available, but selection should be made with extreme caution since the pigmentation can provide a very porous film unsuitable for immersion service. Vinyls were once widely used in a multitude of chemical and food services, but now are somewhat limited to water, fatty acids, and salt solutions. They exhibit poor resistance to solvents and their use has declined as a result of VOC regulations.

Precautions

Care should be taken to ensure that coatings used as linings are well within the shelf life as defined by the material supplier. The storage or shelf life may be materially affected by temperature elevations or exposure to sunlight.[4] Some linings, once frozen, may not be suitable for use. Storage under controlled temperatures and safe ventilation with scheduled package inverting as recommended by the supplier is essential for optimum shelf life.

Surface Preparation

Surface preparation should provide a substrate that is free of contaminants, uniformly roughened, and cleaned to white metal as specified in SSPC-SP 5/NACE 1. The initial surface profile can be created only by abrasive blast cleaning. Observation indicates that with some coating systems in certain

environments the depth of surface profile can significantly alter the results. Surface preparation is discussed in depth in a separate chapter of this book.

Surface preparation of tanks previously been exposed to liquids requires special treatment. Prior to blast cleaning, it may be necessary to remove existing residues with solvent, caustic soda, acid, detergent, or steam. None of these methods is consistently successful.

Conventional wisdom has prescribed a technique of solvent and abrasive blast clean the tank, heat the tank to a temperature at least 25°F (14°C) above the curing or highest operating temperature, and abrasive blast clean to remove visible rust and stains. The rationale was that the elevated temperatures would accelerate the corrosion process, before the moisture is driven off, and the rust and rust stain would be visible indication of the salt contamination that would be removed by abrasive blasting. SSPC TU 4 and the salts chapter of this book describe contemporary methods of extracting samples and determining levels of contamination.

Application Techniques

The first coat is normally applied by spray. If the material's wetting properties are poor or the surfaces are pitted, brushing should be considered. After the first coat has been applied, it is a good practice to brush one or more stripe coats on welds, edges, or any area that is not ideally fabricated to ensure better coverage and continuity.

Humidity must be controlled inside the tank during coating application to combat surface condensation. Common practice has been to specify that the surface temperature remains at least 5°F (3°C) above the dew point. While this requirement will ensure that visible condensation does not form on clean steel, it does not ensure that condensation will not form when temperature conditions are changeable, unless the contractor provides either temperature control or dehumidification (DH). Further, this requirement does not ensure the lower humidity conditions that are favorable to solvent evaporation as required for the coating to cure properly. More and more owners are specifying that DH be used to maintain specific relative humidity conditions in tanks. SSPC SSPC-TR 3/NACE 6A192 provides guidance in using dehumidification in coating work.[5]

It must be recognized that when DH is used in a tank, the effects of salt contamination may be masked by the lack of available moisture in the air with which to react and create a corrosion cell. This situation requires increased attention to testing for and removing salts.



Figure 4. Two-hundred-foot diameter, open top tank being lined via rolling scaffolding. Courtesy Tank Lining Corp.

A spray painter must be properly trained to apply a coating Applying a coating in a criss-cross pattern provides a more uniform thickness and improved film continuity. Some coatings require that a first pass be applied as a fog or mist coat. This very thin but uniform film allows solvents to "flash-off "quickly, and the coating will then "hold" or "take" subsequent and relatively heavier, slower passes. Well-trained, experienced spray painters, with proper supervision, can create the best spraying procedure for any given material. Wet film thickness is measured with a gauge. This is an estimate because the solvents in the coating evaporate during the spraying process. The type of solvent, method of application, and the environmental conditions during the application are all factors that impact gauge readings. Good air circulation is required to remove the solvents.

Linings are spray-applied by conventional air or airless spray **(Figures 4 and 5).** Multiple-coat systems require a thorough visual inspection between coats, with rough areas sanded or scraped then repaired by brushing or additional spray applications. Note previously undetected fabrication or plate shortcomings during an inspection after the first coat. In most cases, these problems can be corrected by

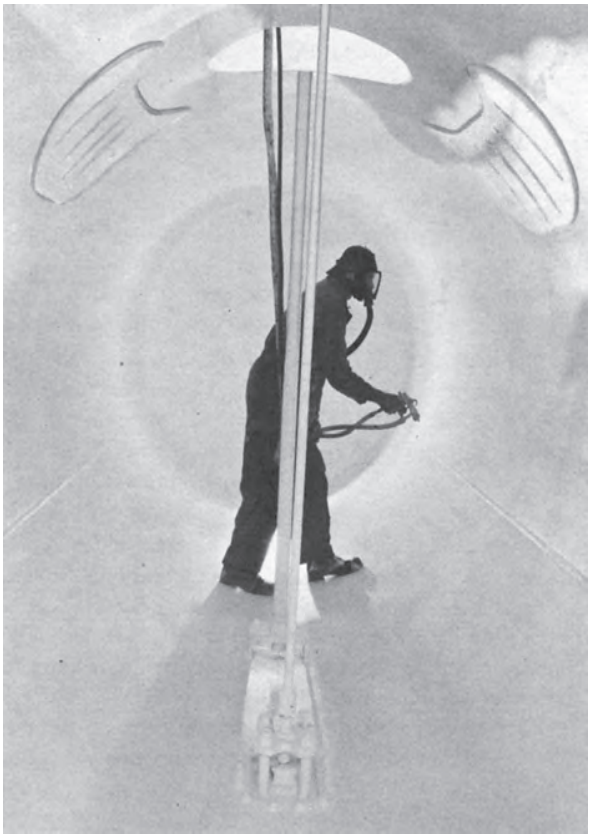


Figure 5. Lining being spray applied in railroad tank car for shipment of clean chemical or food product. Courtesy Tank Lining Corp.

chipping or grinding and the first coat reapplied as a touch-up. If additional welding is required or if the coating material is one in which the depth of anchor pattern is of real significance, then it becomes necessary to reblast those areas and reapply that first coat.

Proper mixing of a coating system is important and the supplier's instructions should be carefully followed. Restrictions on material temperature, relative humidity, cleanliness of equipment, and proportion are, in some cases, critical. Add only ingredients supplied or specified by the supplier and adjust with thinner as precisely as possible to the specified viscosity.

Curing and Baking

Coating materials are commonly classified as air-dry, force-cured, or baked. Force curing an air-dry material does improve its performance characteristics to a degree, depending on the generic type. This process can appreciably increase adhesion, improve crosslinking, ensure that all solvents are removed and provide a more complete reaction. When the lined tank is to be exposed to food, food packaging materials, or any other environment where odor or trace chemical pickup could be of concern, force-curing normally is necessary to eliminate all solvents and products of polymerization.

For all force intercoat drying, an indirect fired heater should be used. An invisible film from the combustion products may be deposited on the surface and affect the adhesion of succeeding coats. The size of the tank and the equipment available dictates the type of heat source. For indirect heaters the common fuels are oil, steam, natural gas, or propane.

Curing high bake coatings, where metal temperatures of 350°F to 450°F (177°C to 242°C) are necessary, usually requires direct-fired heaters. Common fuels are natural gas or propane. To attain these temperatures on large tanks (up to 80 ft. in diameter), the exteriors must be insulated.

Smaller shop-fabricated vessels are usually force-cured and/or final baked in ovens. The prerequisite is an even distribution of heat with reasonable temperature control. The heat source can be electricity, gas, or oil, but, again, the products of combustion should be of primary concern. Ovens provide a more controlled environment and better heat distribution and are more economical for handling small components.

Proper control in curing high-bake systems prevents overcuring on intermediate bakes, which would result in a loss of adhesion, or undercuring of the final coat, which causes poor chemical resistance. Overcuring the final coat, short of charring, is not considered detrimental. There is no correlation between air temperature and metal temperature during tank heating. The only concern for proper cure is the temperature of the lining. For practical purposes, the exterior metal temperature and the lining temperature are identical. It is most convenient, unless baking in an oven, to use the exterior metal temperature as a control by using recording or contact thermometers and heat indicating crayons. This measurement allows the operator to determine when minimum temperatures are obtained and where cold or hot spots exist, thus assuring uniform distribution of heat. NACE provides additional information on force-curing, including special procedures and precautions.[6]

Throughout drying between coats, force-curing, and/or baking, substantial volumes of air

should be directed to ventilate all areas. Inadequate ventilation can result in insufficient cure and/or a build-up of solvent vapors until runs or solvent wash occur.

Inspection

Full-time, competent inspection provides additional assurance that every phase of surface preparation, application, and curing is properly performed. Variations in any phase must be immediately recognized and corrective action taken or performance can be adversely affected, even though the lining may not fail any acceptance inspection test. Inspectors must possess a broad knowledge of coatings work in order to evaluate quality.

The surface should be inspected for contaminants such as grease, oil, dust, or blasting abrasive both before and after surface preparation. Visual gouges, laminations, weld defects, and other defects are best detected at the earliest possible time and corrected before the surface preparation is continued. The intensity and depth of anchor pattern can be measured with a number of instruments or by comparing it to previously prepared laboratory panels.

An extra coat or additional thickness may diminish rather than enhance the quality of the tank lining. Even the most rigid tank moves appreciably as it is loaded, emptied, heated, or cooled. Stresses exist or develop in many of the materials used as linings; therefore, applying the coating to the minimum thicknesses required allows the film to maintain its adhesion and still have a low permeation rate so that it performs effectively.

There are numerous guides available for assisting in developing inspection programs for tank linings. NACE RPO288 is specific to tank linings, while ASTM D 3276 is general for inspecting coatings on steel substrates, and SSPC's *The Inspection of Coatings and Linings* provides guidance in all aspects of developing inspection programs.[7, 8, 9]

Inspecting for discontinuities (holidays) is extremely important when the corrosion rate of the solution involved is extreme or the risk of product contamination is high. When the lining is used solely for protecting from contamination, isolated pinholes may not be detrimental, as when a baked phenolic system is immersed in concentrated sulfuric acid. NACE RP0188-99 provides guidance in continuity testing, utilizing either a high- or low-voltage (wet sponge) tester.[10] The wet sponge tester is effective with coating films up to approximately 20 mils. Discontinuities in heavier films can be located with a high-voltage detector. Little work has been done to determine what detrimental effects voltage has on lining films. When coatings are used as linings in severely corrosive environments, it is imperative that every possible passageway be located and corrected.

Any instrument destructive to the integrity of the coating should not be used for testing. If it becomes necessary to use such an instrument, the damage must be repaired in accordance with either supplier or specification procedures.

Inspecting the cure of most coatings is extremely difficult. Hardness and solvent softening tests require considerable skill. Consult the supplier for instructions on testing a specific coating. For high-bake coatings, the degree of cure is determined by the change in color when compared to control panels.

Maintenance

Maintenance is just as important for coating systems used in tanks as it is for exterior paint systems although the economics and programs differ substantially. To obtain access to a process tank interior, operations must be shut down. For exterior paint systems, it is practical and economical to inspect on some engineered schedule, such as each quarter or each year, and touch-up as needed. Lining systems, on the other hand, must be designed for a maintenance-free extended service life. A common rule of thumb is a minimum of three years, but in most environments a five-year minimum is required and readily obtainable. The economics for each situation should be evaluated. A typical, good grade, proprietary, high-bake thermosetting phenolic performs for five years in the most severe instances and ten years in many more.

When designing a lining system, consideration must be given to its ability to be touched-up or repaired because of physical damage, design changes, industrial accidents, or shortcomings in application. Repair materials should be selected for their compatibility with the original coating material, their adhesion to steel, and their resistance to the environment.

The procedure for repairing a coating is normally identical to the procedure used in initial application. Where the repaired coating intersects the existing coating, it is normally recommended that the existing coating be feathered to accept the repaired

coating. Feathering requires sanding or abrasive blast cleaning to obtain roughness, and then wiping with a solvent to remove the sanding particles. With high-bake and most thermosetting materials the overlap is kept to a minimum as the solvents will not wet the completely cured coating.

References

1. NACE RPO178. *Fabrication Details, Surface Finish Requirements, and Proper Design Considerations for Tanks and Vessels to Be Lined for Immersion Service;* NACE: Houston.
2. NACE TM0174. *Laboratory Methods for the Evaluation of Protective Coatings and Lining Materials in Immersion Service;* NACE: Houston.
3. SSPC-PS Guide 12.00: Guide to Selecting Zinc-Rich Coating Systems; SSPC: Pittsburgh.
4. Zohn, Bryan I. Protective Lining Performance. *Chemical Engineering Progress,* August 1970.
5. SSPC-TR 3/NACE 6A192. *Dehumidification and Temperature Control During Surface Preparation, Application, and Curing for Coatings/Linings of Steel Tanks, Vessels, and Other Enclosed Spaces;* SSPC: Pittsburgh.
6. NACE TPC Publication 2. *Coatings and Linings for Immersion Service;* NACE: Houston
7. NACE RPO288. Inspection of Linings on Steel and Concrete; NACE: Houston.
8. ASTM D3276. *Standard Guide for Painting Inspectors (Metal Substrates);* ASTM: West Conshohocken, PA
9. *The Inspection and Coatings and Linings;* Bernard R. Appleman, ed.; SSPC: Pittsburgh, 1997.
10. NACE RP0188-99. *Discontinuity (Holiday) Testing of New Protective Coatings on Conductive Substrates;* NACE: Houston.

Acknowledgements

The authors and SSPC gratefully acknowledge the participation of Jack Delahunt and Walt Harris as peer reviewers for this document.

About the Authors

Wallace P. Cathcart
Wallace Cathcart was the technical counsel for Trinity Industries, Inc. He also co-founded Tank Lining Corp. and served as its CEO for 34 years.

Albert L. Hendricks
Albert Hendricks was president of the Wisconsin Protective Coatings Corp. where he was involved in manufacturing, testing, research, quality control, application, and specifying beginning in 1958.

Joseph H. Brandon
Joseph H. Brandon, a protective coating specialist with the Naval Facilities Engineering Service Center (NFESC), specializes in industrial coatings for both steel and concrete. A member of the International Concrete Repair Institute (ICRI) and several SSPC and NACE committees, he holds protective coatings specialist certifications from both SSPC and NACE and is a NACE certified coating inspector. He has a BS degree in structural engineering.

Chapter 6.4
Painting Chemical Plants

J. Roy Allen and David M. Metzger (original chapter)
J. Bruce Henley (2002 revision)

Introduction

Chemical plant exposures represent a highly varied, and in most cases, demanding technical challenge to the design and application of effective protective coating systems. These exposures are characterized by a generally high level of chemical activity in the immediate environment and potential corrosivity to metal (primarily carbon steel) and concrete substrates. Properly selected coating systems for use in chemical plants should minimize metal or substrate loss by protecting substrates from attack by an environment that may contain, for example, any of the following:

- Mineral acids
- Organic acids
- Alkalis
- Corrosive salts
- Solvents
- Gases
- Weather extremes

The wide variety of exposures, often combined within the same processing area or plant, necessitates proper selection of painting practices and systems. Such conditions have spurred the development of many specialized chemically resistant coatings, formulated for use in systems at general total dry film thicknesses of 10 mils (250 µm) or greater.

Chemical plant painting requires a systems approach that combines material selection, surface preparation, application, inspection, and regulatory compliance to produce the desired level of protection

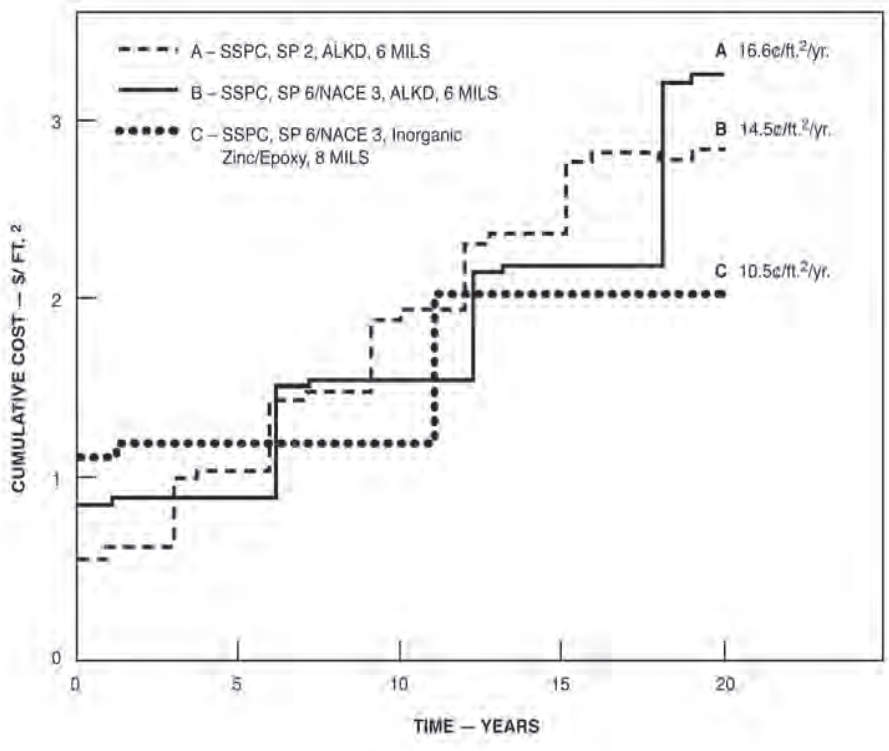


Figure 1. Comparison of actual annual painting costs for three coating systems in a moderately corrosive chemical environment.

for structural steel and equipment in a corrosive environment, without jeopardizing the health and safety of the worker or the public or the quality of the environment. This chapter provides a synopsis of current guidelines and practices recommended for painting metal surfaces in chemical plants. The systems and elements described should be regarded only in the context of atmospheric exposure and resistance to chemical splashes, spills, and fumes. Linings and coatings intended for immersion service or concrete substrates are discussed elsewhere in this book.

Economics of Painting

An economic evaluation of maintenance practices, candidate coating systems, and alternative construction materials is key in the cost analysis of maintenance finishing. Reliable input is also needed on coating performance, expected project life, level of protection, appearance requirements, and initial and continuing costs.

The initial cost of painting alone should not be the overriding factor in an economic analysis. Rather, cost should be evaluated in the context of ongoing repairs estimated to maintain a desired level of protection and appearance for a stated period of time at a minimum cost/ft.^{2}/yr **(Figure 1).**

Sound long-term economics consists of adequate original painting followed by a continuing maintenance program. For example, painted steel surfaces in chemical plants should be inspected immediately and between 6 and 12 months after painting. At that time, touch-up repairs should be made to correct damage or defects in the original job. This practice of inspection and touch-up one year after painting can be a fairly painless (inexpensive) way to ensure that a coating system is performing as designed, yet the practice is very rarely followed.

Establishing priorities and scheduling is very important. Touch-up and repair or repainting at the right time, before excessive failure occurs, can provide substantial savings. Maintenance should occur before coating failure reaches the point where cleaning and priming more than 20% of the surface area is required **(Figure 2).** Not only does this have an economic impact, but the additional surface preparation required could cause an unnecessary inconvenience to operations, especially if abrasive blasting becomes necessary. Containment of abrasive can limit access

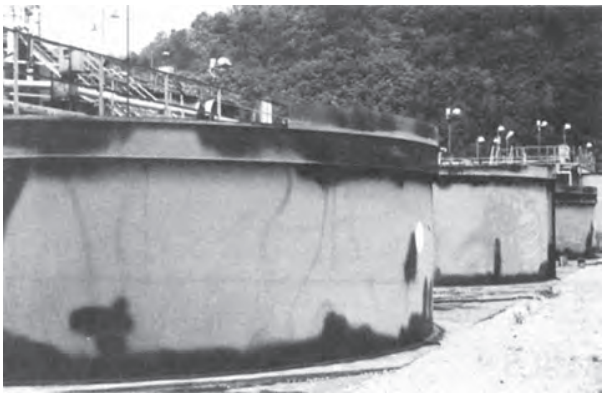


Figure 2. Maintenance is being executed before coating failure on these tanks reaches the point which would require cleaning and priming of more than 20% of the total painted surface.

to gauges and protecting sensitive equipment is critical. A rule-of-thumb is to re-paint when the condition of the paint system is between Rust Grades 7 and 6 of SSPC Vis 2.

Not all painted surfaces in poor condition that require complete cleaning, priming, and finishing should receive top priority. Delaying some of these projects where full coating removal is necessary will not significantly increase the cost of repainting.

A good portion of the maintenance painting budget should be allocated for repair and maintenance of painted surface with less extensive failure. It is especially significant when considering the effects of hazardous materials such a lead in the existing coating system. With governmental oversight for environmental and worker health concerns, the cost to work on coatings containing hazardous materials has increased dramatically. Adding to that the cost of disposing of these hazardous materials and the abrasive used to remove them can make a job almost cost prohibitive. The objective is to maintain adequate protection and appearance at minimum average annual cost. With the development of surface tolerant primers and penetrating sealer primers, expected life for non-abrasive-blasted systems has increased, making the maintenance repaint of coatings with less extensive failure much more desireable.

Surface Preparation

While coating systems must meet certain requirements in the performance evaluation formula, surface preparation represents a significant part of

total coating system cost and is considered by many to be the single most important factor influencing performance. Abrasive blast cleaning provides the best surface preparation. All high-performance coatings will perform better over a blasted surface that one that is not blasted. The better the conditions for blasting, the cleaner the surface. Today, more and more new construction painting takes place in shop environments, resulting in fewer of the inadequate surface preparation problems experienced in the past.

When performing maintenance painting, there are situations where it is not practical, permissible, or economically acceptable to utilize abrasive blasting as the surface preparation of choice. Chemical-resistant coatings depend on adequate surface preparation to optimize system performance properties. Therefore, from a cost/performance standpoint, it is more often justifiable to devise a means for making blasting feasible in chemical plants than for applications in less severe environments. However, with the tremendous success of surface- tolerant primers, the need for a higher degree of surface preparation is reduced, making it possible to power tool clean instead of abrasive blast clean. Good surface preparation is still required for good coating system performance, but the more costly and intrusive abrasive blasting methods are no longer essential.

How a surface is prepared depends on several factors: compatibility with the environment and the coating system to be used, and, of course, economic considerations. Of the variety of methods and equipment available for surface preparation, dry abrasive blasting, wet blasting, slurry blasting, water blasting, pressure washing, and waterjetting are the most efficient.

In maintenance painting of previously painted surfaces, give careful consideration to whether full or spot blasting can be specified. Factors influencing this judgment include the extent and distribution of paint failure, previous surface preparation, type and condition of paint, and compatibility of a newly specified coating with the existing one. If paint failure is as high as 50 to 60% of the surface, and especially if the steel has not been previously blast cleaned, full blasting is advisable.

Where paint failure is between 25 and 50% of the surface and the existing coating is sound and tight, spot blasting is recommended. Except in cases of highly corrosive exposure, high temperature, or immersion, blasting to a commercial standard (SSPC-SP 6/NACE 3) is the recommended surface preparation for atmospheric exposures. If spot blasting, a surface preparation by sweep blasting (SSPC-SP 7/NACE 4) over the remaining surfaces could be utilized.

Adequate and properly adjusted blasting equipment is necessary for efficient cleaning. Frequent blasting errors, which are detrimental to efficiency, include inadequate air pressure or volume at the nozzle and excessive abrasive flow rates. Another important factor is the abrasive used (type, particle size, and shape). Abrasive should be clean, hard, and of a particle size that will produce a 1–2 mil (25–50 µm) surface profile on the steel. If heavy, tight rust or thick paint is to be removed, a coarser abrasive with angular particles is suggested.



Figure 3. The coating on the hand-cleaned and painted portion of this pipe (above weld) totally failed after two years of service in a chemical plant. The coating on the lower portion, which was sandblasted prior to being painted, did not fall.

It is very common that regulations or operating conditions prevent abrasive blast dust from being released into the atmosphere. In these situations, wet blasting or high-pressure water containing a pressure-injected abrasive should be considered. There are many methods available to reduce dusting

that include a combination of water and abrasives. To limit flash rusting, inhibitors can be added to the water stream or to the surface after cleaning, but this treatment must be compatible with the primer. When water-abrasive blasting is used as the only cleaning method, the rust inhibitor is promptly applied to the freshly blasted surface after cleaning. This cuts down consumption of the chemical inhibitor and improves its effectiveness.

When surface, regulatory, or environmental factors prevent abrasive blasting, hand or power tool cleaning is often recommended. While these methods are often necessary, experience has shown that they are not as effective as methods that create a higher level of surface cleanliness. For example, coating performance over chemically corroded steel is greatly reduced when hand or power cleaning is used **(Figure 3).** It is therefore important to specify a primer that will suit the surface preparation. Excessive power wire brushing can produce burnishing—a common mistake that, if not uncorrected, is detrimental to paint performance.

Pressure water cleaning, usually with the addition of cleaners or chemicals, is effective when surfaces are contaminated with alkali, acid, dirt, or paint chalk. Acid cleaners, such as phosphoric acid, neutralize alkaline-contaminated surfaces. Adding detergents or alkaline cleaners neutralizes acid-contaminated surfaces. All chemical additives are strictly monitored and must meet all environmental and worker health and safety requirements.

Pressure water methods are frequently used in conjunction with other methods of surface preparation in chemical plants. Adding a tip to the wand provides a pulsing action that greatly increases “cutting” to remove contaminants, dead paint, and loose rust. Abrasive can even be introduced into the water stream and metered selectively through the wand, reducing the amount of hand and power tool cleaning required later on areas of difficult corrosion. These pressures will remove some, but not all, chlorides from the surface. Chlorides are a primary factor in premature corrosion after painting.

Higher pressures for water blasting (without abrasive) and waterjetting require specialized equipment and worker training. This is discussed in a separate chapter. Using these cleaners prior to hand or blast-cleaning because of the relatively high level of surface contamination, differentiates chemical from general industrial plant painting **(Figure 4).**



Figure 4. The upper portions of the two panels were abrasive blast cleaned to white metal prior to 24 hours of outdoor exposure. Panel on the right was steel corroded in a chemical plant. Rusting was rapid and extensive on corroded panel due to the presence of residual chemicals after blasting. Little rusting occurred on the new steel (on left).

Selecting Chemical-Resistant Coating Systems

Resistance to a variety of types and concentrations of chemical exposure and good overall durability are primary considerations in selecting a coating system for chemical plant service. Because they have a proven track record in chemical environments, several generic high-performance coatings are:

- Epoxies
- Polyurethanes
- Silicones (high-temperature only, not highly corrosion resistant)
- Zinc-rich (as primer)

Because of environmental regulations, many generic coatings that were successfully used in years past, such as chlorinated rubbers, vinyls, and lead-based primers, are no longer suitable for use in the industrial painting industry.

Table 1. Resistance Chart.

Generic Type	Cure Mechanism	Acid	Oxidizing Acid	Alkali	Salt	Solvent	Weather	Max. Temp. (Dry Heat)
Epoxy (Polymide)	Chem. Crosslinking	E	G	E	E	VG	G	250°F
Polyurethane (alipathic)	Chem. Crosslinking	VG	G	VG	E	VG	E	250°F
Silicone (Alum.)	Solvent/Heat	P	P	F	G	F	G	1000°F
Zinc Rich								
Inorganic	Hydrolysis	E *	E *	E *	E	E	E	750°F **
Organic	Chem. Crosslinking	VG *	VG *	VG *	VG	VG	VG	300°F **

E Excellent: no effect, best selection where performance and appearance retention are desired.
VG Very good: no effect on performance, very little appearance degradation.
G Good: little effect on performance, some appearance degradation.
G Fair: performance and appearance affected by exposure.
G Poor: not suitable, coating attacked.

* Results indicate zinc rich coating performance when topcoated. Use of these coatings untopcoated in chemical environments is not recommended.
** Limited by topcoat in the system.

Combinations of these generic classifications are possible when primer and topcoat are incorporated into a system. The system choice depends on the types of chemical resistance desired, the relative importance of appearance, and the quality of surface preparation needed before priming.

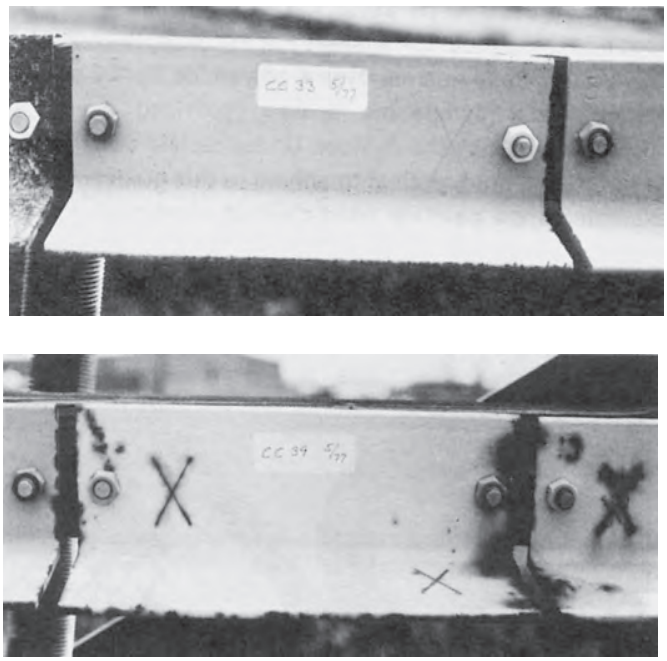
Since conventional alkyds and most water-borne coatings are not as effective in harsh chemical environments, they will not be discussed here. However, they are generally acceptable for use in the peripheral areas of chemical plants, such as tank farms, where severe chemical exposure is not usually encountered. Much progress has been made in water-borne epoxies and acrylics over the last decade. but high-solid, solvent-based coatings generally perform better and provide a longer life. Continued development of water-borne technology is expected to provide coatings that will more fully meet the demands of chemical plant exposures while providing environmentally acceptable levels of solvent emissions.

Paint systems designed for chemical environments are generally applied at heavier total film thicknesses than those intended for milder exposures. Typically, for moderate-to-severe chemical exposure, a dry film thickness of 10 mils (250 µm) or greater is required to counteract the effects of the environment and the substrate roughness characteristics (blast profile). These systems generally include a primer, an intermediate, and a topcoat, or a high-build primer and a high-build topcoat to achieve desired film thickness.

In **Table 1** the relative strengths and weaknesses (resistance) of some generic classes of coating are indicated for various chemical exposures (including weather and temperature). The cure mechanism operative for each of these classifications is also shown.

Generally, the type of exposure and surface characteristics govern selection of the primer and topcoat system. Component compatibility in a multicoat system is essential to achieve adequate performance. Compatibility can usually be assured by using the same generic coatings throughout the system. For example, the use of a polyamide epoxy enamel over a polyamide epoxy primer constitutes a compatible system, provided exposure criteria are met. Many good systems, although not generic, are designed for compatibity and chemical resistance, such as a urethane topcoat over a high-build epoxy intermediate or an epoxy mastic primer.

An effective guideline for primer selection for a chemical environment is: if the steel surface to be painted (in a moderate-to-severe environment) can be abrasive blast cleaned to SSPC-SP 6 commercial blast or better, the highest level of system performance can be obtained by using inorganic zinc-rich primers, especially if it can be done prior to installation in a shop or yard. While these primers must be topcoated when subject to chemical environments, their ability to be topcoated with a wide range of chemical-resistant finishes (e.g., epoxies, polyurethanes, vinyls, etc.) and the level of protection that they afford steel substrates



Figures 5a and 5b. New steel sandblasted, primed with inorganic zinc, and finished with a polymide epoxy topcoat. No failure at scribe (rusting) after six years chemical plant exposure (top). The new steel panel (bottom) was sandblasted and finished with an alkyd paint system. Failure noted after six years chemical plant exposure.

make them sound economic choices. The galvanic protection that zinc-rich primers provide is generally not matched by organic coating alternatives. Normally, thorough cleaning and application of chemical-resistant topcoats may be all that is required for system maintenance **(Figures 5A and 5B).**

In maintenance applications, if the old coating system is not completely removed, compatibility with the previous paint system may be a deciding factor. In this situation, it may be necessary to use a special barrier coat to prevent lifting the original film. Lifting can pose a problem when recoating alkyds or some chemical-resistant coatings that dry by solvent evaporation. High-solids surface-tolerant mastic primers, with less solvent evaporation, have exhibited success where this is a concern. In any case, if the original topcoat is unknown, or if lifting is suspected, primers and new topcoats used for spot repair should first be patch-tested to ensure that lifting or attack of the old coating will not occur (See SSPC-PA Guide 4).

One key to effective corrosion control through the use of high-performance coating systems in harsh chemical environments is simplicity—keep the number of selected systems adequate for the job to a minimum. This reduces chances of failure due to confusion and misuse of systems or system components. Because the requirements for coating chemical plants are demanding, a specialist or reputable coatings supplier should be consulted prior to maintenance painting. Cooperation and consultation with a coatings manufacturer will help assure selection of an optimum system.

An important element in selecting coating systems for corrosive environments is experience. Panel testing candidate coating systems with anticipated surface preparation is an important component of this experience. When panels are exposed to environmental conditions on test racks located at chemical plant sites, the results of controlled tests can be excellent real-time indicators of coating system performance. This overcomes the limitations of laboratory evaluations as the ultimate test of field performance.

Application

The method of application affects the quality and economics of painting. Therefore, selection should be based on the type, nature, and size of the surface to be painted; the application characteristics of the coating(s); and the location of the item or structure. Brush, roll, and spray are the most commonly used methods of application. Spraying usually results in lowest costs and highest application production rates. Unless otherwise indicated, the general order of

application preference is spray, roll, brush. Application rates usually decrease in this order.

Higher production rates are possible with airless spray when compared to conventional air atomization spray. Spray application normally provides better film build on round edges than brushing. Regardless of which method is selected, film build on sharp edges requires great care and often additional coats.

Spray equipment must have adequate controls, be large enough for the job, and capable of spraying the coating material selected. Use qualified people who will execute proper spray techniques that meet the specifications. When it is not possible to spray, a roller should be the second choice, especially for large surface areas. While application by spray or roller is preferred, brushing is often necessary as a complementary method. It serves well for cut-in, trim, and touch-up.

Specifications for protective painting in chemical plants should clearly define the required film thickness and accepted methods of measurement. The application must provide desired film thickness, uniformity, and continuity. To this end, each coat in a paint system should be a different color than the preceding coat. A film thickness less than the critical minimum, which varies depending on the type of coating and exposure, results in a drastic reduction in the protective life of a coating system. SSPC-PA 2 is a specification for measuring dry film thickness. Careful inspection must be exercised throughout the application to ensure that all specifications are met.

Environmental conditions, such as atmospheric temperature, substrate temperature, humidity, wind, precipitation, and chemical contamination, can have a significant effect on the performance of a coating system. The desirable atmospheric temperature range for coating application is 60 to 90°F. Unless specifically formulated, coatings should not be applied when the atmospheric temperature is below 40°F (50°F for epoxy) or above 100°F. Temperatures below 45°F may retard curing or drying. High temperatures will accelerate both. Substrate temperatures above 100°F may also cause rapid solvent release from some coatings and result in bubbling and pinholing. Substrate temperature does not have much of an effect on the spray application of slow drying materials.

Relative humidity, substrate characteristics, and ambient temperatures all affect the application. To avoid condensation on the substrate, most protective coatings should not be applied to steel unless the surface temperature is, and remains, at least 5°F above the dew point.

When materials containing solvents with high evaporation rates are sprayed, the material and surface temperatures may be reduced considerably. For example, if the temperature drops below the dew point, moisture condensation will occur on the surface and in the coating, affecting adhesion and subsequent film integrity.

Relative humidity also affects drying and curing times. High humidity generally slows the drying time for coatings that cure by air oxidation. High humidity accelerates—and may be required for—the curing of certain polyurethanes and inorganic zinc coatings. Information on the effects of temperature and humidity and combinations thereof on drying and curing should be obtained from the coatings manufacturer.

Coatings should not be applied outdoors when high winds can carry dust and dirt that becomes embedded in the coating causing pinholes and poor appearance; interfere with spray painting; carry overspray to areas where it is not tolerable; or cause dry overspray. Coatings should not be applied outdoors during precipitation or when it is imminent.

In chemical atmospheres, the coating system should be completed within the shortest possible time, consistent with proper drying and curing of each coat, to avoid chemical contamination between coats. If contamination occurs, it should be removed, usually by washing with detergent and water followed by thorough rinsing. One means of specifying paint application in accordance with good practice is to cite SSPC-PA 1, *Shop, Field, and Maintenance Painting.*

New Construction Painting

The easiest and best time for painting steel is at construction. Efforts to minimize capitalized costs and project budgets frequently compromise the quality of original coating systems. The quality of original painting has a lasting influence on performance and cost of subsequent maintenance painting, as well as on the life of the facility.

As much cleaning, priming, and coating as practical should be done before installation. Cleaning, priming, and even applying the intermediate and finish

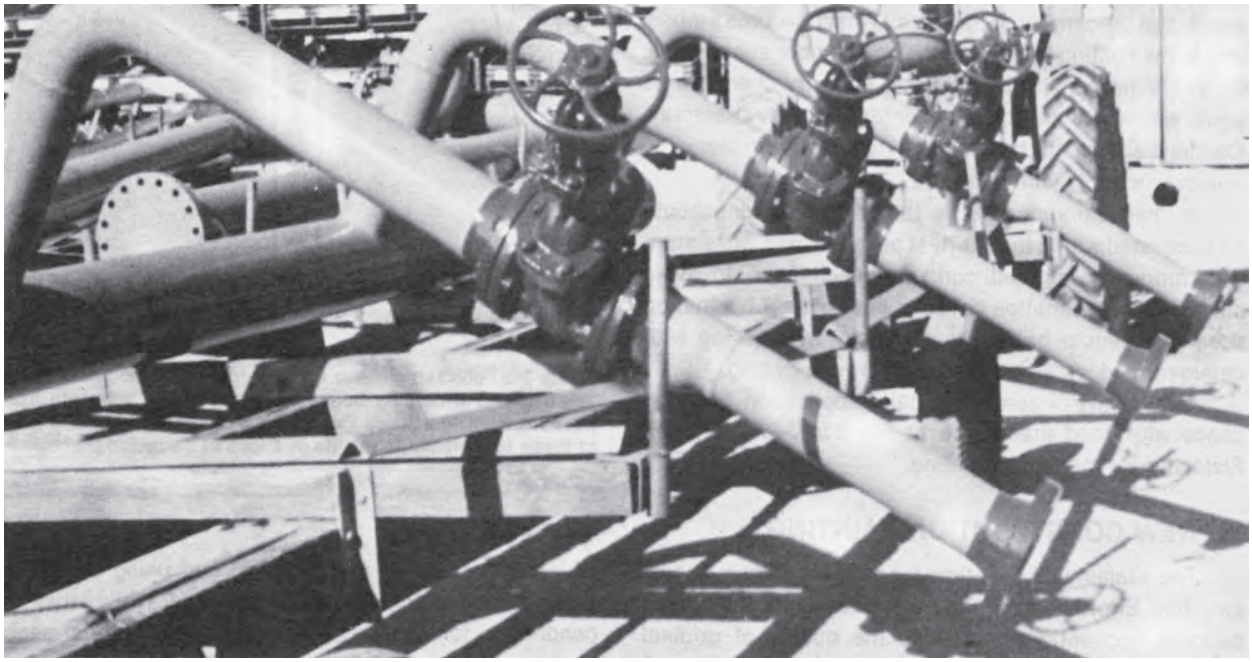


Figure 6. Surface preparation (abrasive blast cleaning) and painting of subassemblies on-site prior to installation reduces initial painting costs, improves quality of application, and results in improved system performance.

coats at the fabricator's shop, a paint shop, or at the site before erection is sound practice that is economical and provides the best application conditions. Proper care in handling during shipping and erection will minimize any touch-up that may be necessary**.**

Design has a significant influence on cost and performance. Protective coatings should be included as one factor in design considerations. Features such as back-to-back angles, skip welds, and inaccessible areas should be avoided. Vents and overflow arrangements should be located to minimize the effect on coated surfaces.

It is difficult to obtain off-the-shelf pumps and motors with chemical-resistant coating systems. Special coatings for these items are prohibitively expensive, and obtaining them unpainted may also be expensive. For critical exposures, it may be necessary to blast clean and paint such things. A compromise is to obtain the manufacturer's coating system with the best surface preparation offered and coat it with a suitable, compatible maintenance primer and a chemical-resistant finish.

Summary

The importance of specifying and using the proper paint system cannot be overemphasized. While initial expenditures for properly engineered, high-performance coating systems may seem high, this investment pays off in considerably reduced long-term maintenance costs.

Once the coating system has been selected, clearly detailed specifications are required to communicate and execute that decision. Painting system specifications, such as those developed by SSPC, should indicate all of the following:

- Coating description, including product numbers or specifications
- Surface preparation description
- Special mixing and/or application instructions and conditions
- Minimum (maximum) dry film thickness per coat
- Minimum (maximum) dry film thickness of total system

To be effective, detailed specifications should be supported by thorough inspection to ensure that all elements of the coating system specification are followed. Many coating systems, properly selected and painstakingly specified, have prematurely failed because inadequate inspection permitted improper application **(Figures 6 and 7).**

Specification and inspection should take safety and environmental issues into account.

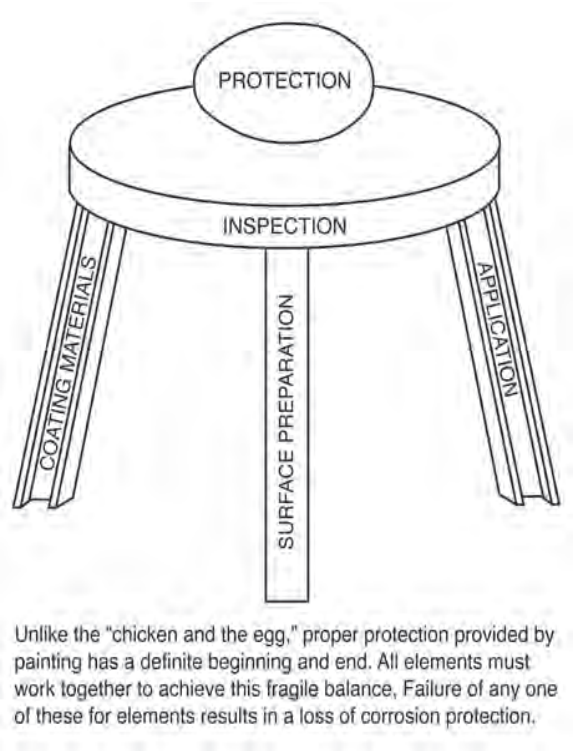


Figure 7. Elements of corrosion protection.

Protecting workers and the environmental during rigging, surface preparation, paint application, and clean-up are paramount. Any special precautions to be observed in operating or processing areas should be included in the specifications or should be a topic of discussion before the painting contract is assigned. Painting a chemical plant should always be considered from a systems standpoint. Attention to all elements of the system provides the best opportunity for economical and effective long-term protection of steel.

About the Authors

J. Roy Allen
J. Roy Allen devoted his career to research and development in the area of nonmetallic chemical plant construction materials at E.I. du Pont de Nemours and Co., Inc. He retired from Du Pont's engineering services division in the 1980s.

David M. Metzger
David M. Metzger held various technical, sales, and marketing positions with E.I. du Pont de Nemours and Co., Inc. after joining the firm in 1968.

J. Bruce Henley
J. Bruce Henley, vice president, engineering services for Brock Enterprises, Inc. specializes in developing and maintaining maintenance painting programs for the chemical plant, refinery, power, pulp and paper, pipeline, and offshore customers of the Brock Group of companies. He has also served as quality manager and estimating manager for the Brock Group. An SSPC-certified protective coatings specialist (PCS), Mr. Henley is a member of the SSPC PCCP advisory committee and numerous other technical committees. He is also a long-time member of NACE and holds a degree from Rice University.

Chapter 6.5
Painting Waste Treatment Plants

James D. Graham

General Considerations

The Clean Water Act classifies America's waterways according to effluent discharge. Since its introduction there has been a continual increase in constructing new waste water and sewage treatment plants along with retrofitting and enlarging existing plants. Public awareness, environmental concerns, and constantly changing regulations have made this very challenging.

Over the years, there has been a sizeable increase in the types and amounts of chemicals used for the various industries, agriculture, and households. The discharge of such chemicals has come under very tight scrutiny by various environmental agencies and the general public. By the nature of the function of treatment plants, their components are exposed to some of the harshest environments imaginable. A 1998 American Water Works Association (AWWA) study estimated the costs of maintaining and upgrading existing treatment plants as exceeding $36.2 billion.

There are basically two types of waste water treatment plants. Sewage treatment plants typically consist of a combination of tanks, piping, and sludge management areas. The plant may use chemical or biological treatment methods or a combination of both. Lagoons associated with the biological treatment of sewage may be considered separate units. Waste water treatment plants typically treat releases of substances from plants that were used to treat and dispose of domestic and or industrial waste water.

The coatings industry, over the last several years has also seen many changes as a result of environmental regulations. Since the late 1800s, coal-tar enamel has been used to protect submerged structures. Coal-tar epoxy coatings then became the coating of choice for submersed steel and concrete because of their high degree of chemical and electrical resistance, mechanical strength, and relatively low cost and long life. More recently, because of advantages in function, application, and aesthetics, color high-build epoxies, Novolac-based epoxies, urethanes, polyurethanes/polyureas, polysulfides, and epoxy siloxanes are now being used throughout the industry.

Specification

Conceiving a good protective coating program in large, complex water treatment plants is not a simple task. It takes research and team work involving the design engineer, corrosion engineer, facility owners, coatings manufacturer, coating applicator, and inspection team. Together, they can establish a coating program that will provide maximum benefits, long-term protection, pleasing appearance, and easy maintenance.

The corrosion engineer/specification writer has the ultimate responsibility to prepare a coating specification. This person must note the chemical, atmospheric, mechanical, and aesthetics in each area of the facility. When preparing the "new construction" specification, consideration needs to be given for touch-up after construction and on-going maintenance.

A well-written paint specification must cover every phase of the coating project. It helps ensure uniform bidding, effective job scheduling, compatibility of both shop and field-applied coatings, and maximizes the dollars spent to assure the longest possible protection for the facility. It also provides the necessary information for fabricators, equipment manufacturers, coating suppliers and the painting contractor of the requirements for surface preparation, number and types of coatings, dry film thickness of each coat, colors, and application requirements.

Selecting the Coating System

Within a single water or wastewater treatment plant, several coating systems are usually required because of differences in substrates and environments. In selecting the most advantages coating system for a waste water treatment facility, the corrosion engineer/specification writer has four prime objectives:

- Long-term protection
- Pleasing appearance

- Ease of maintenance during operation
- Economics (initial costs and maintenance)

To properly select a coating system the service requirements and environmental conditions of the unit, the substrate to be protected, and expectant life cycle must be known. Current high-performance coating systems require sophisticated, expensive surface preparation and application equipment and methods. Generally speaking, today's coatings are more labor intensive and require a higher level of skill to properly apply. These high-performance coatings often have the highest initial costs; however, they normally provide the best value because they withstand the severe service requirements and provide longer-term protection and considerably longer repaint cycles.

The use of high-performance coatings has contributed to simplifying specifications. Specifiers are attempting to use as few coating systems and thinners as possible. Fewer products simplifies application and inspection and minimizes compatibility, maintenance, purchasing, and storage problems.



Figure 1. Covered primary clarifier.

Submerged Surfaces

The use of color coatings on submerged steel and concrete surfaces has become more prevalent with the growth of waste water facilities and an increased emphasis on aesthetics. Color coatings are frequently used in process tanks in place of the coal-tar epoxies. The aesthetic advantages are obvious. It is more pleasing to see a treatment plant with its pumps, grit chambers, clarifiers, aeration tanks, chlorine contact basins, and other large process tanks coated with attractive and durable pastels rather than the traditional black. Light greens and tans are most popular for immersion.

High-performance coatings offer other certain advantages in terms of chemical-resistance, recoat limitations, intercoat adhesion, ultraviolet exposure, repairs, and general maintenance when compared with coal-tar epoxies. When cured, coal-tar epoxies are very slick, solvent-resistant, and begin to degrade quickly in direct sunlight, resulting in intercoat adhesion problems. Depending on the formulation, most manufacturers of coal-tar epoxies require a recoat limitation of 24 to 72 hours and protection from direct sunlight. Top coats applied after that time cannot be expected to provide optimum intercoat adhesion. It is normally preferred that coal-tar epoxies are top-coated within 48 hours. If this time is exceeded, all surfaces must be sweep-blasted to provide "tooth" before top coating. Even then, the adhesion could be compromised due to very little, if any, chemical cross-linking between coats. Because of the complexity and size of today's plants, this recoat limitation presents serious problems. It also eliminates the use of a coal-tar epoxy as a shop coating and requires using a catalyzed epoxy shop primer with top coats applied later in the field.

A system consisting of two coats of coal-tar epoxy (e.g., SSPC Paint System 16) totaling 20 mils (500 µm) dry film thickness has been successfully used for many years on both steel and concrete submerged surfaces. In waste water treatment plants, this system is typically used for concrete pipe interiors handling raw sewage, where hydrogen sulfide (H_2S) is present. Coal-tar epoxies, despite the limitations, continue to play an important role in waste treatment plants. These coatings are excellent for applying to backfill, below-grade surfaces of process tanks, and buildings as a moisture barrier. Polyvinyl chloride sheet linings have also been used extensively and successfully to protect concrete pipe carrying raw sewage. The vinyl sheet liner is mechanically built into the pipe when the pipe is constructed.

Many high-build, high-performance coatings are approved for use in potable water (NSF/ANSI 61) as storage tank linings. This means that the same coating may be specified for water and waste water treatment plants. More recently, a system consisting of

two coats of high-build epoxy totaling 15 mils (380 µm) has become the preferred system for submerged surfaces. It offers these advantages over a coal-tar epoxy system:

- Longer recoat window and wider range of cure temperatures
- Good wetting when rolled on concrete
- Available in a variety of colors
- May be certified by NSF International for lining potable water systems

Severe Damp Atmospheric Exposure

Chemically curing epoxy enamels are used for severe damp atmospheric services on steel and concrete surfaces. Whenever waste water treatment components surfaces are exposed, moisture condenses the cool steel and combines with gases to create highly corrosive conditions. This occurs frequently in wet wells, grit and screen chambers, chemical mixing rooms, pump stations, and dry wells. High-build epoxy coatings are used because of the high-gloss finish, broad color selection, and simplification of product lines required. When specified for exterior atmospheric service, these epoxy systems are usually top-coated with an ultraviolet-resistant finish such as aliphatic polyurethane, which minimizes chalking and loss of gloss. Stripe coating is frequently specified for edges, welds, hard-to-access areas, and rafter/plate interfaces before a full coat is applied. In the past, vinyl systems were successful in severe atmospheric service. However, their use is now restricted because of VOC regulations.

Mild Exterior Exposure

With the exception of addressing the presence hydrogen sulfide gas, selecting coatings for mild exterior exposure is similar selecting them for another industrial environment. The issue is more aesthetic since the gas concentration is not sufficient enough to affect coating integrity. Lead-free coatings should be specified to paint the exterior plant structures, piping, valves, ramps, doors, sash, handrails, motors, and fences in this service environment.

Alkyd coating systems can be used on exterior steel surfaces in a mild environment. They offer a broad color selection and pose fewer compatibility problems with shop primers and other coatings. In addition, alkyds offer simple application properties.

Acrylic emulsion systems are usually specified for exterior concrete surfaces. They provide a pleasing appearance and reduce porosity. An acrylic emulsion can also be used as an exterior finish over other exterior coating systems. These systems offer better color and gloss retention than alkyds, with the newer varieties meeting all VOC regulations and presenting no discoloration problems. Weather-related application problems may occur if acrylic emulsions are applied below 50°F. They do not coalesce properly and film integrity is weakened. This can be a serious shortcoming in new construction because painting cannot always be carried out under ideal conditions

Mild Interior Service

This service condition includes control boxes, pumps, motors, handrails, piping, laboratories, workshops, and pump, blower, and control rooms. Walls, ceilings, doors, frames, and sash are painted for appearance and improved housekeeping.

Alkyd coating systems are normally used on interior metal surfaces and on piping and equipment to provide color coding. They are easily cleaned and maintained. Epoxy systems are more appropriate for severe service such as damp areas and laboratories where splash or spill of chemicals is likely.

Interior concrete block walls can be filled with latex emulsion block filler and top-coated with two coats of single-package acrylic emulsion. Since acrylic emulsions are water-thinned, there are no solvent vapors or odors to irritate other trades working in the immediate area. They also dry quickly, permitting more than one coat to be applied in a day and minimizing movement of staging and rigging. They are very easy to use for both new construction and maintenance painting. In some instances, the block filler is coated with two coats of catalyzed epoxy to simulate an inexpensive tile-like finish. This same epoxy enamel should be used for more severe service areas.

For aesthetics and protection from chemicals, concrete floors are coated with a thick, chemical-resistant epoxy or polyurethane enamel. This increases reflectivity and provides a surface that is easily cleaned. The catalyzed epoxy enamels perform best because of their toughness, and resistance to abrasion, water, and chemicals. Because of the inherent slipperiness of such surfaces, it is a common practice to incorporate granules (e.g., aluminum oxide) into the top-coat to produce a slip-resistant surface. When coating concrete floors, proper surface

preparation is key to a successful coating system.

Elevated Temperature Surfaces

Waste water treatment plants have equipment with hot surfaces that must be coated for corrosion protection. In many instances, especially during maintenance painting, these hot surfaces must be coated as they operate. Thus it is very important to know precisely what the metal temperature is. Heat-resistant coatings require a good surface preparation, at least to SSPC SP 6/NACE 3 Commercial Blast and preferably to SSPC SP 10/NACE 2 Near White Blast at these higher temperatures. The manufacturer's product data sheet (PDS) and application instructions should be followed carefully. Aluminum-filled silicone or another generic type can be used for temperatures in the range of 300°F to 500°F. Straight silicone aluminum should be used in the 800° to 1000°F range. Normally, two coats are applied to room temperature surfaces, and subsequent heating to the operating temperature fuses the resultant aluminum-pigmented silicone film to a 2 mil (50 µm) dry film thickness. This relatively thin film is unable to provide efficient long-term corrosion protection.

Inorganic zinc and thermal-spray zinc coatings can provide excellent corrosion protection on hot steel surfaces up to 600°F (316°C). Thermal-spray aluminum coatings provide good protection up to 1500°F (816°C). Metallic coatings are best applied in a shop.

Service Condition Tables

Generally speaking, any coating system that will give good service in a waste water plant will, in a similar exposure, give good service in a water treatment plant. The reverse may not always be true because of the more severe environments present during a waste water plant exposure.

Tables 1 and 2 list the service conditions typically found in waste water treatment plants. Appropriate coating systems, film thicknesses, surface preparation, and equipment are also summarized.

Oils, greases, and soaps in waste water coat the surface below the water line, preventing easy passage of oxygen and acids and offering some protection to concrete. Most concrete destruction and damage to coating systems in process tanks occurs at the water line. It is here that the coating system is subject to harmful cyclic effects: hot/cold, wet/dry, freeze/thaw, and sunlight, in addition to the abrasive effects of floating matter. Today, most engineers specify a protective coating system applied to the all walls and floors in concrete process tanks.

Table 1. Typical Submerged Service Conditions.

Submerged Exposure	Water Plant	Wastewater Plant
Water	Yes	Yes
Dissolved Oxygen	Yes	Occasionally (at water level)
Hydrogen Sulfide Present	No	Small amount in raw sewage
Carbon Dioxide Present	Not Generally	Usually
Oils, Greases, & Soaps	No	Yes
Floating Matter	No	Yes
Chlorine	Yes	Yes
Alum Present	Yes	No

Steel	Surface Preparation: Minimum SSPC-SP 10/NACE 2 Near White Blast Coating System and Dry Film Thickness		
	Coating System and Dry Film Thickness:		
	High Build Epoxy (color)	2-coat systems	10 mils total
	Coal Tar Epoxy	2-coat systems	16 mils total
	High Build Coal Tar Epoxy	1-coat system	16 mils total
Concrete	Surface Preparation: Sweep-blast preferred, usually only stiff brushed		
	Coating System and Dry Film Thickness:		
	High Build Epoxy (color) *	2-coat systems	10 mils total
	Coal Tar Epoxy *	2-coat systems	14-16 mils total

* First coat thinned 25%.

Typical equipment and structures frequently coated in this service condition are:

- Screw pumps
- Grit chambers
- Screens
- Sluice gates
- Weirs
- Baffles
- Clarifiers
- Settling tanks
- Digesters and the underside of their covers
- Aeration tanks
- Chlorine detention tanks



Figure 2. Anarobic digester piping.



Figure 5. Trickling filters.



Figure 3. Aeration basin.



Figure 6. Back wash pumps.



Figure 4. Chlorine contact basin.



Figure 7. Sediment tank corrosion.

• Aerating, scraping, and mixing equipment in process tanks
• Trickling filters

Table 2. Typical Moist Atmosphere Conditions.

Moist Atmosphere Exposures	Water Plant	Wastewater Plant
Moisture and Oxygen Present	Yes	Yes
Hydrogen Sulfide Present	No	Yes
Carbon Dioxide Present	Not Often	Yes
Sulfur Dioxide Present	Not Often	Not Often
Carbonic Acid Present	Not Often	Yes
Sulfur Acids Present	Not Often	Yes
Cyclic Changes (hot to cold, etc.)	Yes	Yes
Alum Present	Yes	No

Steel	Surface Preparation: SSPC-SP 6/NACE 3 Commercial Blast		
	Coating System and Dry Film Thickness:		
	Epoxy Primer & Epoxy Enamel	3-coat system	6 mils total
	Epoxy Primer & High Build Epoxy	2-coat system	6 mils total
	Vinyl Primer & Vinyl Finishes	3-coat system	5-6 mils total
	Chlorinated Rubber Primer & Chlorinated Rubber Finishes	3-coat system	5-6 mils total

For exterior exposures, a vinyl system would be preferred to an epoxy system since epoxies chalk early and lose gloss on sunlight exposure.

Non-submerged severe exposures create one of the most difficult service conditions for coatings in a waste water treatment plant. Such conditions are present in wet wells, enclosed grit chambers, screen chambers, equipment space inside buildings, sewer covers, exteriors of closed steel tanks, or wherever waste water surfaces are exposed in an enclosed area. Moisture condenses on the cool steel, including pumps, motors, handrails, etc. as well as masonry. This moisture combines with gases to create highly corrosive hydrogen sulfide.

This service condition is present in all areas exposed to moisture, chemicals, and condensation, particularly on below-grade surfaces that are constantly wet, ferrous metals near chlorine delivery, storage and evaporation facilities, catwalks, bridges, and handrails over process tanks, and the top side of digester roof covers.

Table 3: Typical Exterior, Non-submerged Severe Exposures.

Outside Sunlight & Weather Exposure	Water Plant	Wastewater Plant
Actinic Light and Radiant Heat	Yes	Yes
Hydrogen Sulfide Present	No	Yes, sufficient to discolor certain coatings
Sulfur Dioxide Present	Sometimes enough to discolor	Sometimes enough to discolor certain coatings
Carbon Dioxide Present	Small amount	Yes
Salt Air	Occasionally	Occasionally
Abrasion from Blown Sand	Yes	Yes
Cyclic Physical Changes	Yes	Yes

Steel	Surface Preparation: SSPC-SP 6/NACE 3 Commercial Blast, SSPC-SP 3 Power Tool Clean, SSPC-SP 2 Hand Tool Clean		
	Coating System and Dry Film Thickness:		
	Steel:		
	Alkyds, acrylic emulsions, chlorinated rubber	3-coat systems	5-6 mils
	Polyurethanes for maximum gloss & color retention	3-coat systems	5-6 mils
	Concrete:		
	Vinyls, latex emulsions, chlorinated rubber	3-coat systems	5-6 mils

Surface Preparation

The success of every paint project depends on the condition of the substrate. When specifying the degree of surface preparation, the engineer or specification writer must consider all conditions of the surface to be coated; the type of coating system that is to be applied; the environment; service conditions; economics; and physical limitations.

Some coatings have greater bonding or surface wetting properties than others and are more tolerant of minimal surface cleanliness. The engineer must know the limits of the coating system that is specified.

High-performance coatings used in the most severe conditions will weather in moist atmospheres and chemically corrosive environments, requiring the most stringent surface preparation.

Table 4: Interior Severe Exposures.

Inside Dry Atmosphere Exposure	Water Plant	Wastewater Plant
Moisture	Very Little	Very Little
Oxygen	Yes	Yes
Hydrogen Sulfide Present	No	Often enough to discolor certain coatings
Sulfur Dioxide Present	Very Little	Very Little

Steel	Surface Preparation: SSPC-SP 6/NACE 3 Commercial Blast, SSPC-SP 3 Power Tool Clean, SSPC-SP 2 Hand Tool Clean, SSPC-SP 1 Solvent Clean		
	Coating System and Dry Film Thickness:		
	Alkyds, Acrylic Emulsions	3-coat systems	4-5 mils
Concrete Floors	Surface Preparation: Acid Etch with 15-20% solution of muriatric acid to produce texture of fine sandpaper or sweep sandblast		
	Coating System and Dry Film Thickness:		
	Epoxy Enamels	3-coat systems	5-6 mils
	Chlorinated Rubber Coatings	3-coat systems	5-6 mils
Concrete, Masonry	Walls & Ceilings		
	Coating System and Dry Film Thickness:		
	Latex Emulsions, Epoxies, Chlorinated Rubber	2-coat systems	3-4 mils
	Latex block filler added for block or porous surfaces		
Wood	Oil, alkyds, latex emulsions, two finish coats over wood primer		

Steel

The best surface preparation for steel is to remove all rust, mill scale, and surface contaminants. This is most effectively accomplished by abrasive blasting in the field or shop blasting with centrifugal equipment. Abrasive blast cleaned surfaces should be coated the same day as blasted. Properly cleaned steel provides an excellent painting surface with the proper profile to serve as the base for a high-performance coating system.

Concrete

Most new concrete should be permitted to cure at least 28 days under good atmospheric conditions prior to applying a coating system. Concrete floors must be especially well prepared because of the severe service involved. This subject is discussed in greater depth in the chapter on concrete surface cleaning and profiling.

Galvanized Surfaces

Galvanized surfaces may sometimes be coated for aesthetic reasons or to enhance corrosion protection. Alkyds applied directly to zinc can allow moisture and oxygen to reach the metal surfaces. Moisture combines with zinc to form normal corrosion products such as zinc oxides and zinc carbonates. These salts react with oils or fatty acids in the paint binder to form a chemical soap film that destroys the paint bond. Thus non-oil bearing coatings should be used on galvanized surfaces. Properly formulated high-build epoxies adhere well as do oil-free acrylic latex metal primers. Zinc oxide primers serve well under oil or alkyd top coats. Vinyl wash primers perform well as a pretreatment on galvanized steel to promote adhesion. Galvanized surfaces must be free of all oil, dirt, grease, and other foreign matter before coating. Newly galvanize surfaces should be carefully brush-blasted to provide a light profile to enhance adhesion.

Aluminum

Aluminum surfaces must be free of all oil, dirt, grease, and other foreign matter. After cleaning, painting with a coating system that is appropriate for the service condition to which the aluminum will be exposed. Vinyl wash and acrylic latex metal primers are common on aluminum surfaces.

Acknowledgements

The author and SSPC gratefully acknowledge Larry Muzia's peer review of this document.

About the Author

James D. Graham

Jim Graham is the western area outside marketing representative with Corrosion Control Products Company, Gardena, CA. He is responsible for coating inspection, instrument sales, and training throughout the western U.S. and providing support for the company's other offices. Currently vice chair of the Southern California Chapter of SSPC and the AWWA CAL-NEV corrosion control committee, Mr. Graham has also served on the board of the Channel Islands Section of NACE International since 1984 and is the former chair of the Western Area NACE Section. He is an SSPC certified protective coatings specialist (PCS) and a NACE International certified coatings inspector. He also authored a chapter on water and wastewater treatment plants in SSPC's *The Inspection of Coatings and Linings*.

Chapter 6.6
Painting Petroleum Refineries

W.E. Stanford (original chapter)
SSPC Staff (2002 revision)

Introduction

Petroleum refineries have very aggressive environments that require extensive corrosion control. Expensive corrosion-resistant metals are often used in especially severe environments. The steel used in lesser aggressive environments must have protective coating systems to provide many years of corrosion control.



Figure 1. Containment at petroleum refinery. Courtesy Eagle Industries.

Petroleum refineries and petrochemical plants have the additional problem with leakage from contained products in processing equipment, storage tanks, piping, fittings, etc. Thus, the risk factor of corrosion failures must take precedence over usual economic considerations of cost per year of coating service. For this reason, costs for monitoring conditions and maintenance painting to maintain continuous protection are much more important for refineries than for most other industrial facilities. These actions also serve to better prevent product contamination and operation shut-down related to failures. Appearance, morale, and community relations are important considerations but to a significantly lesser extent.

Refinery painting presents a broad spectrum of exposures that involves a variety of physical and chemical conditions. Because of this, coating procedures and materials selection change from area to area. Although all areas cannot be covered in this chapter, some of the most common ones will be discussed to aid in creating an effective maintenance program that provides the desired level of corrosion control.

History of Refinery Coating

The evolution of coating technology in the past 50 years has resulted in more efficient materials performance than was previously obtained from oil-base, aluminum, and other similar coating formulations. However, twenty years ago, coating systems that would perform for up to 25 years were not uncommon. A typical high performance exterior system would be an organic or inorganic zinc-rich primer with suitable topcoats. The total dry film thickness of such high performance systems would be 8–10 mils. These systems could be applied on new construction and be virtually maintenance free for the expected life of the equipment. However, new environmental regulations have caused either the modification or elimination of many of the top performing coatings of the past. Also, the higher solids (lower VOC) coatings are often more difficult to apply satisfactorily. Thus, newer coating systems with limited field testing must be monitored more closely for early signs of deterioration.

Maintenance Personnel

Individuals responsible for coating maintenance must work effectively with the entire

organization to achieve program goals in the most efficient manner. The coatings specialist is called upon to be organizer, manager, corrosion engineer, recordkeeper, and performance analyst with a knowledge of materials composition, selection, application methods, and equipment and with the ability and authority to use this information.

Administration of good maintenance programs is paramount to the success and overall performance of coatings. However, when management delegates responsibilities for maintenance coating to people already overburdened or underqualified or provides insufficient funding, the coatings program and and corrosion protection suffer. Low priorities given to coating work can result in a series of rushed or deferred projects and inadequate specifications, material selection, improper surface preparation, and application. These result in higher costs and risks.



Figure 2. Maintenance painting at petroleum storage site. SSPC file photo.

Work Planning

As described in SSPC-PA 5, a coating program for the maintenance of refineries should begin with an audit that includes:

- Identification of all coating systems on all facilities
- The condition of all the coating systems and the surfaces that they are protecting
- All coating defects, their size, distribution, and causes

With these data, assessment of coating maintenance requirements, scheduling, costs, and necessary equipment to accomplish the work can be determined to help decide:

- when best to repair damaged coatings
- whether spot repair or total coating replacement is best
- what coating materials should be used
- how to group coating actions to reduce costs

Without a detailed plan, the work cannot be accomplished in an efficient manner.

Technology

Careful consideration must be given to “normal” and “upset” operating conditions before coating materials are selected for a specific refinery painting job. These data should reflect temperatures (high and low), cycling, chemical exposures, and mechanical conditions to which the coating will be subjected. Also consider whether the equipment is indoors or outdoors and its geographical location. The coatings specialist must also know how the equipment will be used in the refining process. For example, above-ground storage tanks (ASTs) used to store finished volatile products are usually painted white to reflect solar radiation and reduce vapor pressure to decrease product loss by vaporization.

Coating requirements often encountered in refineries (from a technical and operational point of view) are resistance to chemicals (including crude oils), permeability, tolerance of temperature extremes, abrasion and impact resistance, flexibility, and weather resistance.

Other properties, such as heat emissivity and solar-heat reflectance, should be considered where insulating qualities or heat transfer is important. With this information, desired physical and chemical properties can be established for the coating system for each type of service and environment.

Resistance to Chemicals and Crude Oil

Petrochemicals produced in refineries are very aggressive to most coating films. Crude oil, for instance, can cause extensive corrosion damage, especially when water separates from oil onto the bottom of storage tanks where coating deterioration has occurred. High concentrations of hydrogen sulfide in crude oil also result in corrosion damage.

For these problems, proper applications of inorganic zinc-rich primers with epoxy polyamide topcoats, epoxy phenolics, coal-tar epoxies, and polyesters have performed satisfactorily in the past on exposures ranging from fumes, splash, and spillage to total immersion.

Coating Permeability

The rate at which water or solvents penetrate dry coating films varies greatly among generic coating types. Coating penetration seriously affects the service life of some systems in operations where moisture condenses on equipment during heating and cooling cycles and permeability through the coating increases.

Similarly, the water penetration rate increases in more humid weather. Some coatings used to control these conditions in atmospheric service are epoxy mastics and inorganic zinc-rich primers with epoxy polyamide and aliphatic polyurethane or acrylic topcoats at a total dry film thickness of 6-8 mils.

Temperature Resistance

High- and low-temperature resistance is often required in refinery coating. The temperature may be ambient or that of the steel skin on process equipment. Atmospheric temperatures can range from -40°F in northern climates to 130°F in southern climates. Process temperatures can range from -40°F to a high of 1200°F. (Temperatures as low as -40°F can be found in refrigeration systems and as high as 1200°F on boilers.)

Coating materials selected for this broad temperature range include epoxy, modified epoxy, phenolics, modified phenolics, acrylics, silicone acrylics, polyurethanes, inorganic zincs, silicones, and heat-inducting, glass-filled inorganics. For those surfaces that undergo rapid changes of temperature, coatings must also be resistant to thermal shock.

To obtain accurate steel surface temperatures, the skin temperature of equipment surfaces should be measured using remote-sensing thermometers, since it can be higher or lower than recommended operating temperatures. Significant damage can occur to coatings with inadequate heat resistance.

Abrasion and Impact Resistance

In a refinery, coated surfaces can be damaged by airborne abrasives such as sand, coke dusts, and/or products containing particulate matter. In daily maintenance operations and during refinery turnaround, coated equipment is bumped together when new piping or vessels are installed. During maintenance repair, heavy wrenches and tools are often dropped on coated surfaces. Another source of damage is steel cables and slings that are used to hoist coated parts into place. Because of these conditions, coatings must have properties that will resist abrasion and impact damage.

Coatings such as self-cure, ethyl silicate zinc-rich primers that cure rapidly to form a hard film are desired so that they can be placed into service sooner. In some environments where the pH range is between 6.0 and 9.0, inorganic zinc-rich coatings are not topcoated. Where top-coating is necessary, epoxies, acrylics, polyurethanes, and other fast-curing coatings are used to coat equipment after installation.

Flexibility

Wind, temperature, or process pressures can cause structural components to flex. For example, in large, floating roof storage tanks, roof sections can flex as much as 10 inches under high wind velocity. In process operation, the heating and cooling of thin shell vessels produces flexing as well as contraction and expansion. Materials that will meet requirements for coefficient of thermal expansion include epoxies (flexible), polyurethanes, neoprene, and other similar materials. Each parameter should be investigated before a coating system is selected.

Weatherability

Resistance of coating materials to ultraviolet radiation and temperature extremes varies widely. Close to the Equator, coatings must withstand intense solar radiation. Close to the Arctic Circle, coatings must withstand intense cold. In hot, humid, and cold climates, epoxies, acrylics, alkyds, and polyurethanes are good candidate materials.

Heat Emissivity

As the need to conserve energy increases, emissivity becomes important. Coating materials can be used to decrease or increase heat transfer to save energy. Consider compression areas where gases are passed through piping to storage under pressure. In this case, compression requirements can be decreased if process equipment temperatures are decreased using solar-reflective materials. In other applications, heat can be absorbed to assist in raising the temperature of a tank's contents for pumping, such as with some crude oils. Where reflectance of solar energy is required to conserve volatile finished products, white coatings can be used advantageously. Heat/light reflection of black is near 0, aluminum and medium gray 40–50, and white above 80.

Composition

Desired coating materials must be specifically identified for proper procurement. It is not a good practice to specify solely by generic name (e.g., epoxy), because of the considerable differences among epoxy variations. The performances of epoxy polyamides and amine-cure epoxies may vary widely from each other, and one may perform successfully where the other does not. For example, when the application of an uncured coating is subject to condensation or high relative humidity, an epoxy amine may not cure properly. The amine catalyst can be leached out of the coating by moisture and thus not be available to react with epoxy resins. Epoxy polyamide should be used in such cases because curing will continue, although at a slower rate, even when moisture is present. Other materials, such as self-cure inorganic zinc-rich and moisture-cured polyurethane coatings, have been used successfully under moist conditions.

Coating compositions of commercial products may vary because of environmental restrictions or changes in raw materials. For coating applications in refineries, the generic materials most frequently used are alkyds, acrylic latex, coal-tar epoxy, epoxy, epoxy phenolic, chlorosulfonated polyethylene, inorganic zinc-rich primers, mastics, organic zinc-rich primers, polyester, silicones, silicone acrylics, and polyurethanes.

Specifications

To assure satisfactory coating performance, clear, accurate specifications for coating application should be written. An engineering standard prepared by the combined efforts of research, engineering, and inspection departments can make the job of writing specifications easier. The manual will include information on surface preparation, coating materials, areas to be painted, exposures, and special applications. Whatever system is used, all specifications should clearly establish:

- Types and levels of surface preparation
- Schedule of primers and finish coats for different surfaces
- Wet and dry film thicknesses of primer and finish coats
- Number of primer and finish coats
- Equipment to be used for applying materials (as recommended by the coating manufacturer)
- Safety requirements
- Weather limitations for temperature, humidity, and wind for surface preparation and for coating application and curing
- Inspection requirements
- Spot repair procedures, when needed

Laboratory Testing

An effective program for materials research and new product evaluation should be maintained to update technology and coating performance in refinery maintenance. Research projects provide guidance in selecting materials and improving coating service performance. The data provide a basis for projecting economic costs and service life expectancy, and ultimately, for making decisions on coating system investment. At the same time, materials that are not adaptable to refinery conditions are screened, eliminating early and costly maintenance coating repairs and replacement. SSPC-TU 5, *Accelerated Testing of Industrial Protective Coatings*, describes in some detail recommended procedures for laboratory testing of coatings.

Laboratory screening should include a series of tests that simulate refinery conditions and utilize standard ASTM test procedures. The data from these tests cannot be used to predict coating field performance but may serve as a screening tool for elimination of poorer performing materials.

Test parameters for physical and chemical exposure must be accurately established before testing can be initiated. These parameters should include skin temperatures of equipment, surface irregularities, chemical concentrations, adjacent process effluent, contamination drift, weather conditions, thermal shock or cyclic conditions, and other pertinent history available from engineering and operations. Laboratory tests commonly used on coatings include:

- Abrasion—ASTM C 190
- Cathodic Disbonding—ASTM G 8
- Drying Time—ASTM D 1640
- Exterior Exposure (Coastal & Inland) — ASTM D 1014
- Flexibility—ASTM D 6222
- Cyclic Salt Fog/UV Exposure—ASTM D 5894
- Fresh Aerated Water Immersion—ASTM D 879
- Solvent Resistance—ASTM D 2792
- Temperature Resistance—ASTM D 2488

- Weatherometer—ASTM D 822
- Heat Emissivity—ASTM E 307
- Permeation—ASTM D 1653

To substantiate laboratory data, as much in-service data as practical should be obtained. Documented evidence, such as case histories of materials in similar refinery conditions, should be considered. To reduce the risk of making errors in the application of paint to test panels in the laboratory, arrangements should be made with the manufacturer to provide first-coated test panels. Usually, the coating manufacturer will supply coated panels and/or wet coating samples. Other manufacturers should be excluded from test information. After the first series of screen tests, some in-house panels should be coated to establish material workability, ease of clean up, drying times, hiding power, and other data. If some of the test results are suspect, additional panels can be prepared for retesting.

Field Testing

Once rapid screen tests are completed, field evaluation will substantiate laboratory results for promising coating systems. This phase will generate in-service data to assist management when making investment decisions on coating systems. Personnel making the field tests also have an opportunity to evaluate film forming, handling, and curing characteristics. Field test applications on exterior and interior tank surfaces yield beneficial data that can be used to determine expected performance of a coating system. At refineries, the inspection department usually develops test records and a report of test items is compiled at regular intervals. This background and data are then filed for future reference.

Surface Preparation

Steel

In all refinery coating applications, the proper level or degree of surface preparation is vital in obtaining satisfactory coating performance. As discussed elsewhere in this book, the recommended level of surface cleaning is dictated by the severity of the environment and the particular primer used

For new work and for total recoating, abrasive blast cleaning is recommended. SSPC-SP 6/NACE 3 (commercial blast cleaning) may be adequate for mild service, but SSPC-SP 10/NACE 2 (near-white blast cleaning) or SSPC-SP 5/NACE 1 (white metal blast cleaning) are typically recommended for more severe environments. It is often most practical in total refinishing, as well as new coating, to have the surface preparation done in a shop where the primer or total system can be applied under optimum conditions.

In spot maintenance painting, hand tool cleaning (SSPC-SP 2) or power tool cleaning (SSPC SP 3) are often used to prepare small areas for painting. This is discussed more fully in the maintenance painting chapter of this book.

Other Surfaces

Surface preparation of galvanized steel, copper, aluminum, wood, and concrete surfaces is discussed elsewhere in this book.

Removing Sludge and Other Materials

Removing sludge from the bottom of a crude oil tank is a big problem, particularly when the tank is a large floating roof (250 m bbls/cap). The sludge is usually a heavily caked or viscous residue, difficult to shovel and expensive to remove using other cleaning methods. The most effective approach is to pump residue using a vacuum tank truck. Remaining wax or dirt-filled residue can then be broken up manually or by the use of ultrahigh pressure (UHP) waterjetting (>25,000 psi) into chunks and then removed by shoveling. If the tank structure permits, a section of the shell can be removed so that a front-end loader can extract the residue. To remove residual oil on steel surfaces, detergents and steam cleaning units are effective. Final clean-up of bottoms can be accomplished using mops and rubber squeegees to remove water and other residue from low areas. Surfaces should be allowed to dry before surface preparation operations begin. Cleaning is usually handled through contractors who have the equipment needed. To test for residual crude oil on the cleaned surface, black light (at about 60 angstroms wave length) can be used. When oil is present, the oil will fluoresce under the black light. When no fluorescence is noted, oil has been effectively removed.

In maintenance applications, when reworking a lining on a tank or vessel, especially a thick film or reinforced system, ultrahigh-pressure waterjetting UHP WJ) technology, as described in SSPC-SP 12/NACE 5, has been very useful in the cost-effective removal of

the existing liners. UHP WJ is not only effective in removing the liner, but it removes contaminants that would not otherwise be removed with less pressure. To apply a new lining to the tank may require additional abrasive blast cleaning, according to the surface profile requirements of the primer.

In recent years, low- and high-pressure washing and high and ultrahigh-pressure waterjetting have been used to clean storage tank exteriors and other equipment in areas where airborne particulates are not permitted by regulation or where equipment cannot be exposed to dust. When these methods are used, rust inhibitors are not required to control flash rusting for many primers.

Coating Application

Coating materials are often applied in refinery operations by qualified contractors (e.g., QP 1 certified with successful oil refinery experience). Contractors handle all provisions related to materials, personnel, and equipment.

Large jobs, such as exterior storage tank coating, are usually let out for bids either on a per job basis, or on an annual renewable basis. At the refinery, maintenance painting crews are also employed for special coating applications on process equipment and smaller projects.

Application equipment commonly used at the refinery are paint spray guns (typically, airless and conventional), rollers (with proper roller composition), and brushes. The recommended type of application equipment is provided by the coating manufacturer. Specialized spray equipment with intermix spray caps and fiberglass choppers are sometimes used to apply fiberglass-reinforced coatings on storage tank bottoms and walls. They are also used to apply fireproofing with fiberglass fillers. Where heavy monolithic materials are required, the gunnite process may be utilized.

Often, the most effective and economical method of cleaning and applying coatings to new refinery components is to do it in the controlled environment of a shop. Shop coating is discussed in some detail in a separate chapter of this book.

Field cleaning and painting is usually more expensive and subject to field contamination and delays. However, completing the process after construction avoids the problem of receiving shop-coated steel damaged during shipping and handling.

Inspection

In refinery coating operations, competent inspections can yield big dividends. Adequate inspection averts production losses and improves materials performance and operational efficiency. Coating inspection in refineries and petrochemical plants is described in SSPC's *The Inspection of Coatings and Linings*. It also describes some of the requirements of the inspector:

- A copy of and familiarity with the plant plans
- A copy of and familiarity with the coating specification, including inspection requirements
- Copies of and familiarity with the specified test methods
- Instruments for field testing and knowledge of how to use them
- Access to all work requiring inspection
- All necessary safety equipment
- An understanding of field authority

As work progresses, the inspector should record all required and other pertinent observations and test data in a daily log. These records can serve as valuable future references.

Safety During Coating Operations

Because of the hazardous nature of coating operations in refineries, a safety plan must be prepared by the contractor and approved by the owner, and responsibility for the safety of owner and contractor personnel must be established. All personnel involved in the work must have the proper safety training and equipment. All materials at the site must have material safety data sheets and be stored in an approved manner. All operations must be conducted in accordance with approved operating procedures.

OSHA's process safety management (PSM) standard (24 CFR 1910.119 and 1926.64) emphasizes the application of management controls, rather than specific engineering standards, when addressing the risks associated with handling or working near hazardous chemicals. The benefits of implementing PSM include preventing accidental fatalities, injuries, and illnesses and avoiding physical property damage. In 1990, OSHA initiated the Special Emphasis Program in Petrochemical Industries (PETROSEP) to determine whether management systems governing health and safety procedures for maintenance activities, contractor activities, and operations are in place to control

risks in the petrochemical field. The PETROSEP program outlines both plant manager and contractor responsibilities in integrating the PSM philosophy into the safety culture of the work site.

Of special concern in refinery safety is work in tanks and other confined spaces. Before entry, the interior air must be tested with meters to determine if toxic or explosive vapor concentrations are present. As work progresses, intermittent tests should be performed to ensure that ventilation is adequate to keep solvent vapor at concentrations below explosive or toxicity limits.

The American Conference of Governmental Industrial Hygienists has published *Threshold Limit Values (TLV) of Airborne Contaminants for 2002 for Chemical Substances and Physical Agents in the Workroom Environment.* It can be used to determine hazardous limits.

During the application of polyester coatings with peroxide catalysts, fires may occur unless materials are handled carefully. It is important to dispose of waste materials in specified containers to avoid spontaneous combustion. A checklist of some safety concerns can be found in the safety chapter of this book.

Summary

When proper coating materials and systems are selected and properly applied, corrosion in refineries can be controlled. Effective refinery maintenance includes:

- Selecting qualified contractors who have an excellent safety record and the techincal capability to perform refinery work.
- Establishing coating schedules based on an accurate refinery coating audit.
- Initiating cooperative programs for testing between laboratory and field exposures, with a good exchange of technical data between personnel.
- Preparing coating specifications that clearly specify proper coating systems and levels of surface preparation and coating application and curing.
- Inspecting and testing coating application, safety provisions, and regulation conformance.
- Evaluating economics to establish viability of coating investment.
- Planning a total coating program that assures quality coating work on every project.

When these provisions are followed, corrosion protection can be assured and annual coating costs can be reduced. In addition, longer equipment service life and fewer production interruptions will be achieved. The trend in refinery coatings is to use the higher performance systems on long term projects (15 years and up) due to better return on investments and reduced maintenance costs. Another way to look at it: any combination of paint system, surface condition, and environmental condition creates a repaint cycle that yields a minimum average annual painting cost. Determining and using this cycle will result in minimizing painting costs versus protection.

Acknowledgements

SSPC gratefully acknowledges the input of Bruce Henley and Mark Schilling in revising this chapter.

About the Author

W.E. Stanford

W.E. Stanford retired as senior project chemist in the technology and materials department of the former Gulf Oil Science and Technology Company in the early 1980s. He was also active in the American Petroluem Institute as well as SSPC. This chapter, recently revised by SSPC staff, is based on his original research.

Chapter 6.7
Painting Power Generation Facilities

Ronald R. Skabo (original chapter)
Bryant (Web) Chandler (2002 revision)

Introduction

There are several methods for generating electrical power, such as fossil, nuclear, hydro, solar, wind, and geothermal. Recent years have seen growth in nonpublic hydropower facilities operated by the aluminum industry and other refiners. These plants include technically sophisticated and demanding requirements for dams, penstocks, and tunnels. Gas-turbine fired peaking plants and co-generating facilities are also being built at a remarkable rate. The scroll compressors in these plants require coatings on the intake and exhaust ends that provide heat and abrasion resistance well in excess of the norms.



Figure 1. Structure in a power facility.

This chapter deals specifically with painting fossil fuel and nuclear power plants, which still generate the greatest percentage of megawatts in the United States. It does not cover distribution facilities that consist of substations, transmission towers, etc. While there are no major differences in the basic approach to good painting, and while a properly engineered coating system can be developed for a power generation facility just as it can for a chemical plant or petroleum refinery, each facility has special conditions or regulatory restraints that will affect the selection of coatings systems.

Historically, power generation facilities were not located in aggressive environments. Thus, painting systems were often selected on the basis of the lowest initial cost. While high performance was not a major consideration in the past, there were some exceptions, most notably, power plants located in seacoast environments, where higher quality coatings were justified because of humid, salt-water environments.

Because of the special requirements for paint performance now mandated by government agencies, the quality of surface preparation, application, paint, and inspection has been raised to a level never before required. In coal-fired fossil fuel plants, air quality standards have forced installation of flue gas desulfurization (FGD) systems that have created chemical plants within power stations—aggressive, corrosive environments that tax the best methods of protection. Other factors that have resulted in painting changes include increased maintenance costs, safety, environmental, and aesthetic concerns and a focus on decreasing downtime and production disruptions.

Specific Plant Requirements

Nuclear Power Plants

The regulatory restraints on nuclear power plants affect all facets of critical coatings work. The painting requirements for nonradiation areas are generally the same as for fossil plants or other industrial complexes, critical components and equipment excluded. However, in radiation areas, the criteria includes the ability to withstand decontamination chemicals and the conditions postulated for a Design Basis Accident (DBA) or Loss of Coolant Accident (LOCA).

ANSI Standard N5.12 defines the most critical areas of a nuclear power plant as Coating Service Level I. Of major concern are the consequences of coating failure on safe plant shutdown, mainly within the primary containment structure that houses the nuclear reactor. Less critical areas are defined in

Service Level II, which references coatings essential to normal operating performance. The United States Nuclear Regulatory Commission (NRC) controls public health and safety issues, including painting requirements, relating to nuclear power plants. The nuclear power generating industry requires strict performance criteria for coatings: extensive testing and quality assurance and quality control programs for manufacturers, applicators, and inspectors. A paint's resistance to long-term radiation exposure and decontamination procedures is the primary concern. Other forms of corrosion resistance and aesthetics are less important.

Table 1. Nuclear Power Plants.

General	Criteria for selecting these systems include identification of specific surface and substrate condition. Coatings criteria include temperature, humidity, radiation level, decontaminability and chemical resistance. Level 1 coatings test involves resistance to fire, radiation, design basis accident and unusual environmental conditions.
Suppression Chambers	White Metal Blast Clean (SSPC 5/NACE 1); use inorganic zinc primers (without topcoats), epoxy or epoxy modified phenolic primers and topcoats, or metallized aluminum with epoxy or epoxy-phenolic topcoats.
Steel Containment	White Metal Blast or Near-White Metal Blast Clean (SSPC SP5/NACE 1 or SSPC SP10/ NACE 2) with inorganic zinc primer topcoated with an epoxy or epoxy-phenolic; inorganic zinc primer uncoated' or prime and topcoat with an epoxy or epoxy-modified phenolic.
Concrete Walls and Floors	Epoxy surfacers and epoxy or urethane topcoats as appropriate for the location.
Structural Steel; (Outside of Containment)	Generally the same as fossil plants.
Hydraulic Structures	Generally the same as fossil plants.
Mechanical Equipment	Generally the same as fossil plants unless located inside containment.
Water Treatment	Generally the same as fossil plants.

The DBA coating test involves exposing a painted steel or concrete substrate to a temperature/ pressure/time environment, plus certain spray solutions such as sodium borate, sodium thiosulfate, sodium hydroxide, and/or boric acid. Depending upon the nuclear reactor design, the temperature/pressure/ time sequence can vary, with temperatures often exceeding 300°F (150°C) and pressures approaching 70 psi (483 kps). In addition, the coating must withstand anticipated radiation levels and then be able to be decontaminated to acceptable levels. The severity of these tests limits the generic types of coatings that can pass and places a greater than normal emphasis on the total coating system. Coatings that meet these criteria for steel surfaces are inorganic zincs or modified epoxies. As with any critical application, there can be no compromise in the quality of surface preparation and work.

Table 2. Fossil Power Plants.

Coal Handling	Commercial Blast Clean (SSPC SP 10 or 6/ NACE 2 or 3); organic or inorganic zinc primer with epoxy topcoat, or a total epoxy system (primer and topcoat). If abrasion is involved than consider abrasion resistant topcoat.
Structural Steel	Commercial Blast Clean (SSPC SP 6/NACE 3); Organic or inorganic zinc primer with topcoats of either epoxy, polyurethane, acrylic latex for exteriors; silicone alkyd on interior
Hydraulic Structures	Interior surfaces of circulating water lines, condenser waterboxes, and water treatment equipment are often protected with phenolic, epoxy or coal-tar epoxy systems, flake glass polyesters, or sheet rubber. White-Metal Blast Clean (SSPC SP 5/NACE 1) is generally specified, although Near White Metal Blast (SSPC SP 10/NACE 2) is often used.
High Temperature Surfaces	Near-White Blast Clean (SSPC SP 10/NACE 2) or better; use an all-silicone system, ceramic, or an inorganic zinc alone or topcoated with a silicone.
Mechanical Equipment	Commercial Blast Clean (SSPC SP 6/NACE 3) alkyd primer and alkyd enamel topcoat
FGD Systems (Exterior)	Commercial Blast Clean (SSPC SP 6/NACE 3); epoxy topcoat over inorganic zinc or use a total epoxy system. Some units may be insulated.
FGD Systems (Interior including Stacks, Duct Work, Venturi Area)	White Metal Blast Clean (SSPC SP 5/NACE 1); conditions and designs vary greatly; reinforced epoxies, rubber, foam glass block and cementitious materials have all experienced varied success.
Water Treatment (Exterior Exposure)	Commercial Blast Clean (SSPC SP 6/NACE 3); use and inorganic zinc primer ant topcoats of epoxy or polyurethane.
Potable Water	White Metal Blast Clean (SSPC SP 5/NACE 1); use coating systems suitable for potable water that have received the NSF Std. 61 Approval.

Fossil Power Plants

For many years, a great number of fossil fuel power plants were fired with gas or oil. These are relatively clean fuels that do not create serious atmospheric corrosion problems or place special demands on paint performance. Even with coal fuel, there was little effect on paint requirements since coal was generally high quality and low sulfur. In recent

years, the use of high sulfur coals and local, state, and federal regulations against discharging pollutants into the atmosphere have created new challenges for painting in these power plants.

Flue gas desulfurization (FGD) systems for coal-fired power plants impact the choice of lining materials for vessels, absorbers, and ductwork, often very aggressive environments. Using lime and limestone during neutralization can expose coated surfaces to highly alkaline and abrasive environments. Another problem is the highly acidic condition around the wet coal. Surface drainage from a pile of high sulfur coal can have a pH value of 2 or less. This must be recognized when engineering a coating system for secondary containment, steel structures, or other plant equipment.



Figure 2. Maintenance painting of power plant stack.

Common Paint Problems

One of the more aggressive environments common to both nuclear and fossil fuel generating facilities is the water treatment area. Demineralization units require acid and caustic for regeneration, creating a potential for chemical exposure to spillage areas and adjoining painted surfaces. Frequent inspection and maintenance are a must if successful service life is to be achieved with most lining systems in immersion service. The more aggressive the environment, the more frequent the inspection. Few systems can be placed in immersion service without some failure occurring during the first year. Frequent wash down and neutralization is recommended where chemical spillage occurs. It is also important to note that most work in older facilities involves replacing "dead" coatings that must be handled with extreme caution.



Figure 3. Steam power plant.

Surface Preparation

With few exceptions, prior to the existence of nuclear plants and FGD systems, the power generating industry did not need to specify high quality surface preparation. Today's plants require higher performance coating systems to satisfy requirements for nuclear service, withstand the rigors of FGD systems, reduce maintenance costs, and provide better plant appearance. SSPC and NACE joint surface preparation standards, including white metal blast cleaning (SSPC-SP 5/NACE 1) for immersion service, are frequently cited.

Surfaces that are condensing and running wet (i.e., inside chimneys downstream of FGD systems) are considered immersion service conditions. Such an environment can be more aggressive than conventional immersion service because of the higher rate of moisture vapor transmission and the possible acidic or caustic environment. In less critical areas, coating systems may be applied over an SSPC SP 6/ NACE 3 commercial blast or SSPC SP 11 power tool cleaning to bare steel. High pressure or ultra-high pressure (UHP) waterjetting is effective in removing soluble contaminants. If the dust generated during surface preparation or poses an environmental or

operational problem wet abrasive blasting may be a possible solution. Although there are exceptions, the use of hand tool or power tool cleaning (SSPC SP 2, SSPC SP 3, and SSPC SP 11) is usually limited to touch-up, repair, or small items.



Figure 4. Corrosion failure inside 1000 ft. flue gas stack of desulfurization unit after less than two years of service. Over 1700 holes were found in the polyester lining and the stack itself due to acid attack.

Types of Coatings

Coating system performance is gauged by durability in severe chemical exposure (FGD systems); resistance to radiation, chemicals, and heat (nuclear plants); and overall aesthetics. These parameters and other regulatory restraints make it necessary to carefully consider all aspects of painting requirements and to specify the appropriate coating for each plant section. Older, high-solvent (non-VOC compliant) coatings have been replaced with high solids or 100% solids epoxies, polyurethanes, polyureas, fluoroelastomers, and silicone and ceramic technology. Water-borne paints can provide long-term protection when used in the proper environment.

Primers

Since large quantities of steel are now shop primed, shop production must not be obstructed by long delays in waiting for primers to dry. Fast-drying primers are available in most generic types, including alkyds (modified), epoxies, water-borne acrylics, moisture-cured urethanes, and inorganic zinc. Because of their quick drying properties, these products usually require a cleaner surface than slow drying “penetrating” primers.

Another consideration is extensive on-site storage of shop-primed equipment and structural steel, especially when construction times for fossil and nuclear power plants range from 4 to 10 years. Most construction primers are not intended to withstand long-term outdoor storage without a topcoat. A partial answer to this problem is found in zinc-rich primers, particularly inorganic zinc.

Inorganic zincs have excellent resistance to most outdoor weathering environments, but are not problem-free. Since zinc is a very reactive metal and is amphoteric (corroded by both acid and alkaline environments), it can be attacked if the construction site storage area is subjected to acid or alkaline fall-out from any up-wind facilities. Coal dust can be detrimental to inorganic zincs, either through their galvanic relationship (carbon versus zinc) or the acidic conditions of some high sulfur coals. There have been problems with storage of inorganic zinc primed structures due to inadvertent contact with uncoated steel, another galvanic corrosion problem. At the very least, steel that is primed and placed in storage should be pressure washed with clean potable water prior to apply any intermediate or finish paint. Without care, long-term outdoor storage can result in extensive rework, repriming before the final topcoat can be applied.

Finish Coats

Finish coats are typically applied after erection, even though many innovative techniques have been proposed and used. When considering coating systems for immersion service all constituents that may come in contact with the coating can be critical, even in minute amounts. If possible, test various coating systems to achieve real life exposure data. Immerse for as long as possible and throughout the complete range of conditions expected.

In nuclear applications, inorganic zinc, modified phenolic, and epoxy-based materials have an edge over other generic types. Rigorous conditions imposed by DBA test criteria have shown that these materials generally perform best.

Suggested Reading

American Society for Testing and Materials. *Manual of Coating Work for Light-Water Nuclear Power Plant Primary Containment and Other Safety-Related Facilities;* ASTM: West Conshohocken, PA.
ANSI N512. *Protective Coatings (Paints) for the Nuclear Industry;* ANSI: New York.
ANSI N101.2. *Protective Coatings (Paints) for Light-Water Nuclear Reactor Containment Facilities;* ANSI: New York.
ANSI N101.4. Quality Assurance for Protective Coatings Applied to Nuclear Facilities; ANSI: New York.

Bibliography of ASTM Standards Pertaining to Nuclear and Fossil Plants

Nuclear Plants

D 3843 *Practice for Quality Assurance for Protective Coatings Applied to Nuclear Facilities*
D 3911 *Test Method for Evaluating Coatings Used in Light-Water Nuclear Power Plants at Simulated Design Basis Accident (DVA) Conditions*
D 3912 *Test Method for Chemical Resistance of Coatings Used in Light-Water Nuclear Power Plants*
D 4082 *Test Method for Effects of Radiation on Coatings Used in Light-Water Nuclear Power Plants*
D 4227 *Practice for Qualification of Coating Applicators for Application of Coatings to Concrete Surfaces*
D 4228 *Practice for Qualification of Coating Applicators for Application of Coatings to Steel Surfaces*
D 4286 *Practice for Determining Coating Contractor Qualification for Nuclear Powered Electric Generation Facilities*
D 4537 *Guide for Establishing Procedures to Qualify and Certify Inspection Personnel for Coating Work in Nuclear Facilities*
D 5139 *Specification for Sample Preparation for Qualification Testing of Coatings to be Used in Nuclear Power Plants*
D 5144 *Guide for Use of Protective Coating Standards in Nuclear Power Plants*
D 5163 *Guide for Establishing Procedures to Monitor the Performance of Safety Related Coatings in an Operating Nuclear Power Plant*
D 5498 *Guide for Developing a Training Program for Coating Work Inspectors in Nuclear Facilities*
D 4538 *Terminology Relating to Protective Coating and Lining Work for Power Generation Facilities*
D 5962 *Guide for Maintaining Unqualified coatings (Paint) Within Level 1 Areas of a Nuclear Power Facility*

FOSSIL PLANTS

D 4618 *Specification for the Design and Fabrication of Flue Gas Desulfurization System Components for Protective Lining*
D 4619 *Practice for the Inspection of Linings in Operating Flue Gas Desulfurization Systems*
D 4538 *Terminology Relating to Protective Coating and Lining Work for Power Generation Facilities*
D 5161 *Guide for Specifying Inspection Requirements for Coating and Lining Work (Metal Substrates)*

Acknowledgements

The authors and SSPC gratefully acknowledge the participation of John Conomos in the peer review process for this document.

About the Authors

Ronald R. Skabo

Ronald R. Skabo spent more than 40 years working in corrosion control, materials selection, cathodic protection, failure analysis, and other aspects of protective coatings in the petroleum, heavy chemical, and engineering and construction industries. A former engineering group director at CH2M HILL, he received a BS degree in chemical engineering from Montana State University.

Bryant (Web) Chandler

Bryant (Web) Chandler is a coatings consultant with S.G. Pinney & Associates, Inc., where he specializes in all types of liquid coatings for metallic and nonmetallic substrates. Additionally, he has extensive experience with rubber linings and thermal spray coatings. He is a member of ASTM, ICRI, AWWA, ASM, AWS, SNAME, SSPC, NACE, and the National Board of Registration for Nuclear Safety Coating Engineers and Specialists. He serves on several SSPC and NACE committees and is a SSPC protective coatings specialist (PCS) and a NACE certified coating inspector. Author of numerous articles with SSPC and McGraw-Hill, Mr. Chandler has a BS degree in metallurgical engineering.

Chapter 6.8
Painting Steel Structures in Pulp and Paper Mills

Randy Nixon and David C. Bennett

Introduction

This chapter aims to provide engineering and maintenance department personnel in pulp and paper mills both with a proven framework for establishing and executing a successful maintenance coating program, and with associated guidelines for ensuring quality coating work. Cost-effectiveness in maintenance coating programs is achievable only when the program is systematically organized and comprehensively executed.

The major elements necessary for a successful maintenance coating or painting program as presented in this chapter are:

• Using current technology for coating systems

• Matching the surface preparation methods to the condition of the substrate

• Keeping the largest percentage possible of all the painted steel surfaces in the preventative maintenance condition

• Applying consistent quality standards for all coating work to avoid premature and widespread coating failures, which require costly recoating work

Guidelines and coating systems are also recommended for painting new steel, which may be needed to replace severely corroded structures or may be installed for other reasons.

Scope

This chapter deals primarily with the protecting carbon steel structures and equipment exposed to normal exposure conditions in an integrated kraft (alkaline) pulp and paper mill. These conditions include general interior and exterior atmospheric exposure in the mill; splash and spillage of process liquids; wash-down exposures, and aggressive process vapor exposure within a mill.

Internal surfaces of process tanks and paper machine wet-ends exposed to immersion or constantly wet conditions are not covered. Coating galvanized steel, stainless steel, concrete, and other nonmetallic substrates, and painting hot surfaces are discussed in other chapters.

Maintenance Coating Programs

To be truly cost effective, a maintenance coating program needs to systematically involve condition surveys to ascertain the condition of the coatings on the steel structures and timely maintenance coating work. The primary goal should be to preserve existing coating assets (i.e., the money already spent on the existing coatings). Preventive maintenance of coatings always economically trumps recoating, which in turn easily trumps replacing severely corroded steel. Properly maintained coating systems help ensure operational reliability, improve personnel safety and motivation, and lower mill maintenance coating costs. The elements of a successful maintenance coating program are:

• A coatings condition grading system that is adequately simplified, depending upon mill process complexity and associated exposure condition variations and severity. Most effective programs involve 3 or 4 condition grades.

• Condition surveys to define the condition of the protective coatings, substrate conditions where coatings have failed, and related exposure conditions. The initial survey sets up the program and subsequent surveys define its progress.

• Knowledgeable, experienced personnel to conduct the coating condition surveys. More reliable and consistent data are obtained if the same personnel routinely conduct the surveys. A program coordinator designated, trained, and supported by mill management can be a critical success factor.

• Selecting proper coating materials to adequately resist the effective mill exposure conditions. Coating materials also should be chosen to match the surface preparation methods and curing conditions in each coating project.

• Clearly written, work scope requirements covering:

– Clear definition of mill expectations for job quality and a clear understanding of those expectations by those performing the work. (Incentives for exceeding the quality and productivity expectations should be considered.)

– Identification and location of project work.

– A tailored scope of work surfaces to be coated for each specific project.

– Services provided by the mill, including storage, parking, and utilities.

– Debris containment, work enclosure, and process area access requirements.

– Specific project schedule requirements.

– Pre-job conference participation requirements for the contractor or in-house coating crew, mill personnel,

Materials handling, waste disposal, and clean-up requirements.

• Clearly written coating specifications covering:

– Specific coating systems and products.

– Definitions and reference standards used in the coating specifications.

– Surface preparation methods.

– Requirements for degree of cleanliness and surface profile for each type of substrate.

– Coating application requirements, including film thickness values.

– Curing requirements and verification methods. Quality control requirements, including testing procedures and test frequencies.

• Prequalification of the contractor(s) to ensure an experienced and competent workforce. If mill personnel do the coating work, the same requirements for competency and experience should apply. This includes requiring experienced and diligent project supervision.

• Structured communication and coordination of work among the mill program coordinator, mill management, mill operating department personnel, and the contractor to optimize scheduling, productivity, and quality of all project work.

• Thorough documentation of all program-related correspondence and reports, work performance records, QC inspections, etc.

Coating Condition Surveys

The format of the condition survey can be tailored to each mill's needs. Normal page format is recommended for easy field use by surveyors and contractors. A maintenance coating condition survey should be repeated often enough (at least biannually) to set coating priorities and to ensure that ongoing program progress is reflected on the spreadsheets. Regular surveys are an important program management tool. They are key to lowering costs by allowing more areas to attain Grade 1 status and by preventing surface areas from degrading from preventive maintenance Grade 1 and Grade 2 conditions to the far more costly recoating (Grade 3) condition. In fact, maximizing the extent of spot-coating maintenance (i.e., small-scale PM) and minimizing more costly, large-scale PM and coating replacement work is the key to cost-effectively extending the useful life of coating systems.

Every coating condition survey must produce the following:

A. A recent plot plan and legible, reasonably current drawings of the structures and floors in the mill areas where steel structures will be painted.

B. A spreadsheet that lists, by department number, building number, or building matrix number (i.e., column lines east to west or north to south and floor elevation), all structural steel, tanks (exterior), piping, pipe supports, stacks, ductworks, and other steel structures.

C. A listing, cross-referenced to each mill area as denoted above, describing the physical, chemical, and thermal exposure conditions.

D. The spreadsheet in item B must indicate the generic type and product name, where known, of the existing coatings and their service age. If this information is not known, a coatings testing laboratory can usually identify the generic type of coating. The main reasons for knowing this are to avoid compatibility problems with new paint materials, which can be directly addressed by doing compatibility tests on the old coating, and to learn how that generic type of coating previously performed in that mill area.

E. A spreadsheet recording the coatings condition grading for each mill area and for each coated structure or component.

Coated Steel Condition Grading

Condition assessment should be based on the condition of the entire structural component, with the smallest unit area for assessment being about 200 ft^2 (20 m^2). All significant surface areas of painted steel that need corrosion protection should be assigned one of the following condition grades:

Grade 1: Small-Scale Preventive Maintenance (1-PM)

In Grade 1, the coatings are spot-repairable because coating deterioration covers no more than 15% of the total coated surface area if the failed spots are distributed randomly over the entire component. Grade 1 also applies where coating degradation affects up to 30% of the total surface area, but coating failure is concentrated in one or two local areas. The recommended tool for evaluation is SSPC-VIS-2, *Method of Evaluating Degree of Rusting on Painted Steel Surfaces* (also ASTM D 610-85). Coating failure includes blistering, peeling, cracking, pinpoint rusting, inter-coat delamination, etc.

Grade 2: Large-Scale Preventative Maintenance (2-PM)

In Grade 2, the coatings are repairable either by spot coating or localized coating replacement. Grade 2 coatings may also only require additional coating film thickness (topcoating) to upgrade protection for portions of the subject surfaces.

In these cases, more than 15% of the coated surfaces have broken down when spread out over the total area or more than 15% of the coated surfaces have failed, but are concentrated in a few localized areas. It also applies in areas where the original coatings are beginning to fail sporadically at over 20% of the coated surface and the existing coating system was applied too thin in areas when compared to the program film thickness specifications.

Grade 3: Coating Replacement (3-CR)

In Grade 3, the coatings need wholesale coating replacement because coating degradation exceeds the limits for Class 2.

Grade 4: Steel Replacement (4-SR)

In Grade 4, the steel has not been adequately protected by the coatings and is so badly corroded that its structural purpose is no longer assured. Typically, Class 4 steel is no longer coated and has lost more than 25% of its original section thickness.

Surface Preparation Considerations

As in all maintenance coating work, the surface preparation method must be based on available work time, environmental conditions, the type of coating system to be applied, and access limitations. Abrasive blast cleaning, even with careful containment, is not permitted in many mill areas to avoid abrasives contaminating products and damaging bearings.

As shown in the section on coating system recommendations, the coating systems for the four condition grades include various surface preparation methods and procedures, all of which are covered by at least one of these surface preparation standards:

- International Standard ISO 8504:1992. *Preparation of Steel Substrates Before Application of Paints and Related Products – Surface Preparation Methods*
- NACE Standard Recommended Practice RP-01. *Surface Preparation of Steel by Water Blasting*
- SSPC-SP 1. *Solvent Cleaning*
- SSPC-SP 2. *Hand Tool Cleaning*
- SSPC-SP 3. *Power Tool Cleaning*
- SSPC-SP 6/NACE 3. *Commercial Blast Cleaning*
- SSPC-SP 10/NACE 2. *Near-White Blast Cleaning*
- SSPC-SP 11. *Power Tool Cleaning to Bare Metal*
- SSPC-SP 15. *Commercial Grade Power Tool Cleaning*

Solvent cleaning in accordance with SSPC-SP 1 (or other aggressive degreasing methods) should be used to effectively remove non-water soluble greases or oils prior to proceeding with any of the other preparation methods.

It is important, to preserve the money invested in surface preparation by applying the primer or first coat of paint to all cleaned and prepared surfaces soon enough after cleaning to prevent rust bloom or surface contamination. Timing the application of primers and other coats of paint should be purposely arranged to minimize inter-coat contamination.

SSPC-VIS 1, *Visual Standard for Abrasive Blast Cleaned Steel* and SSPC-VIS 3, *Visual Standard*

for Power and Hand Tool Cleaned Steel, are good reference standards for assessing the effectiveness of surface preparation. SSPC Guide 3, *Guide to Safety in Paint Application*, SSPC Guide 61, *Containing Debris Generated During Paint Removal Operations*, and SSPC Guide 71, *Disposal of Lead Contaminated Surface Preparation Debris,* provide useful information relevant to most maintenance painting work.

Other Surface Preparation Methods

• Wet abrasive blast cleaning generally involves some combination of water and abrasive to clean and prepare steel surfaces. Its main value is to eliminate dust and airborne debris. Wet abrasive blast cleaning methods reduce containment costs and help decontaminate the surfaces by removing soluble salts. Adding solids to the water provides more "cutting power" and the most aggressive systems can remove tightly adhered rust scales. However, it helps to dislodge and fracture thick rust scales first with hammer blows or other tools. Corrosion inhibitors are often added to the water to delay flash rusting long enough for drying and primer application. Verify with the paint manufacturer that the coating system being used (first coat) is compatible with an inhibited surface. This topic is discussed in greater depth in a separate chapter of this book.

• Hydro-blasting with high and ultra-high pressure water blasting and no added abrasive material is generally cost-effective for maintenance coating work in many pulp and paper mills, particularly where large surface areas justify the higher equipment costs. These methods are most useful where grit contamination is prohibited, such as around paper machines, bleach washers, or pulp dryers. Hydro-blasting also decontaminates steel surfaces by removing soluble salts. Hydro-blasting methods do not change the profile of steel surfaces, they only reveal whatever profile exists under the rust or old coating. As with all wet cleaning methods, a corrosion inhibitor can be added to the water to prevent flash rusting.

• Less conventional blast cleaning methods include soda, dry ice, and soft media blast cleaning, also covered in separate chapters. These can be effective for special maintenance coating work on a limited basis, usually where no dust can be tolerated and only limited containment is possible. Dry ice and soda blast cleaning lack adequate cutting power to make these methods cost-effective for large surface areas. The soft media blasting method (using foam-encapsulated abrasives) can generate more cutting power, if the right medium is selected. However, this method is slower and more expensive than more conventional surface preparation methods.

Debris Containment

In mill coating work, containment of the surface preparation and coating application work is more often than not a critical requirement. Airborne rust scale, spent abrasive, and loose coating chips represent a high potential for contamination of mill processes, safety risks for personnel, or possible damage to rotating equipment. It is essential that proper containment be adequately planned and included in the cost estimates for all maintenance coating work. Containment can also assist in achieving proper ambient condition for coating work and allows the introduction of controlled heat to reduce cure times if appropriate.

Vacuum blast cleaning where the space around the nozzle is vacuum assisted to collect the abrasive and debris can be effective to eliminate the need for containment. Vacuum-assisted blast cleaning is slow, cumbersome, and expensive, but can be a useful tool in maintenance coating work in mills.

Soluble Salt Decontamination

The deposition, collection, and concentration of soluble salts such as chlorides and sulfates are commonplace on carbon steel surfaces in many areas of pulp and paper mills. If these soluble salts are not effectively removed by cleaning and surface preparation, they promote premature and widespread coating failure in the form of coating cracking or blistering. Soluble salt contamination is a frequent cause of coating failure in bleach plants, pulp mills, recovery boiler buildings, and paper machine areas.

It is very important to eliminate contaminating ions like chlorides and sulfates as part of surface preparation. Testing can be performed to detect the presence of these ions before maintenance coating work is done and to ensure they have been adequately removed by the surface preparation procedure. Simple, quantitative field test methods are readily available. More information can be found in

Maintenance Painting of Steel Structures in Pulp and Paper Mills available from TAPPI Press and in the chapter about soluble salts in this book.

Water washing with clean, warm water (120°F min.); steam cleaning, and hydro-blasting with clean water all are effective direct methods for removing soluble chloride and sulfate salts.

Coating New Steel

Coating new steel for new construction or replacement steel (coating condition grade 4-SR) is best accomplished under shop conditions with field touch-up after the steel is erected. Shop coating typically involves preparing the surfaces with centrifugal blasting equipment and applying the coatings under near-ideal, controlled conditions. Curing for recoat times and final cure can also be properly controlled under shop conditions. In new construction, as much coating should be shop-applied as practical.



Figure 1. Finish coating structural steel for a pulp and paper mill. Courtesy Tnemec Company, Inc.

Extra care must be taken when handling newly painted steel. The coatings should be allowed to fully cure prior to handling; the coated steel should be stored on proper dunnage, and nonmetallic straps should be used for tie-downs and hoisting and rigging.

Where welded connections are required for field erection, the steel should not be coated at least 4 in. away from the welds and should be masked to protect the surface preparation. Following erection, touch-up coating work can be performed in the field just like Class 1 maintenance coating work.

Shop-bolted connections should be prepared and coated in the shop. Field-bolted connections should be prepared and coated in the shop as specified in the engineering specifications. Faying surfaces are normally only primed in the shop. In some cases it makes more sense to do the entire topcoat application after the steel is erected, provided the job standards allow for this.



Figure 2. Shop priming new structural steel for a pulp and paper mill. Courtesy Tnemec Company, Inc.

Steel fabrication and coating shops should be carefully monitored by the mill coatings program coordinator or the mill representative via inspection visits to ensure quality standards are met for all coating-related procedures.

Generic Coating Material Recommendations

While there are many generic coating materials that can provide effective corrosion protection for carbon steel in various mill environments, damp or wet operating conditions and surface preparation limitations often require the use of surface-tolerant primers. Also, experience in multiple mills has shown that 5 or 6 products are very adequate for steel in most applications. Keeping the specified coating types to a minimum further uncomplicates the maintenance coating program. The performance track record of many mills and associated coating suppliers is the basis for the coating types recommended below. Specific corrosive environments may require other specialty coating selections.

Primers for Maintenance Coating

Aluminum-filled, polyamide-cured, epoxy mastic primers applied by brush or spray to a minimum of 6 mils dry film thickness (DFT) are good maintenance coating primers. These products are formulated to tolerate moderate amounts of tightly adhered rust and slight dampness. They have good adhesion to a wide variety of tightly adhered, existing coatings, including epoxies, urethanes, and alkyds. Such mastic primers therefore also work well as tie-coats for the topcoats recommended in this chapter.



Figure 3. Field application of zinc-rich organic epoxy primer on exterior of a bleach tower in a pulp mill. Courtesy Tnemec Company, Inc.

Organic zinc-rich primers based on two-component epoxy or polyurethane polymer binders are also effective maintenance coating primers. They typically have shorter recoat times than the epoxy mastic primers and their comparable topcoated performance to the mastics makes them an especially good choice when recoat time is constrained. Organic zinc-rich primers are brush or spray applied at 3 to 5 mils DFT. These systems should not be used where the substrate is extremely rough or pitted due to their lower film build characteristics. **Note:** Inorganic zinc-rich primers are not suitable for maintenance coating work in mills.

Primers for New Steel

Both the aluminum-filled epoxy mastic primers and organic zinc-rich primers (epoxy- and polyurethane-based) described above for maintenance coating work are suitable and recommended for new steel coated in the shop. In general, 3–4 mils DFT of an organic zinc-rich primer is less costly and better suited to shop application than an epoxy mastic primer.

In addition to the zinc or aluminum-filled primers, inhibited polyamide-cured epoxy primers, without aluminum or zinc additions, are generally appropriate for new steel. These primers are typically applied to a minimum of 4.0 mils DFT.

Topcoats for Maintenance Coating

General considerations. The topcoat always should be tailored to the environmental conditions, most notably whether they are acidic or not. In general, two-component polyurethane topcoats generally provide more chemical resistance than polyamide epoxy topcoats at pHs below 4 and less resistance in more alkaline conditions, i.e., at pHs above 10.

Secondary considerations are the amount of moisture present during application and curing conditions, which works against some polyurethanes, and aversion to chalking of the topcoat, which slowly affects most epoxy topcoats exposed to ultraviolet light and strong sunlight.

Where the thickness of an existing coating that otherwise is in good condition is too low—typically defined as less than 80% of the program-specified thickness—the entire surface should be topcoated using Grade 1-PM system recommendations. Such uniform topcoating requires sanding, abrasion, or other surface preparation, including optional use of a tie-coat, to achieve adequate inter-coat adhesion, which should be verified by testing.

Table 1. Surface Preparation and Coating System by Grade.

	Surface Preparation	Coating System
Grade 1–PM: Small-Scale Preventative Maintenance (PM)	Remove soluble salts from all surfaces. Remove oils and greases, per SSPC-SP 1. Power tool clean to bare metal and tight coatings, in accordance with SSPC-SP 11. (Clean difficult access areas per SSPC-SP 2 or SSPC-SP 3.)	Primer: Aluminum-filled, polyamide epoxy mastic, at 5 mils DFT min. or organic zinc-rich (polyamide epoxy), at 3-5 mils DFT. Second coat: pH < 5: amine adduct epoxy top coat at 5-7 mils DFT. Consider polyester polyurethane at 2-3 mils DFT for gloss retention. pH > 4: polyamide epoxy at 4-5 mils DFT. Consider 2-3 mils DFT acrylic polyurethane for gloss retention, up to pH 11. Third coat (optional):[1, 2] pH < 5: amine adduct epoxy top coat at 5-7 mils DFT. An alternative third coat for gloss retention is 2-3 mils DFT polyester polyurethane. pH > 4: polyamide epoxy, at 4-5 mils DFT. Alternative third coats for gloss retention are 2-3 mils DFT acrylic polyurethane, up to pH 11, or an additional 3-4 mils DFT of a more glossy polyamide epoxy where curing conditions do not suit polyurethanes.
Grade 2-PM: Large-Scale Preventative Maintenance (PM)	Remove soluble salts from all surfaces. Remove oils and greases, per SSPC-SP 1. Power tool clean to bare metal and tight coatings, in accordance with SSPC-SP 11. (Clean difficult access areas per SSPC-SP 2 or SSPC-SP 3.) Use hydro-blasting (or wet abrasive blast cleaning with appropriate containment) as conditions dictate. Dry abrasive blast clean to SSPC-SP 6/NACE 3 where this is permissible.	Same as for Grade 1-PM.
Grade 3-CR: Coating Replacement (CR)	Decontaminate and degrease all surfaces, per SSPC-SP 1. Use hydro-blasting or wet abrasive blast cleaning (with appropriate containment) as conditions dictate to remove all rust and old coatings, aiming for surface cleanliness equivalent to commercial blast, SSPC-SP 6/NACE 3. Dry abrasive blast clean to SSPCSP 6/NACE 3 where this is permissible.	Same as for Grade 1-PM, applying complete two- or three-coat system over all surfaces.
Grade 4-SR: Steel Replacement (SR)	In the shop, abrasive blast-clean per SSPC-SP 6/NACE 3, with a 2-3 mil anchor pattern. If new steel is coated in the field, cleaning and surface preparation should be the same as for Grade 3-CR.	Primer: (See chapter section about primers for new steel) Organic zinc rich epoxy, 3-4 mils DFT Second (and third) coat: Same as for Grade 1-PM.

1 The high performance epoxy and polyurethane coatings listed here both perform very well over the 4-10 pH range. This makes it unnecessary to define a single pH value as the dividing point for using epoxy or polyurethane and is why the pH ranges overlap.
2 A two-coat system with 10 mil DFT total min. is a good "workhorse" system for ordinary conditions. A three-coat system with a minimum DFT of 14 mils is for more aggressive service conditions.

A three-coat system should be considered where exposure conditions are more aggressive, with frequent splashing, spillage, or wetting and drying. The minimum DFT for a three-coat system should be 12 mils.

The most resistant three-coat system usually consists of the selected primer; an intermediate coat of polyamide epoxy; and a suitable topcoat, typically a gloss epoxy or acrylic, aliphatic polyurethane for acidic conditions. As noted above, two-component polyurethanes are moisture-sensitive when they cure, so if the curing conditions cannot be adequately controlled, the third coat should be 3–4 mils DFT of gloss polyamide epoxy.

Spray application methods typically produce more uniform, better performing coats of paint than can be obtained with brush or roller application. It also is generally good practice with multiple coat (2 or 3) systems for each coat to have a significantly different color. This helps ensure proper coverage of the previous coat and also provides a built-in inspection tool, allowing each coat to be differentiated later if need be. Using lighter colors rather than dark colors for topcoats makes it easier to evaluate the coating system application quality and to see rust bleed-through and other coating anomalies later. (Some facilities use dark topcoats precisely for the opposite reasons.)

Non-acidic environments—pH above 4. A high-build, two-component polyamide epoxy topcoat is recommended in most interior mill environments if the pH is above 4. The topcoat should be applied between 4 and 5 mils DFT. The total minimum DFT for two-coat systems should be 8 mils. Chalking can be avoided by using a two-component, acrylic aliphatic polyurethane

topcoat. Urethane topcoats are typically thinner than epoxies, with a DFT of 2-3 mils per coat.

Acidic environments— pH below 5. In acidic exposure conditions, the chemical resistance of an amine adduct-cured (or amidoamine-cured) epoxy and a two-component polyester aliphatic polyurethane are similar. The epoxies are higher build and typically are applied at 5-7 mils DFT per coat. Polyurethane coatings normally are lower build than epoxies and generally are applied between 2-4 mils DFT per coat.

If exposure conditions warrant a three-coat system, the polyurethane topcoat is usually applied over an intermediate coat of either amine adduct-cured (or amidoamine-cured) epoxy. A polyester aliphatic polyurethane topcoat is better suited for acidic conditions (under dry curing conditions) where chalking resistance also is an important specification requirement.

Topcoats for New Steel

The same topcoats recommended for maintenance coatings are appropriate for coating new steel. Most new steel is coated in controlled, "shop" conditions.

For acidic exposure conditions, use an amine adduct or amidoamine type epoxy topcoat. Where conditions are severe enough to warrant three coats, apply two coats of amine adduct-cured epoxy for a minimum total system DFT of 14 mils. For gloss retention, the final coat should be a polyester polyurethane applied over the primer or to a polyamide epoxy intermediate coat for more severe conditions. (An amine adduct-cured epoxy intermediate coat is more chemically resistant but costs more.)

Quality Control

All coating work covered by the maintenance coating program and new construction in the mill should include a strong emphasis on quality control. Experience, claims, certifications, and references should be checked out, mainly to verify that the contractor's workforce has performed similar coating work in the previous 3-5 years. These same requirements also should apply to in-house coating crews who do projects for the maintenance coating program. It is also important to ensure that the painting workforce is fully trained in mill safety and painter safety requirements and practices.

The main focus of QC inspections should be verifying the specified quality requirements and associated recommendations from the selected coating supplier are met. QC inspection should only be performed by trained and experienced coatings inspectors who are familiar with the coating maintenance work being performed. Mill personnel or third party inspectors can be employed. All test instruments used should be properly calibrated and proper calibration documentation must be available. Scheduling and planning of project work and QC activities must be carefully planned to ensure access to all on-going work for critical inspection hold points.

QC inspections should include:

- Test for removal of grease, oil, and process contaminants, using visual inspection and the white cloth, wipe test.
- Inspect degree of cleanliness of surface preparation using SSPC-VIS 1. Test surface profile using the plastic film replication technique per ASTM D 4417.
- Inspect for removal of sharp corners, edges, weld spatter, slivers, etc.
- Test for soluble salt contamination (chlorides and sulfates) before and after water washing, hydroblasting, or other cleaning methods.
- Perform ambient temperature and humidity tests and surface temperature tests frequently during and following coating application work.
- Perform wet film thickness measurements routinely during coating application.
- Perform dry film thickness measurements following adequate cure time, in accordance with ASTM D 1186.
- Check that coatings have properly cured per the coating manufacturer's recommendations.
- Visually inspect finished coating work for unacceptable defects such as excessive runs, sags, pinholes, holidays, blisters, overspray, or embedded debris.

Documentation of quality control inspection and testing must be diligently and systematically performed. Daily, weekly, and monthly inspection reports should be prepared for large projects. Reporting should cover QC test and inspection findings; nonconforming work and rework instructions; product quantities used; productivity data; and lost-time incidents. A sensible, enforceable, written warranty should be negotiated by the mill and the contractor to ensure quality work is emphasized.

Summary

Pulp and paper mills can achieve substantially reduced costs for asset maintenance and also improve personnel safety by establishing and fully implementing a systematic maintenance coating program. The program must entail systematic condition surveys to optimize project management. Lowest program costs are achieved by maximizing the percentage of coated steel surfaces retained in the Grade 1-PM condition. Using the recommendations for maintenance coating on new steel surfaces should enhance the overall cost-effectiveness of all protective coatings.

Acknowledgements

The authors and SSPC gratefully acknowledge Web Chandler's peer review of this document.

About the Authors

Randy Nixon

Randy Nixon is the president and founder of Corrosion Probe, Inc., which provides its clients with design, engineering, and testing/inspection services in civil/structural, mechanical, and corrosion materials engineering. The chief technical editor of SSPC's *The Fundamentals of Cleaning and Coating Concrete,* he is an active member of SSPC, WEF, TAPPI, ACI, NACE, ICRI, ASTM, and BIA.

David C. Bennett

Dave Bennett is a principal engineer at Mechanical and Materials Engineering. He has 30 years experience in materials and corrosion engineering, principally in the pulp and paper industry. Mr. Bennett is known for his expertise in pressure vessel and tank integrity management. He has extensive experience as a consulting engineer and as in internal staff consultant and has coauthored TAPPI's *Short Course on Solving Corrosion Problems in Pulp and Paper Mills.* He has authored more than 30 papers on corrosion and materials topics and cowrote the *Concrete Handbook: A Practical Guide for Protecting and Improving the Durability of Concrete in Pulp and Paper Mills* and *Guidelines for Maintenance Painting of Steel Structures in Pulp and Paper Mills,* both for TAPPI Press.

Chapter 6.9
Painting Hydraulic Structures

Alfred D. Beitelman

Introduction

Corrosion protection and the aesthetic appearance of exposed steel surfaces are two key aspects of maintaining hydraulic structures. There are several important reasons for this:

• When allowed to persist, inadequate corrosion protection can cost the government and private sectors millions of dollars per year due to the premature need for recoating, major structural repairs, or even total replacement.

• Both the application and removal of protective coatings can have significant implications for environmental quality and worker safety, raising concerns about environmental compliance and public health.

• Unsightly coatings or conspicuous corrosion can undermine public confidence in hydraulic structures, such as locks and dams, which are often highly visible projects that provide crucial services to industry, government, and large local or regional populations **(see Figure 1)**.

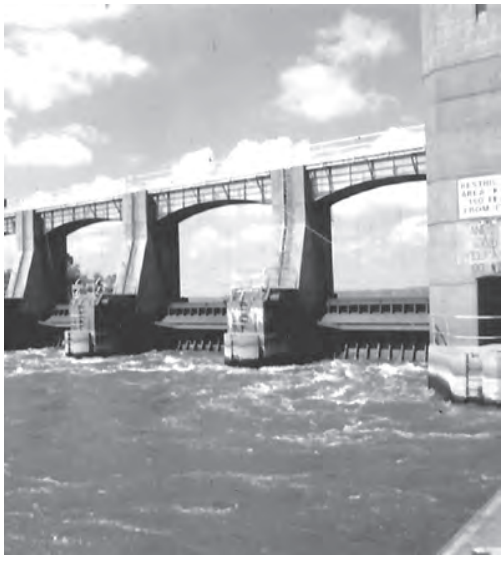


Figure 1. Hydraulic structures on the Mississippi River has as much as 500,000 ft^2 (46450 m^2) of steel surface per installation requiring protective coatings.

Engineers understand both the importance of corrosion protection, as well as the possibility that normal coating maintenance may be postponed due to economic constraints. Often, in order to add a safety factor that will help to compensate for inadequate coating maintenance, engineers will over-design structures and members to better withstand corrosion-related material losses.

It can be seen, then, that corrosion protection poses difficult challenges for the designers and operators of hydraulic structures. Inadequate corrosion protection and inappropriate coating selection can cause an intolerable waste of natural resources and money. However, excessively high safety factors or coating standards (both in terms of corrosion protection and aesthetic appearance) are also wasteful. Therefore, a major objective of corrosion prevention and coating maintenance activities should be to *optimize* protection through proper material selection and effective coating application techniques.

Today, as in the past, the coatings on hydraulic structures are subjected to a wide variety of environmental conditions. Exposures may range from temperate inland atmospheres to aggressive marine fogs infused with high chloride content. Sheet piles and lock gates may be partially or fully immersed either in fresh water or salt water.

Additional challenges are posed by the physical impact of floating ice and debris, which can prematurely destroy protective coatings, as well as stringent environmental regulations that limit the selection or application of some products. Although many available paints can withstand the severe requirements described above, real-world coating performance is also highly dependent on effective application in the field. Thus, the ideal coating is one that: (1) is formulated to both withstand the environmental exposure at a given site and comply with environmental regulations, (2) is easy to apply properly in the field, and (3) maintains its protective properties and appearance in spite of adverse service conditions.

Topics discussed in this chapter address many aspects of coatings for steel hydraulic structures, however coatings formulated for the concrete and other nonmetallic portions of hydraulic structures and coatings for buried structures are not discussed. The term "hydraulic structures" is used in a broad sense to mean not only the locks and dams associated with navigation, flood control, and hydropower, but also the service bridges, piping systems, machinery, and other items associated with these structures. The metallic portions of these structures all share a common problem: corrosion. The main purpose of coating is to prevent or delay corrosion. However, considering the high visibility of these structures, it is also important to recognize the role of aesthetics when selecting and applying paints and coatings for hydraulic structures.

Government Regulations

In the United States, health, safety, and environmental regulations of the past half-century have had a significant impact on the coatings industry. Most coatings applied to hydraulic structures are applied in the field. Coatings applied in the field are usually regulated by environmental regulations in a class called "architectural coatings." The early architectural coatings regulations were enacted at the state or local level. They placed limits on the types of solvents used in these coatings. Later, regulations placed limits on the total amount of volatile organic compounds (VOCs) in various classes of coatings. It was not until 1999 that the first federal architectural coatings regulation went into effect. Until that time, state and local regulations were seldom applied over a broad area, and often were in effect only for specific cities or counties. This inconsistency resulted in the development of dual formulations for coatings—one that met the restrictive regulations, and another that was either less expensive or a more durable product than the regulation formulation. When used on immersed areas of hydraulic structures the regulation-compliant products often have service lives of less than half those of the standard products.

The VOC regulations enacted in the late 1970s and early 1980s were also very regional, and their requirements varied widely. The regulations defined a number of categories, each of which could have a different VOC requirement. Most of the regulations exempted architectural paints, so there was little impact on the painting of existing hydraulic structures. However, when new structures were to be constructed, fabricators often wanted to coat steel components in the fabrication shop. Shop painting was often covered under "miscellaneous metal parts" in the VOC regulations. If the shop was located in an area where the coating of miscellaneous metal parts was regulated, either a compliant high-solids coating had to be used or the subsection had to be installed and painted in the field. On large structures, this often led to the use of different kinds of coating systems with different life expectancies.

The 1999 federal architectural VOC regulation applied only to manufacturers of coatings. It included a large number of categories. The category for "impacted immersion coatings" had a VOC limit high enough that lacquer-type coatings could be used for this application. Under this category, a manufacturer could market a high-VOC coating for use on a tainter gate but the coating could not be marketed for use on the service bridge above that gate.

The environmental regulations associated with hazardous waste, as well as those associated with worker safety, have had a major impact on all field painting operations including those associated with hydraulic structures. In the past, many of the coatings applied to machinery, service bridges, and other atmospherically exposed steel equipment contained lead. Lead primers were often applied directly over intact mill scale when the structure was erected. Occasional maintenance has allowed many of these original coating systems to remain in place for well over 60 years. Although the new regulations did not forbid the continued application of lead-based coatings, the industry essentially discontinued their use by the mid-1970s due to both worker safety concerns and the expensive anticipated cost of removing deteriorated systems.

The worker safety and waste disposal regulations have also had an impact on the abrasives used for surface preparation. Abrasive blasting using river sand or other silica-containing abrasives was common on hydraulic structures when the spent abrasive could be allowed to fall back into the river. Worker exposure to silica was low when the wind was free to blow the dust away. When requirements for proper containment and disposal came into effect, compliance with regulations for worker exposure to silica became very costly. This led to more extensive use of slag abrasives. Some contractors even began finding it more cost-

effective to use recyclable steel grit in order to reduce their hazardous waste costs.

Design Considerations

Hydraulic structures are, for the most part, simply steel structures that require the same kinds of industry-accepted design considerations as any other structure. Yet the fact that these structures are often subject to constant immersion makes certain of these considerations critical for proper corrosion protection. Engineers must not design areas that are inaccessible for proper surface preparation and paint application, nor allow skip welds, sheared edges, or weld spatter. Extensive use of corrosion-resistant metals without proper electrical isolation can actually cause accelerated corrosion of mild steel. Even cathodic protection can destroy a coating system if it has not properly designed and maintained. When coatings are to be replaced the engineer must make sure that sharp edges of pits and corroded members are properly rounded. In some instances, it may even be necessary to fill pitted areas with weld metal or other compounds to improve water flow or to restore structural integrity.

Surface Preparation

The required level of surface preparation is dictated both by the exposure and the type of coating being applied. On hydraulic structures, the most critical exposure is immersion. Modern coatings require a degree of cleaning that removes all surface contamination that might result in osmotic blistering or a loss of coating adhesion. Abrasive blasting is an additional requirement for proper mechanical adhesion of most coatings. Research has shown that coatings have a much lower adhesion to a surface prepared with steel shot than to one prepared with steel grit.[1,2] Virtually any other abrasive may be used if it produces the required profile and does not deposit a residue on the surface that is water-soluble or is otherwise incompatible with the required coating. Blast additives designed to reduce dusting or lead extractability are subject to these same requirements when used on hydraulic structures.

The degree of cleaning and the required profile vary somewhat based on the specific coating, but most coatings for immersion will perform satisfactorily with a near-white-metal blast having an angular profile of at least 2 mils (50µ). Often structure owners specify a higher grade of cleanliness because of their experience with the quality of cleanliness actually attained with manually operated blast equipment in the field environment. By specifying a higher grade of cleanliness, unacceptable residues of corrosion or coatings requiring reblasting and revacuuming are less common after the first blowdown and inspection.

Wet blasting, or water blasting, is not common for surfaces that will be in constant immersion. Wet-blasted surfaces flash rust very quickly, resulting in surface contamination that would cause coating blistering after immersion. Corrosion inhibitors, whether added to the water during blasting or used as a wash immediately after blasting, produce mixed results depending on the mechanism they use to inhibit corrosion as well as their compatibility with the coating system. Inhibitors that leave a water-soluble residue on the surface should not be used because of the potential for osmotic blistering. Corrosion-inhibiting products that change the chemistry of the steel surface may prevent certain chemical reactions between the coating and substrate necessary for proper adhesion. Coating manufacturers are often reluctant to guarantee their products when applied to immersion surfaces that have been pretreated with a corrosion inhibitor.

The amount of surface preparation for atmospheric areas of hydraulic structures varies widely. On new steel, coatings are routinely applied directly over mill scale cleaned with hand tools or power tools. Higher-performance coatings are often applied over some level of abrasive blast cleaning as required by the specific coating. When touch-up work is to be performed, spot-blasting is common. However, the practice of performing an overall brush blast of an existing coating in preparation for an overall topcoat often leads to failure. It is often found that contractors use the same abrasive for brush blasting as for the thorough cleaning of corrosion spots. This practice damages the adhesion of many intact coating systems, resulting in early failure of the newly topcoated system. Water blasting is an effective method for either spot cleaning or total coating removal, but on structures with lap joints or riveted construction, additional time must be allowed for the water to escape from joints. Failure to allow sufficient time results in early failure of the new coating in the areas of the joints.

Coating Application

The application equipment used on hydraulic structures is dictated by the type of coating to be

applied, as well as by the configuration of the surface. Airless spray is used to apply the greatest volume of epoxies, urethanes, and oil-based coatings. This equipment operates at high pressure, allowing painters to use long hoses and work at various elevations on the structure without significant pressure changes or inconsistencies in spray characteristics. However, while airless spray equipment may be ideal for efficiently applying a uniform coating to a large, flat surface such as the skin of a gate, the same equipment often results in excessive thickness, runs, or sags when applying paint to areas having complex structural members, tight angles, rivets, or other surface irregularities.

The occasional run or sag can easily be brushed out, but coatings applied at excessive thicknesses often result in improper cure, solvent entrapment, and other coating defects that can have a significant impact the life of the coating system.

Solution vinyl coatings (lacquers) are still used extensively on gates of hydraulic structures that are subjected to a substantial amount of impact from floating debris. In order for these coatings to attain their high durability quickly, they must be formulated and thinned with solvents that evaporate from the coatings rapidly. In fact, these coatings dry so rapidly that any air introduced into the film becomes trapped, resulting in either a honeycombed film or one containing pinholes. Conventional (air atomization) spray equipment is best suited for these coatings.

When compared to airless equipment, conventional spray equipment produces finer particles that travel at a much lower velocity resulting in less splashing and fewer problems with pinholes and entrapped air. The controls on the gun also enable the painter to quickly make adjustments, allowing the gun to be moved to within 3–4 inches (8–10 cm) of the substrate. This feature allows the painter to spray in very tight areas and to maintain a uniform spray pattern in areas of high air currents that are common on the face of large gates. An additional benefit of conventional spray guns is the capability of using them to blow the last traces of abrasives from the surface just prior to application of the first coat of paint.

It is often desirable to perform maintenance on lock gates in the winter, when the river is closed to traffic. For winter applications, vinyl coatings can be applied using conventional hot spray equipment. This equipment heats the paint to about 160–180°F (70–80°C). Typically, by the time the paint reaches the gun its temperature has dropped significantly but its viscosity remains low enough for proper atomization. Using this type of equipment, solution vinyl paints have been applied at temperatures as low as -20°F (-29°C).

Plural-component spray equipment has been used in a number of field applications, usually with less than satisfactory results. Problems are often encountered in maintaining proper mixing ratios. Other problems relate to the inability to properly coat complex areas of a structure with the large gun and multiple stiff hoses. Use of this equipment in a shop environment has been more satisfactory, but the application of even a marginally uniform coating thickness on complex structures remains a challenge.

Coating Systems

Coal Tar Enamel

Coal tar enamel dates back centuries, and was used almost exclusively on hydraulic structures constructed in the late 1800s and early 1900s. The original coatings applied to gates of the Panama Canal (officially opened in 1914) were still providing near-perfect protection on interior surfaces of gate chambers after 75 years. The same coating system has provided excellent protection on buried pipes for well over 100 years.

Today coal tar enamel continues to be a common system on buried tanks, pipes, conduits, and other items that can be coated in a paint shop. The product is still applied in the field overseas, but field application in the United States is rare. The reason for this change is largely based on safety considerations and on a lack of skilled applicators. The hot enamel, application temperature 450–500°F (230–260°C), released oils that were irritating and hazardous to workers, and the open-flame heating often resulted in fire.

Some of the original systems are still in service on the interiors of penstocks and surge tanks as well as other structures not exposed to either sunlight or the physical abuse of debris-filled water. Repair of minor damage is frequently accomplished by spot-blasting and application of a coal tar epoxy system. Total removal of the coating with common dry abrasive blasting is very slow. High-pressure water blasting followed by dry abrasive blast to remove the remaining coating and produce a suitable surface

profile is more efficient. Some contractors have found it cost-efficient to remove most of the coating manually by shattering it with ball-peen hammers before dry abrasive blasting. On some projects where excessive coating buildups are often found in horizontal structural members and removal by any method would be very labor-intensive, the coating has been allowed to remain and was topcoated with either vinyl or coal tar epoxy. In these areas the intercoat adhesion has been satisfactory and no failures have been noted.

Whenever coal tar enamel is removed from a surface by abrasive blasting, some residual tar remains embedded in the surface profile. Even a white metal blasted surface will have a somewhat dark appearance. Light-colored replacement coatings will usually cause this tar to bleed, resulting in a brownish hue. Although the result may be aesthetically undesirable, it has not been found to cause any reduced performance in either vinyl or epoxy replacement coatings.

Coal Tar Mastic

Cold-applied coal tar mastic may be specified as SSPC Paint 33. Unlike coal tar enamel, this product contains solvents and can be easily applied by unskilled labor. It is usually applied with minimal surface preparation and without an additional primer. The coating thickness as well as its moisture resistance is considerably less than that achieved by hot-applied product. Although the coating can withstand immersion, its chief applications on hydraulic structures are in areas of high humidity and condensation, such as ferrous surfaces below the operating floor of pumping stations, in gate wells, and in surge tanks. The coating is occasionally used for added protection on buried galvanized culverts along flood-control levies and other buried items that can be afforded suitable protection with this low-coat material.

Coal Tar Epoxy

Coal tar epoxy may be specified as SSPC Paint 16. As the name indicates, this is an epoxy coating that contains coal tar. Although it can be applied directly to an abrasive-blasted surface, it is commonly applied over a zinc or non-zinc epoxy primer in order to increase adhesion and reduce rust undercutting at breaks in the coating. The coating is used extensively in immersion in both fresh water, salt water, and water made highly corrosive by intense industrial contamination, sewage, or mine discharge. It is also used on buried structures.

Coal tar epoxy has provided long-term service on interior surfaces of flooded compartments, spiral (turbine) cases, penstocks, and other large-diameter, low-to-moderate-velocity water conduits, and on exposed ferrous surfaces in dewatering and drainage sumps. It affords excellent protection to the exterior steel surfaces of buried tanks and pipe, but is not normally specified on small- or medium-diameter pipe that can be coated in the shop at reasonable cost with hot-applied coal tar enamel or some other system more compatible with high-production shop coating equipment. It is routinely specified for underground, underwater, and incidental atmospheric-exposed sections of inland steel piling, and is also used on sector gates, steel piling, and other structures immersed in seawater and diluted seawater.

Coal tar epoxy coating becomes quite hard and is not significantly damaged by fouling organisms. Therefore, anti-fouling coats are not necessary except for operational reasons such as prevention of weight increase, surface roughness, or repainting difficulties.

Coal tar epoxy also adheres well to clean, sound concrete and has good resistance to many chemicals, so it is very useful on concrete surfaces that contact sewage and other materials tending to cause chemical damage. When used on concrete exposed to such environments, the surface preparation consists of light blast cleaning to etch surfaces and remove contaminants.

Damaged areas of coal tar epoxy are easily repaired by spot-blasting the damaged area and then patching with the same material. The spot-blasting will suitably abrade both the substrate and the surrounding coating for proper adhesion. In applications where the black color of the coal tar is undesirable, it can often be topcoated with aluminum epoxy mastic (provided the mastic is resistant to the exposure conditions in the area). Topcoating with most coatings usually causes the tar to bleed, resulting in a brownish appearance.

Problems with coal tar epoxies are few. As with most epoxies, intercoat adhesion to coatings that have fully cured is poor. Experience has shown that under the most extreme conditions it is desirable to apply both coats of a two-coat system in the same day. This procedure greatly reduces concerns about intercoat adhesion while the high temperatures rapidly drive off the solvent, eliminating solvent entrapment

concerns. In cases where the recoat window has been exceeded, the applicator can re-establish proper adhesion conditions either by brush blasting to roughen the surface or using a strong solvent to soften the surface. However, both procedures present challenges. Brush blasting is more common, but it is difficult to avoid damaging good coatings in complex areas of structures. The strong solvents are very toxic; they cannot be allowed to puddle but must be topcoated before they completely evaporate and the epoxy re-hardens. Another problem with coal tar epoxy is that high temperatures reduce pot life. To combat this problem, applicators keep the mixed paint in a shaded area, and in extreme conditions they immerse the paint pot in a container of cool water.

Another problem, more common with amine-cured epoxies than with polyamides, is blushing. Blush is usually caused by applying the paint in cool or damp environments, which are common when painting along rivers and in sump areas. Under these conditions, some of the catalyst may migrate to the surface of the coating. The coating still cures satisfactorily, but if the blush is on an intermediate coat it must be removed for proper adhesion of the topcoat.

Conventional Epoxy Coatings

Conventional epoxy coatings may be specified as SSPC Paint 22, or by using government specification MIL-DTL-24441. Private industry also offers a wide range of proprietary epoxy coatings that may or may not meet the requirements of these specifications. One of the significant differences in epoxy coatings is the catalyst or curing agent employed. Two commonly used catalysts for field-applied coatings are amines and polyamides. Amine-cured epoxies tend to be harder and more chemical resistant while polyamide-cured epoxies tend to be more water-resistant and more flexible. For this reason, polyamide-cured products are more common on hydraulic structures. Polyamide-cured epoxies have the superior chalk resistance and re-coatability, but epoxies generally are not rated highly for either of these characteristics.

Epoxies present a number of problems when used on hydraulic structures. Chalking due to sunlight is not a problem in immersion, but above the waterline it can result in the loss of 1 mil (25 µm) of amine-cured coating or 0.5 mil (12.5 µm) of polyamide-cured coating per year. To combat this problem, atmospheric areas of epoxy are usually topcoated with a UV-resistant coating. After curing normally, epoxies develop a hardness and chemical resistance such that neither additional coats of epoxy nor any other coating will adhere properly to them. Under the hot summer sun, this degree of curing can take place in a very short period of time, in some cases requiring that a topcoat be applied the same day as the previous coat. The hardness also results in a tendency for the coating to shatter when impacted by floating debris. Solvent entrapment, a common problem caused by excessively heavy application, is difficult to avoid when applying an epoxy onto the complex, detailed surfaces of hydraulic structures, many of which are riveted construction **(see Figure 2)**.



Figure 2. Complex surfaces on the structural side of miter and lift gates create challenges for both blasters and painters.

The effect of solvent entrapment in atmospherically exposed coatings may be increased porosity, but in immersion the effect may be blistering and early failure. The low and high application temperature limitations of epoxies have the effect of reducing the amount of time available to apply the coating during the summer heat and reducing the painting season as temperatures drop. Even with all these problems, epoxies remain the most widely used coatings for service in immersion and high-humidity areas.

The air pollution regulations of the past several decades have spurred manufacturers to modify conventional epoxy formulation. High-solids epoxies and 100% solids products are becoming more common. Formulators often develop the higher solids

content by using lower molecular weight epoxies and catalysts. While this allows reduction of the amount of solvent in the coatings, it also often reduces water resistance. As a result, many of these new products provide satisfactory service in atmospheric exposures on hydraulic structures but have significantly reduced service lives on immersed areas.

For most applications, the Army Corps of Engineers uses epoxy zinc primers under conventional epoxy topcoats. Where sunlight may cause unacceptable chalking, a urethane topcoat is applied, adding a significant expense to the system. These coating systems are commonly used for atmospherically exposed areas of service bridges, tanks, penstocks, and similar structures that require high performance and are visible to the public. In immersion applications, conventional epoxies do not perform as well as coal tar epoxy systems. They are chosen, however, because of their lighter color for both for aesthetics and for better visibility in poorly lit recesses of structures.

Polyurethane

Polyurethane, often simply referred to as urethane, is perhaps the most versatile resin used in the coatings industry. Polyurethane coatings can range from extremely hard to very soft, brittle to elastomeric, and water sensitive to very water resistant. They may be easy to apply or may require plural component application equipment and licensed applicators. They are often more costly than other coatings, but have properties that other coatings cannot match. Perhaps their most well known property is resistance to UV degradation. Two-component aliphatic urethanes are commonly applied as topcoats over conventional epoxy systems that are exposed to sunlight on surge tanks, penstocks, gates, cranes, and service bridges.

There are variations in aliphatic urethanes. Specifications such as MIL-PRF-85285 and SSPC Paint 36 do not directly specify the resin system to be used. However, in order to meet the more stringent requirements of the government specification, manufacturers commonly use a polyester resin, whereas they can use a less costly acrylic resin to meet the requirements of the SSPC specification. The polyester resin is more highly cross-linked than the acrylic resin, and is therefore tougher and more solvent-resistant. It performs somewhat better in conditions of physical abuse, but is very difficult to topcoat after curing for as little as several days. When used on hydraulic structures for the simple purpose of providing UV protection to underlying coatings, properly formulated urethanes with different resins are essentially equal.

Fast-reacting two-component urethanes have been applied to hydraulic structures with plural-component spray equipment on several occasions. These are highly cross-linked materials and were used on high-abrasion areas of dam gates. The lack of solvents and rapid reaction time allow virtually any thickness to be applied in a multiple-pass operation. Laboratory testing has indicated excellent toughness, adhesion, and water-resistance, but significant application problems were encountered in the field. Attainment of uniform thickness in structurally complex areas of dam gates was not possible due to the physical size of the gun and the stiffness of the attached hoses. In areas of insufficient coating thickness, application of additional material after as little as 12 hours resulted in virtually no intercoat adhesion. Shop applications on simply configured items have been satisfactory, but application to complex items such as trash racks have resulted in a “snowdrift” effect on the backsides of many members.

Manufacturers can slow the reaction time of some polyurethane resin systems to allow a pot life of several hours. Solvents are added to reduce viscosity, and the coatings can thus be applied using common airless spray equipment. This practice limits the thickness that can be applied in a single coat, but it produces a more uniform coating. Polyurethane coatings have been applied as topcoats over conventional epoxies on tainter gates in an attempt to improve the impact-resistance of an otherwise brittle coating system. Some manufacturers recommended direct application to the epoxy while others require the use of a bond coat. In all cases, intercoat adhesion failures have been noted in the high-abrasion waterline areas of gates on navigation dams.

High-build elastomeric urethane was found to be effective on high-abrasion areas of dam gates. This coating contains many microscopic bubbles, so it is applied over another type of coating in order to ensure proper corrosion protection. It has been applied over a vinyl paint system at thicknesses ranging from 25–75 mils (625–1825 µm). Adhesion and impact-resistance is excellent. The coating is also applied at a thickness of over 1/8 inch (0.6 cm) to protect the vinyl under tainter gate lifting chains and cables.

Moisture cure (MC) urethanes use moisture

from the atmosphere as the catalyst for curing. The single-package coatings include zinc-rich primers, low-build midcoats and topcoats, mastics, and coal tars. Some manufacturers recommend their products for immersion while others do not. Application is usually accomplished with airless spray. These coatings are often subject to problems related to the high humidity encountered on hydraulic painting projects. Once the paint can is opened to the environment it begins to react with any moisture present. Even the process of incorporating thinner into the paint using a power agitator can introduce moisture and result in a significant increase in viscosity. Some applicators gently pour a layer of solvent over the paint in the paint pot in order to isolate the paint from atmospheric moisture. Another problem relates to the curing process, during which carbon dioxide gas is released as a byproduct. When the coating is applied too heavily in a high-humidity environment, the surface can rapidly skin over, trapping gas trapped deeper in the coating to form bubbles. Avoiding excessively heavy application is often difficult in tight areas and on riveted construction; in such areas it is common for the spray applicator to carry a brush to quickly brush out any heavy applications. Bubbles noted after cure are usually sanded out and coated over.

Although MC urethanes have not been in use as long as many of the other coating systems, they appear to offer many desirable properties for service on hydraulic structures. While not as tough as vinyl coatings, they do resist mildly abrasive waters and retain their flexibility even at low temperatures. The single-package products theoretically have no pot life problems, but care must be exercised to avoid contact of the bulk material with moisture.

Applications can be made at high humidity levels, but the coatings cannot be applied to substrates that have actual condensation. Application temperature limits are quite wide, with coatings having been applied at near-freezing temperature without difficulty. MC zinc/MC coal tar systems in service on miter gates for 8 years show no ill effects of immersion; the same system has been in service on stoplogs and tainter gates in brackish waters for 2 years without failure. MC zinc/MC micaceous iron oxide systems in service on navigation tainter gates for 9 years show physical damage on leading edges but continue to perform satisfactorily on more protected areas. Also, MC zinc/MC aluminum systems in service for 6–8 years on gantry cranes, service bridges, and other atmospheric exposures remain in excellent condition, continuing to provide corrosion protection with no notable chalking. Use of MC aluminum as a maintenance coating over existing oil-based systems has been successful on some applications, but has resulted in intercoat adhesion failures at other locations.

Vinyl

The first applications of vinyl coatings onto hydraulic structures took place in the late 1940s and early 1950s. Some of those early coatings are still providing a high level of corrosion protection after 50 years. Vinyls are specified as SSPC Paint 8 or 9, as well as by using Bureau of Reclamation specifications or Army Corps of Engineers formulations. These vinyls use high molecular weight resins and have resulting volume solids contents of less than 20%. The high VOC content must be given consideration when specifying these coatings.

In the past the Bureau of Reclamation, Corps of Engineers, Tennessee Valley Authority, and other government and private operators of hydraulic structures used vinyls extensively for the protection of immersed structures. The coatings were cost-effective and readily available. Today, alternative coatings—notably epoxies—are being used on many structures that do not receive significant amounts of impact from floating ice, logs, or other debris. Vinyls continue to be used on navigation dams and other structures where the level of abrasion is high and frequent maintenance is not practical.

Vinyl coatings are lacquers, meaning they do not polymerize after application but simply dry by solvent evaporation. This results in a number of unique properties:

• Since no chemical reaction takes place when vinyls are applied, the coatings can be applied through a very wide temperature range. The only requirements are that at high temperature, the paint remains wet long enough to flow out after striking the substrate, and at low temperature, the paint is given enough time for the solvent to evaporate before the item is put into service. The coatings are routinely applied at ambient temperatures over 90°F (32°C) with associated substrate temperatures up to 125°F (50°C) and the same paint is applied at ambient and substrate temperatures as low as -20°F (-29°C). This flexibility

allows for a reduced inventory of paint and the ability to paint lock structures during the winter, when river traffic is stopped, without the need for heated enclosures.

• Being a thermoplastic material, a resin can be selected that has the most appropriate degree of flexibility and toughness, and these properties will be retained even at low temperatures. Thermoset coatings, such as epoxies, tend to shatter when impacted at low temperatures.

• The coating must be built up in multiple thin coats, but each coat is usually dry enough to recoat in less than one minute. As a result, an entire coating system can be applied to an area in a single day.

• Lacquers are always soluble, so at any time the coating can be washed from the surface with a suitable solvent to observe the quality of the surface preparation, or additional coating thickness can be added after months or years without concern about intercoat adhesion.

Although they are very versatile, vinyls do have properties that must be given proper consideration. The resins may be nontoxic but the solvents pose concerns related to VOC limitations, flammability, and toxicity. Proper ventilation and the use of respirators in confined areas is a fundamental requirement. Furthermore, the fast evaporation of the solvents can result in pinholes and entrapped air in coatings that are not properly applied. Applicators can eliminate these problems by using good application principles and properly designed conventional spray equipment.

Performance of vinyl coating systems has been documented on many structures. In atmospheric exposures on gates and service bridges, original coatings applied 40–50 years ago are still providing excellent protection without maintenance, with only minor corrosion found along the edges of plates and structural members. It is also common to find these coatings providing 40-year service lives without any maintenance on the insides of tainter and roller gates where the exposure is constant immersion but abrasion is minimal. On miter gates, the coatings are usually found to be providing almost perfect protection when the gates are dewatered at normal 15- to 20-year intervals. Spot repair during dewatering has extended the coating life to 50 years. Service life of coating systems on dam gates is directly related to the level of abrasion to which an area is subjected. The downstream waterline area suffers the most intense level of impact **(see Figure 3)**. At dams on the Mississippi River, these zones may show areas of bare substrate in 10–20 years; the same zone on dams on the Ohio River may be bare in 1–2 years. Repainting of the upstream areas of gates on both rivers is usually not considered in less than 25 years, and is often postponed beyond 30 years.



Figure 3. The downstream waterline area of tainter gates on navigation dams receives the greatest amount of abrasion due to floating debris. The service life of coatings in directly related to the level of abrasion to which they are subjected.

Zinc-Rich Primers

The use of zinc-rich coatings frequently causes controversy within the painting industry. Most major manufacturers have both organic and inorganic zinc-rich products available, but recommendations on their use vary widely. On hydraulic structures it is found that inorganic zincs are seldom used. While inorganics provide excellent protection for atmospheric steel, their field application to complex structures such as service bridges and machinery often produces non-uniform thickness, resulting in mudcracking. Application of topcoats to porous inorganic zincs often results in bubbling. In immersion, the zinc component is galvanically very available, resulting in the development of zinc salts. If undisturbed, these salts will continue to provide corrosion protection but the coating erodes rapidly in areas where the salts are removed by flowing water or debris.

Organic zinc primers often use a lower zinc-to-resin ratio. The resin tends to encapsulate the zinc in such a way that the zinc is not galvanically available to protect adjacent bare steel. It could be argued that

these coatings are not truly “zinc-rich,” but these primers have nevertheless been found to provide excellent adhesion to the substrate and to significantly reduce rust undercutting at breaks in the coating both in atmospheric and immersion applications. The use of the same generic resin in the primer as in the topcoat (vinyl zinc under vinyl topcoats; epoxy zinc under epoxy topcoats) produces coating systems with the ultimate intercoat adhesion.

Detrimental zinc salts do not develop even in immersion service. Most specifications for systems having organic zinc primers require the primer to be a minimum of 2.5 mils (10 µm) thick, with the total system thickness being whatever is recommended for that system. The maximum recoat time for the primer is limited by the shorter of either the recoat window of the resin or the amount of time at which atmospheric moisture would react with zinc on the surface of the primer (often 1 week).

Thermal Spray Coatings

Thermal spray consists of heating a solid coating material enough to liquefy it, then propelling it to a substrate where it immediately cools and hardens. A number of thermal spray polymeric coatings have been tried on hydraulic structures, but the application rates have been slow and adhesion marginal. The performance of the applied coatings was poorer than normally experienced with more commonly applied coatings, so the process has not been used extensively.

A form of thermal spray called metallizing has met with greater success. Two types of metallizing processes have been used on hydraulic structures: (1) flame spray and (2) arc spray. In the flame spray process, a single wire made of the coating material is passed through an oxyacetylene flame, which melts the metal and propels it onto a substrate. In the arc spray process, two electrode wires made of the coating material are energized with electricity, which melts the material; the molten metal is immediately propelled to the substrate with a jet of air provided by the equipment.

The Corps of Engineers conducted some of the earliest work with metallizing on tainter gates and roller gates in the late 1930s through the mid-1940s. Only flame spray equipment was available at that time. It was concluded from this work that although coatings could be applied to provide a level of corrosion protection, the process was unacceptably slow, and conventional solvent-based coatings could provide a more cost-effective means of protection. In the mid-1980s, both flame spray and arc spray were evaluated as an approach to provide corrosion protection to areas of tainter gates exposed to extreme levels of abrasion. Again it was found that flame spray functioned in a satisfactory manner, but the arc spray equipment constantly shorted out, resulting in downtime and poor coating quality. In the early 1990s, improved arc spray equipment eliminated the shorting problem, making the technology a viable method of application. Application rates with arc spray equipment were significantly faster than with flame spray, making the cost of a metallized coating competitive with some organic coating systems.

At the time of this writing, no consensus has been rendered regarding the long-term performance on hydraulic structures of various metallized coatings. Work performed in the mid-1980s concluded that corrosion-resistant metals such as aluminum bronze, 304 stainless, and 316 stainless steels were very porous. Various sealers were evaluated to seal the porosity, but in immersion service corrosion rapidly removed each product from the substrate.

Zinc, being anodic to steel, did not allow substrate corrosion to take place until the zinc had completely sacrificed itself. Although zinc is a soft metal, it was sufficiently abrasion-resistant to withstand the most abrasive conditions to which the gates were exposed. A 12–15 mil (300–380µ) coating of pure zinc offered near-perfect protection of the area for 8 years, but at 10 years the area was totally corroded. This finding would imply that metallizing with zinc, or other metals anodic to steel, may offer cost-effective protection to areas of hydraulic structures exposed to such an extreme level of abrasion that organic coatings exhibit a very short life. Conversely, organic coatings may be more cost-effective where they are sufficiently durable to withstand the abrasion.

Other Coatings

Many other coatings are used for various applications on hydraulic structures. Most of these products are either not used extensively, or their use and performance on hydraulic structures is not significantly different than it is on other industrial structures. The products range from oil-based primers, used as a direct replacements for existing red-lead-in-oil, to

aluminum epoxy mastics, new-generation phenolics, neoprenes, polyureas, and specialty coatings for unusual applications.

Factors Affecting Service Life

The service life of a coating system depends on many factors. Obviously the coating must be properly selected for the service, but this is actually becoming more difficult as new resin systems are introduced by the coatings industry. Manufacturers cannot afford to conduct long-term testing before introducing a new coating. Many of the newer VOC-compliant coating systems are generically the same as previous systems, but made with lower molecular weight resins that are more water-sensitive. Unfortunately, it has been seen that many of the newer high-solids (i.e., reduced VOC) epoxies appear to perform well in accelerated weathering tests but not in long-term immersion. Accelerated weathering data may provide a method of comparing similar coatings exposed to the same aggressive environment, but may not relate to a coating's actual ability to perform in service. In other instances, however, new products appear to be providing superior application and performance properties on structures exposed to atmospheric conditions.

Perhaps the factor affecting service life that is most difficult to control is the quality of application. Even with the highest-quality coating and the most reputable contractor, the most important factor becomes the workmanship of the person doing the surface preparation and painting. In general, the importance of surface preparation is well understood. Surface preparation on many areas of hydraulic structures requires a high-quality abrasive blast (e.g., SSPC SP 5/NACE 1 white metal or SSPC SP 10/NACE 2 near-white metal). Workers usually understand the requirements of these specifications, and compliance in easily visible areas is common.

Noncompliance is usually limited to complex areas where the blaster cannot directly see the surface of the metal. These areas frequently require the use of a side blast nozzle to prepare the surface and a mirror to inspect the work. The shaded sides of rivets and areas between back-to-back members also present challenges to even the most experienced blasters. Workers must be trained to understand failure modes such as osmotic blistering, which occurs at any point where the coating is not tightly adhered to a sound substrate. Any residual rust or poorly adherent coating remaining on the surface will result in sites where osmotic blistering is inevitable. Quality assurance inspectors must be aware that simply by touching a freshly blasted surface, sweat or skin oils can adhere to the metal and cause osmotic blistering if painted over. If touching the surface cannot be avoided, inspection personnel should wear cotton gloves.

The difficulty of applying paint to hard-to-access surfaces also leads to many coating failures. Painters usually know the requirements of the specification, and provide quality application and proper thickness on easy-to-reach surfaces, but proper thickness on edges and difficult-to-coat areas is often a problem. Spray application to tightly configured flanges often requires that the spray gun be moved to within 2–3 inches (5–7.5 cm) of the substrate. Although this can be accomplished with conventional spray using adjustments on the gun, many applicators do not make the adjustments. Airless spray, which cannot be easily adjusted for such tight applications, often results in entrapped air and excessive coating thickness. Premature corrosion can be greatly reduced by requiring special attention, such as hand striping or applying a preliminary spray pass on all edges, irregularities and hard-to-access areas.

Numerous external factors affect the service life of coatings on hydraulic structures. Some of the critical factors—intense sunlight, long-term immersion in water, and impact and abrasion caused by floating debris—have already been discussed. Biological factors create few if any coating failures. The growth of algae only presents aesthetic concerns. Zebra mussels and barnacles may cause significant operational problems, but they appear to have no adverse effect on the coatings typically used on hydraulic structures. There is some indication that zebra mussels may actually provide an additional level of protection to the coating system. Microbiologically influenced corrosion (MIC) does not affect coatings, but it does cause accelerated corrosion where the coating film is breached.

Determining the end of a coating's service life on a hydraulic structure is difficult because of the wide variety of exposure conditions. A vinyl paint system on a single gate may be gone in major spots on the downstream waterline in 15 years, while the upstream area may have only a few minor spots of corrosion and the atmospheric area may be in almost-new condition.

Good painting practice would probably suggest that the downstream waterline area be completely repainted, the upstream area be spot-repaired, and no work be performed on the atmospheric area. This approach was common several decades ago when painting was performed using in-house painting crews. The paint unit could float the work barges into place, dewater the structure, judge the amount of deterioration, plan a logical repaint strategy, and perform the work.

Today, most painting on hydraulic structures is done by contract. Often the engineers preparing the contract cannot dewater the structure to determine the true condition of the existing coating. This has often resulted in specifying complete replacement of coatings that were in excellent condition, and also has led to spot painting when full replacement should have been specified. It is difficult to clearly define in a contract document the amount of work to be performed or the quality control requirements to be enforced when less than complete removal and replacement of the coatings is needed. As a result, many repainting contracts require complete removal and replacement of all coatings on a structure even though some areas are fully protected and may not require maintenance for decades.

References

1. Beitelman, Alfred D. *Evaluation of Surface Preparation and Application Parameters for Arc-Sprayed Metal Coatings;* Technical Report No. 99-40; U.S. Army Engineer Research and Development Center/ Construction Engineering Research Laboratory: Champaign, IL, 1999.
2. Varcalle, Dominic J.; Beitelman, Alfred D. *An Evaluation of Application and Surface Preparation Parameters for Thermal Spray Coatings;* Technical Report No. 99-68; U.S. Army Engineer Research and Development Center/Construction Engineering Research Laboratory: Champaign, IL, 1999.

Acknowledgements

The author and SSPC gratefully acknowledge Herbert Hooper and the Tennesse Valley Authority for their peer review of this document.

About the Author

Alfred D. Beitelman
Alfred (Al) Beitelman is director of the U. S. Army Corps of Engineers Paint Technology Center in Champaign, Illinois. The Center specializes in coatings for all of the Army's facilities, including the hydraulic structures operated by the Corps of Engineers. A member of SSPC, NACE, and ASTM, he holds certifications as an SSPC protective coatings specialist (PCS) and a NACE level III coating inspector. He has a BA degree in chemistry.

Chapter 6.10
Coatings for Buried and Immersed Metal Pipelines

Richard W. Drisko

Introduction

This chapter describes the fundamentals of selection, application, inspection, and performance of coatings buried in soils or immersed in water. Pipeline coatings provide barrier protection to isolate the metal piping from its aggressive environment. Some pipeline coatings may also provide insulation or other special properties.

Since organic coatings are seldom perfectly applied and always subject to deterioration during service, buried and immersed pipelines are normally cathodically protected. Indeed, many countries, including the United States, require cathodic protection on buried and immersed gas and oil lines.

A coating on a buried or immersed pipeline that provides a high electrical resistance to its surrounding soil or water significantly reduces the electrical current required for cathodic protection. The cathodic protection will, in turn, protect from corrosion, areas of metal that are exposed to the environment by coating deterioration. In order for coatings to perform well jointly with cathodic protection, they must be resistant to the alkalinity that is always generated on cathodes, and the cathodic protection voltage must be maintained at a safe level.

Desirable Properties of a Pipe Coating

In order for a pipeline coating to perform successfully in a buried or immersed environment, it must have the following physical and chemical properties:

• **Good electrical resistance.** The coating must provide a barrier protecting the steel from aggressive electrolytes in the soil or water.

• **Good chemical resistance.** The coating must be resistant to chemical attack by the prevailing environment.

• **Resistance to cathodic disbonding.** Cathodic protection may deteriorate the coating by driving water through it or by evolution of hydrogen gas caused by excessively high (e.g., above -1.1 volts) cathodic potentials. ASTM test G 8 for cathodic disbonding of pipeline coatings (the salt crock test) may be used to measure a coating's resistance to cathodic disbonding.[1]

• **Good adhesion to metal surface.** Good coating adhesion is required to minimize damage during shipment and handling and to minimize coating deterioration during service.

• **Heat resistance.** In services where the piping becomes heated, the coating system must be resistant to the prevailing temperatures.

• **Ease of quality application.** The coating must be relatively easily applied to form a quality film for it to be practical for use on piping. Thus, coatings normally perform better when shop-applied under controlled conditions than when field-applied.

• **Resistance to damage during handling, storage, and installation.** The coating must have sufficient resistance to impact and abrasion and have good ductile properties to resist damage during handling storage and installation. Coatings with exterior exposure for an extended period of time must be resistant to deterioration by the sun's ultraviolet light.

• **Ease of repair.** The coating must be easy to repair since damage is likely to occur during handling, storage, transport, and installation. Welding piping during installation will damage coated areas and necessitate repairs. Thus, it is a common practice to leave areas uncoated where welding is to occur.

In addition to the above, there are a few special requirements for joint coatings used on weld areas of pipelines:

• The joint coating must be compatible with the pipe coating during both application and pipeline operation.

• The application temperature must be less than the temperature limit of the pipe coating.

• The joint coating must adhere well to both the cleaned metal and the pipe coating.

• The weld must be ground relatively smooth and any weld spatter removed.

Coal tar can be used to coat joints of pipe

containing coal tar or asphalt coatings. These and other coated pipes are more commonly joint coated with cold-applied polyvinyl chloride (PVC) or polyethylene (PE) tapes with a synthetic rubber adhesive. They may also be protected with heat-shrink sleeves.[2]



Figure 1. Grinding of girth weld for coating.



Figure 2. Liquid coating applied to girth weld.

Application of Coatings and Laying of Pipeline

Buried Pipelines

Today, it is a common practice to furnish coated pipe to the field in 20, 40, or 80 ft. (6, 12, or 24 m) lengths, weld the pipe sections together, clean the exposed metal, and apply a joint coating to the joined metal sections.[3] The weld covers the entire circumference of the joined sections where the shop-applied coating was not applied (cut back) from the ends. The cut-back distance necessary for preventing heat damage to the coatings typically ranges from about 6 inches for a polyethylene to 1 inch for a fusion-bonded epoxy coating. It should be noted that new laser welding equipment produces much less heat and consequently causes much less coating damage that the usual welding equipment.



Figure 3. Field repair of coating damaged during transportation to site.

Because of health and environmental concerns, greater use is being made of portable containment systems for both surface preparation and coating application in weld areas. A less commonly used practice for coating and burial of pipelines is to weld the complete line together, clean the piping, and apply the coating system in the field (over the ditch) in one continuous, seamless operation. This eliminates damage during transportation and handling, but field conditions are often unsuitable for coating application.

Immersed Pipelines

Pipelines laid in seas, rivers, or lakes are typically applied from barges (called lay barges). These barges are specially designed to permit welding shop-coated piping and repair of coatings at the welded areas. Occasionally, coated marine piping is welded and coated ashore before being towed into position.

Pipelines with diameters above 8 to 12 inches typically require a concrete weight coating applied over the corrosion protective coating to prevent floating. In some cases, pre-cast concrete weights may be used instead of concrete weight coatings.

Generic Coating Types

This section describes generic types of coatings that are commonly used on buried and

immersed metal pipelines.

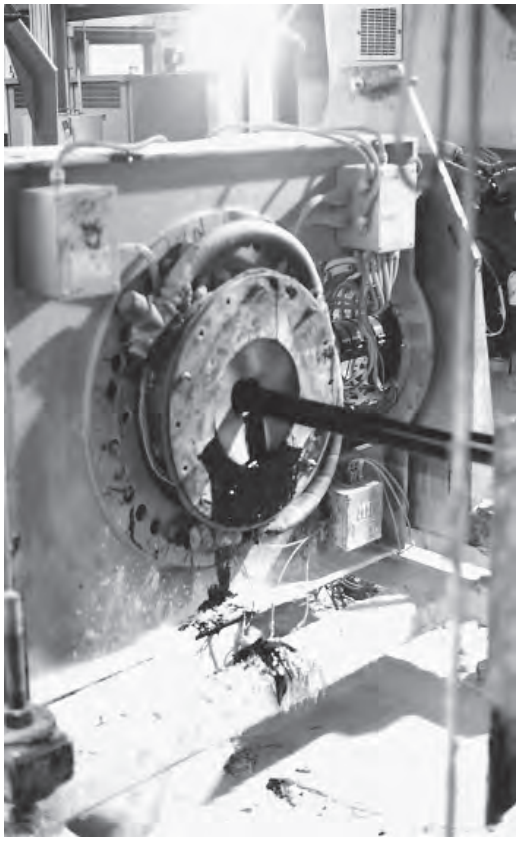


Figure 4. Pipe entering dye for extrusion application of coal-tar coating. Courtesy Dura Bond Coating, Inc.

Coal-Tar and Asphalt Coatings

Coal-tar enamels and asphalt coatings were the first coating systems used on buried pipelines. They were reasonably cheap to procure and easy to apply, and they required only a low level of metal cleaning for coating. Presently, most coal-tar systems consist of primer, coal tar, glass fabric, and felt. Additional coal tar and felt layers can be used to increase the thickness.

Coal tar and asphalt systems can be applied in the shop or field, but performance has been notably better when shop- rather than field-applied. If coal tar or asphalt is exposed to the sun over long periods of time, it may be necessary to apply a white wash or paper on them to prevent deterioration by ultraviolet light.

Several U.S. states and foreign countries prohibit or discourage the use of coal tar coatings because of heath and safety concerns. Coal tar contains polycyclic aromatic compounds, some of which are carcinogenic. When coal tar is heated for application, many of these compounds vaporize into the atmosphere. Similarly, the use of coal tar in combination with epoxy or polyurethane resins is likely to greatly diminish.

Being much less aromatic than coal tar, asphalt contains lower levels of carcinogenic compounds, but its use is also being restricted in some locations. Asphalt mastics consist of a dense mixture of sand, crushed rock, and fiber bound with asphalt. A primer is normally used prior to extrusion of the hot mix.

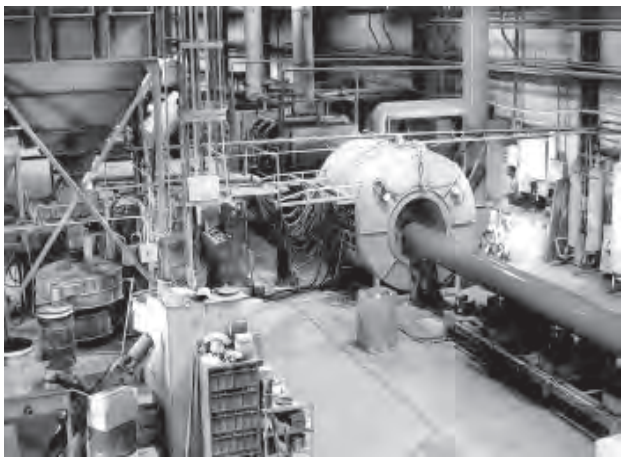


Figure 5. Overview of powder coating chamber. Courtesy Dura Bond Coating, Inc.

Fusion-Bonded Epoxy Coatings

Fusion-bonded epoxy (FBE) coatings are thermosetting powder coatings typically applied electrostatically to electrically ground metal components. The powder is later fused into a hard, continuous, cured film by heating in an oven. A high level of cleaning (e.g. SSPC-SP 5/NACE 1 or SSPC-SP 10/NACE 2) and precise application are necessary for outstanding performance.[4, 5] North America currently seems to prefer FBE coating systems for buried and immersed pipelines, while Europe favors the three-layer FBE-polyolefin system.[6]

FBE coatings may be a one-layer thin and brittle system (with good resistance to soil stresses) or a two-layer thicker system with greater resistance to mechanical damage and damage from high temperatures. These coatings are also used as primers for two coats of polyolefin. The FBE provides good adhesion to the pipe, and the polyolefin, good resistance to

mechanical and environmental degradation. Use of FBE coatings on water systems is described in ANSI/AWWA C213.[7]



Figure 6. Applying powder coating. Courtesy Dura Bond Coating, Inc.

Polyolefins

Polyethylene (PE) and polypropylene (PP) coatings are the olefins predominantly used today in coatings for buried or immersed pipelines. They were originally applied by sintering (baking sprayed material) or by hot extrusion over a soft (e.g., butyl) adhesive. This method sometimes resulted in films with poor adhesion that cracked.

Earlier problems were resolved by the development of a three-layer FBE-polyolefin system consisting of coat of FBE, a coat of FBE copolymer with PE or PP, and a coat of PE or PP. PP is the one most commonly used in Europe today. This system has excellent heat-resistance. One author states that the three-coat FBE-PP system is the only anti-corrosive system appropriate for temperatures above 194˚F (90˚C).[8]

Tape Wraps

Tape coatings for piping became popular in the early 1960s. They consisted mostly of polyethylene

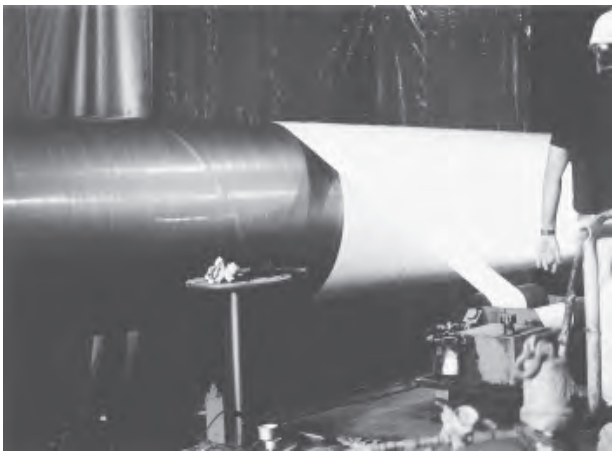


Figure 7. Applying tape to pipe in shop. Courtesy Dura-Bond Industries.



Figure 8. Manual application of tape to pipe. Courtesy of Dura Bond Coating, Inc.

(PE) or polyvinylchloride (PVC) backing with a thermoplastic adhesive on the pipe side. They required only a low level of surface preparation and were easily applied to piping. More information concerning them can be found in ANSI/AWWA C203 and ANSI/AWWA C209.[9,10] Tape coatings were susceptible to soil stress problems and the PVC system to embrittlement due to loss of plasticizer over time. Tapes can be shop or field applied, and are often applied by hand to field joints. In all cases, the tape must be tensioned against the pipe

during application to provide good adhesion.

The use of cold-applied petrolatum tape and petroleum wax tape coatings for buried steel pipelines is described in ANSI/AWWA C217.[11] These products are not recommended for immersion use. They consist of a petrolatum or wax primer and a covering loosely woven tape saturate with the petrolatum or wax.



Figure 9. Heat shrinking of sleeve in field.

Heat-Shrink Sleeves

Heat-shrink sleeves may be used to protect weld areas from corrosion, as described in ANSI/AWWA C216.[12] There are two basic types of sleeves. The tubular sleeve has no longitudinal seams and so must be slid over an end of the piping before the joint is made. The wrap-around sleeve can be wrapped around the weld area after the joint is made and sealed with a heat-activated closure strip or a mechanical zipper.

Inspecting Pipeline Coatings

Inspecting pipeline coatings is thoroughly described in SSPC's *Inspection of Coatings and Linings*.[3] Obviously, all shop coated piping should be inspected for dry film thickness, holidays, and visual defects before it is transported to the field.[13, 14, 15] It should then be examined again before burial to detect coating damage. Field-applied coatings should be similarly inspected.

Coal-Tar Enamels

For coal-tar enamel systems, the inspector should:

• Verify that the specified levels of cleanliness and profile are attained. If the enamel is also used as a joint system, slightly roughen the existing coating to permit good adhesive of the joint enamel.

• Check for the correct temperature with a thermometer or pyrometer whenever pre-heating is required.

• Monitor the application for temperature of the enamel to be applied, for complete embedment of glass fabric, and, after cooling, for dry film thickness and holidays in the coating system.

FBE and Powder Joint Coatings

For FBE and powder joint coatings, the inspector should verify that:

• The specified levels of cleanliness and surface profile are obtained.

• The specified temperature has been achieved by heating.

• The manufacturer's instructions for application and curing have been followed.

• The specified dry film thickness has been obtained

• All detected holidays have been repaired.

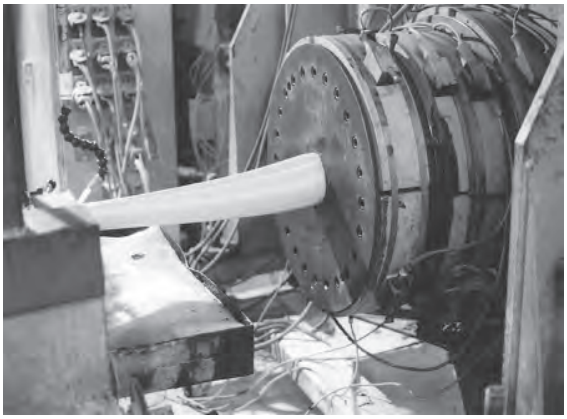


Figure 10. Extrusion of thermoplastic coating on to pipe.

Thermoplastic Tapes

For thermoplastic tapes, the inspector should verify that:

• The specified level of surface preparation has been achieved.

• The proper temperature exists for application (some tapes require pre-heating).

• The manufacturer's primer has been applied in accordance with the specification.

• Tape overlaps properly at the correct tension during spiral lapping and the adhesive continuously extrudes along the overlap edges.

• All detected holidays have been repaired.

Heat-Shrink Sleeves

For heat-shrink sleeves, the inspector should verify that:

• The exposed steel and adjacent coated surface surfaces have been prepared according to specification requirements.

• The pipe has been heated to the specified temperature.

• The entire under-sleeve area has been completely covered by the primer (if priming is specified). It may be necessary to apply a filler putty to weld areas and/or edges of overlapping coatings or tapes that might otherwise permit "tenting" (voids caused by surface irregularities) to occur.

• Sleeve is properly placed and closed.

• No tenting, detachment, presence of air bubbles, or other defects in excess of those permitted by the specification.

• The entire system may, at the purchaser's option, be inspected for discontinuities (holidays) using holiday detectors.[14,15]

Summary

Significant improvements have been made in coating systems for buried and immersed pipelines during the last 50 years. If environmental concerns or new operational requirements must be met, they are likely to change further. For the near future, FBE and three-layer FBE-olefin systems are expected to dominate at the expense of coal-tar and asphalt.

References

1. ASTM G 8. *Standard Test Method for Cathodic Disbonding of Pipeline Coatings;* ASTM: West Conshohocken, PA.

2. Fairhurst, D. The Future of Pipeline Coatings. *Journal of Protective Coatings,* November 2000, pp 33-38.

3. *The Inspection of Coatings and Linings;* Appleman, Bernard R. ed:, SSPC: Pittsburgh, 1997.

4. Wilmott, Martyn; Highams, John; Ross, Richard; and Kopystinski, Adam. Coatings and Thermal Insulation of Subsea or Buried Pipelines. *Journal of Protective Coatings and Linings,* November 2000, pp 47-54.

5. SSPC-SP 5/NACE 1. *White Metal Blast Cleaning;* SSPC: Pittsburgh and NACE: Houston.

6. SSPC-SP 10/NACE 2. *Near-White Blast Cleaning;* SSPC: Pittsburgh and NACE: Houston.

7. ANSI/AWWA C213. *Fusion-Bonded Epoxy Coating for the Interior and Exterior of Steel Water Pipelines;* AWA: Denver.

8. Fairhurst, D.; Willis, D. Coating Systems for Pipelines Operating at Elevated Temperatures. *Journal of Protective Coatings and Linings,* March 1997, pp 64-82.

9. ANSI/AWWA C203. *Coal-Tar Protective Linings for Steel Water Pipes—Enamel and Tape—Hot-Applied;* AWA: Denver.

10. ANSI/AWWA C209. *Cold-Applied Tape Coatings for the Exterior of Special Sections Connections, and Fittings of Steel Water Pipelines;* AWA: Denver.

11. ANSI/AWWA C217. *Cold-Applied Petrolatum Tape and Petroleum Wax Tape Coatings for the Exterior of Special Sections, Connections, and Fittings for Buried Steel Water Pipelines;* AWA: Denver.

12. ANSI/AWWA C216. *Heat-Shrinkable Cross-Linked Polyolefin Coatings for the Exterior of Special Sections, Connections, and Fittings for Steel Water Pipelines;* AWA: Denver.

13. SSPC-PA 2. *Measurement of Dry Coating Thicknesses with Magnetic Gages;* SSPC: Pittsburgh.

14. ASTM D 4162. *Practice for Discontinuity (Holiday) Testing of Nonconductive Protective Coating on Metallic Substrates;* ASTM: West Conshohocken, PA.

15. NACE Standard RPO274. *High-Voltage Electrical Inspection of Pipelines Prior to Installation;* NACE: Houston.

Acknowledgements

The author and SSPC gratefully acknowldge Jerry Byrd's peer review of this document.

About the Author

Dr. Richard W. Drisko

Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society for Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy's center of expertise on coatings for shore structures. He is a professional corrosion engineer in the state of California, an SSPC certified protective coatings specialist (PCS), and a NACE International certificated corrosion specialist. Dr. Drisko received his BS, MS, and PhD degrees from Stanford.

Chapter 6.11
Painting Ships

Earl Bowry

Introduction

The sea is relentless in exposing weaknesses in structures and protective systems, constantly seeking to turn steel into rust. Ship steel rusts before a ship is built, during construction, and throughout the service life. At the present, a liquid-applied coating system combined with proper design and cathodic protection are the most important tools in combating ship corrosion.





Figures 1 and 2. Tug boat in dry dock and service.

When steel plate arrives at the newbuilding yard it is cleaned and painted with a pre-construction primer. During construction, it is cleaned again and painted with longer-term coatings. Once it is placed into service, crew members and drydock workers continually clean and paint it **(Figures 1 and 2).**

This chapter covers common problems and typical painting systems in use. It also directs the reader to other sources of specialized information. Ship corrosion can and has caused catastrophic failures resulting in loss of life, significant financial tolls, and serious environmental damage. Knowledge, proper planning, and good painting practices can prevent these issues from arising.



Figure 3. Closeup of ship rust.

Problems Encountered

From huge aircraft carriers and very large crude carriers to the barges that supply them and the tugs that push them out to sea, ships are subjected to immersion in water, severe weather, bending stress, abrasion from cargo and passage through the water, chemical attacks, dissimilar metal corrosion, radical temperature changes, extreme UV attack, and biological organisms **(Figure 3)**.

In addition, coatings applied during newbuilding are frequently damaged during the

construction phase, and the repair, if any, often occurs at the last minute. It is not unusual for the construction of a large vessel to take several years. During this period, new technology, new owners, or a new purpose may require fundamental changes. Owners and ship builders need to understand that the coating system may also have to be changed to meet the new requirements **(Figure 4).**



Figure 4. Burned paint.

The use of an existing vessel may change from the intial design, such as when a hopper barge that previously carried coal is used to haul fertilizer. The lining system, if any, which was designed for coal has to be appropriate for fertilizer. Likewise, if a cruise ship making regular runs in warm water shifts to an Artic route it might require a different anti-fouling coating.

Regardless of any changes, coating system maintenance needs to continue for the life of the vessel. With crew sizes shrinking to meet competitive demands fewer resources are available. A small spot of rust could become a fractured plate before it is fixed. Today's coating systems are expected to perform better than ever before and with less maintenance. The proper selection of a coating system along with the correct application at newbuilding and during major overhauls is required to meet this higher standard of need.

Ocean-going ships present special concerns. It is not unusual for a vessel to be built in Norway, make port calls in the U.S., Germany, and China and be drydocked for the first time in Korea. The similar or compatible and locally compliant paint must be available in all locations and the local applicators must be familiar with the specified products.

Naval ships **(Figure 5)** have unique needs. While ocean-going vessels are dockside for very short periods of time, a Naval ship may spend 50% of its life sitting still—only to steam at twice the speed of a typical cargo vessel when it does go out to sea. These facts impact greatly on the need for antifouling coatings. The U.S. Navy's restricted-use technical manual covers surface preparation, painting, and other preventive measures. It should be noted that the Navy does a great deal commercial coating testing, and has, in many cases, selected to use commercially available instead of "mil-spec formula" products. This is especially true in such critical areas as tanks, flight decks, and underwater hulls. NAVSEA Standard 009-32 (current edition) is a non-restricted document that contains a chart showing locations on the vessel and the approved coating system for each area. It can be downloaded from the Internet at http://www.supship.navy.mil/ssrac4/standard.htm.



Figure 5. Naval vessel in drydock.

Solutions

Ship painting must be well-planned with all potential problems anticipated. Select new construction coating systems that are easy to repair and offer the longest possible service life. Keep accurate records of what was applied, how it was applied, and the conditions of application.

Inspect newly applied coating systems within the first year to identify and correct any failures caused by improper surface preparation and/or application.

ISO 9223: Corrosion of Metals and Alloys—Corrosivity

of Atmospheres states that further inspection and evaluation may occur every third year in a medium corrosivity area (Category C3) or every second year in a high corrosivity area (Category C4). SSPC's book *The Inspection of Coatings and Linings* also describes inspection procedures particular to ship painting **(Figure 6).**

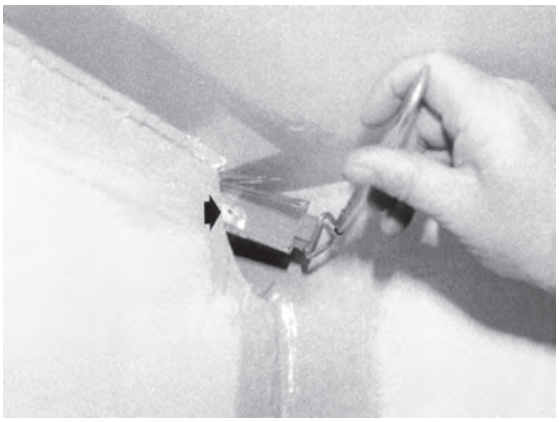


Figure 6. Inspection procedure.

No single paint or coating system is appropriate for every situation. Surface- tolerant epoxy has been used extensively in land-based industrial maintenance painting for over 30 years, and in the marine market for the past 10 to 15 years. This product provides a great deal of flexibility and extended service in ship painting. Although not as simple to use as a single package alkyd enamel, its excellent performance and tolerance of less than perfect surface preparation will mitigate the higher cost as well as the extra skill and work involved.

Other epoxy technologies that are gaining favor in the marine market use solvent-free penetrating sealers for maintenance painting and edge-retentive materials for tank linings. Because of environmental concerns, organotin antifouling products are being phased out. New materials using proprietary biocides are available from many of the major marine coating suppliers.

New high-performance water-borne acrylic coatings and blends of epoxy and acrylic resins have also seen a recent surge in use in both the industrial and marine markets. VOC emission regulations as well as health and safety issues in many countries have forced coating manufactures to modify existing materials, and develop new versions of older products **(Figure 7).**



Figure 7. Surface-tolerant epoxy.

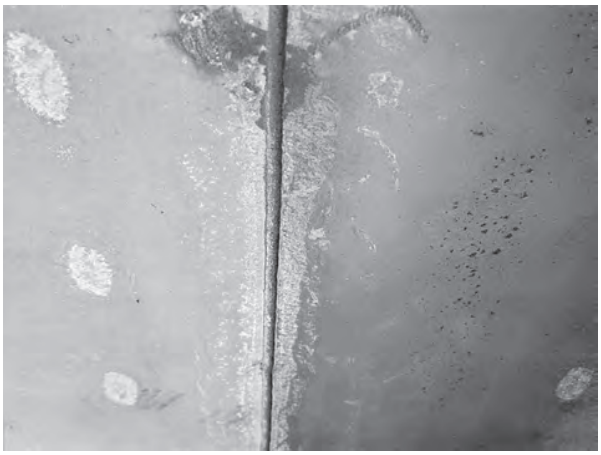


Figure 8. Preconstruction primer and weld.

New Construction Painting

Shop, or pre-construction primers, are quick-drying materials applied as thin films after cleaning to provide protection before and during fabrication. The plate steel (sometimes over 8 million ft.^{2}) used in ship building is shop-cleaned as it passes through a centrifugal blasting unit, and then automatically sprayed to a uniform film thickness. The coating systems used range from short oil alkyds to inorganic zincs, including water-borne epoxies and even very low solids products, such as iron oxide vinyl/phenolic-based materials. The type of coating as well as the thickness at which it is applied will affect the fabrication process. Cutting speed, weldability, weld contamination, and fumes are all factors that must be considered when selecting the coating. Total plant solvent emission guidelines and federal, state, and local air pollution regulations must also

be considered **(Figure 8 and 9).**

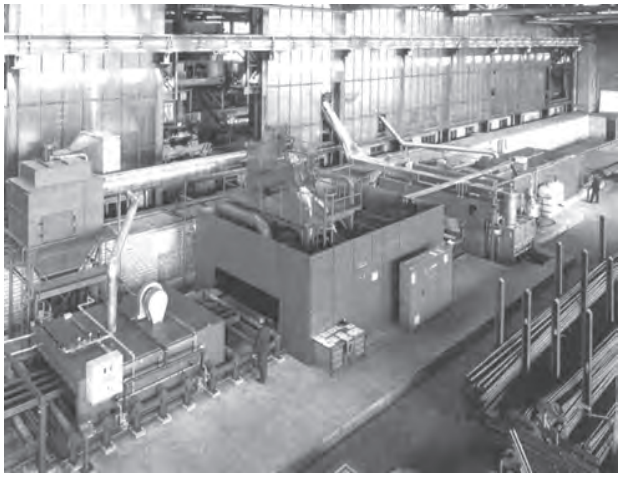


Figure 9. Preconstruction blast and paint line.

Maintenance Painting

Ship maintenance painting is normally divided into two areas: shipboard painting ("painting while underway") and painting at drydock.

Shipboard Maintenance Painting

Even with reduced crew sizes, shipboard maintenance painting is an unending process that must be planned during the new construction phase. Every vessel should have a manual of recommended maintenance painting practices that includes product data sheets, material safety data sheets, and a coating schedule for each area. This document must also address the surface preparation required for various conditions and contain detailed and heavily illustrated instructions on how to mix and apply the necessary coatings.

Environmental conditions should be outlined, and the crew made aware of curing times as well as application temperature limitations. If a vessel's original coating maintenance manual has been lost it is imperative to create a new one based on tests of the existing paint and the coating manufacturer's recommendations **(Figure 10).**

In addition, all necessary equipment must be housed on the ship, including sprayers, power mixers for two-component paints, and a paint locker holding the correct coatings and thinners. Placing a large illustration demonstrating proper mixing techniques and correct application of thinners on the paint locker will help educate the crew.



Figure 10. Power mixing.

Brushing and rolling large areas is not recommended during shipboard painting because it is too difficult to match the appearance of the original spray-applied coating. It is also impossible to achieve the recommended film thickness for high-build epoxies and many two-component urethanes with one brush or roller coat.

Sometimes a coating contractor's crew travels with the vessel to perform those jobs that are much larger than what the ship's crew would typically handle. This can work out very well when the part of the vessel to be painted will not be in use during a particular passage.

It is also common to have a contractor supply a smaller group of workers to perform standard maintenance painting when ship crews do not have time to do this.

Drydock Maintenance Painting

Underwater hull inspection and major repair work are completed while a ship is in drydock. Abrasive blast cleaning of interior areas can take place in the yard without causing problems for the ship's crew. Temperature on the low exterior wall is drastically reduced and tank access improved during drydock **(Figures 11 and 12).**

Planning and preparation is key to a successful drydocking. The cost of having a ship out of service, added to the daily cost of the drydock itself is very high. All materials and equipment should be onsite prior to the vessel's arrival.

Most marine coating manufacturers will supply sufficient material for the job and will accept any

unused material after the work concludes. The port engineer and the coating supplier's technical service representative should keep a daily record of the materials used and arrange for the return of unused material.

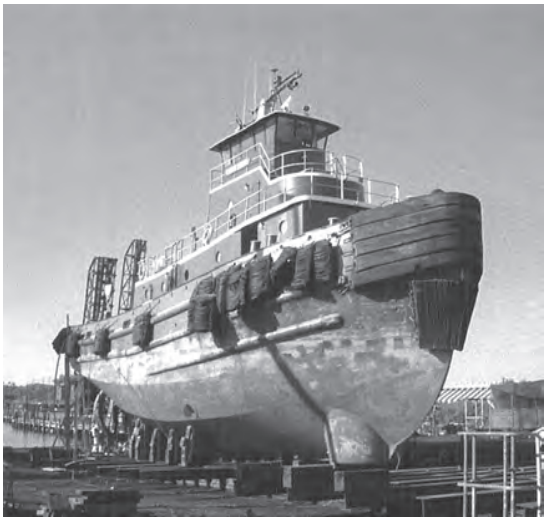


Figure 11. Tugboat on railway.



Figure 12. Flat bottom in dry dock.

Detailed daily records are crucial as claims concerning underwater coating failures can be very costly. Knowing what happened, how, and when will resolve many issues.

Painting Systems

Tank Painting

Tank painting is perhaps the most difficult ship coating task. Normally a shipyard job, it requires special equipment for abrasive blast cleaning and dehumidification. Sharp corners, rough welds, back-to-back angles, and inaccessible areas cause paint failures that are not always readily apparent. Steel edges should be rounded over, weld splatter removed, and welds ground smooth with no undercutting **(Figures 13, 14, and 15).**



Figure 13. Skip welding.

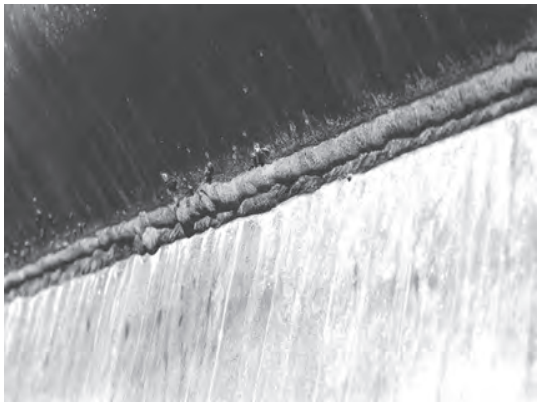


Figure 14. Splatter and rough weld.



Figure 15. Sharp edges.

Air, substrate, and paint temperature as well as airflow and the internal humidity level all must be

within the range shown on the manufacturer's data sheet. Multiple coats and stripe coats are highly recommended as single coats will almost always leave pinholes and holidays. The one exception to this rule is the use of high-build urethanes if they are formulated and applied correctly.

The time interval between coats is generally limited to both a minimum and maximum and is very important for intercoat adhesion. Inspecting each step is one of the most significant activities on any tank job. While high pressure and ultra-high pressure water blasting is acceptable in many areas of ship painting, tanks, with their close spaces, benefit best from the "ricochet action" of dry abrasive blast cleaning. This also eliminates the problems associated with removing the water used in the cleaning process and inadvertently increasing humidity. The degree of blast cleanliness and the profile required should be based on the coating to be used and agreed to by the paint supplier, owner, and applicator.

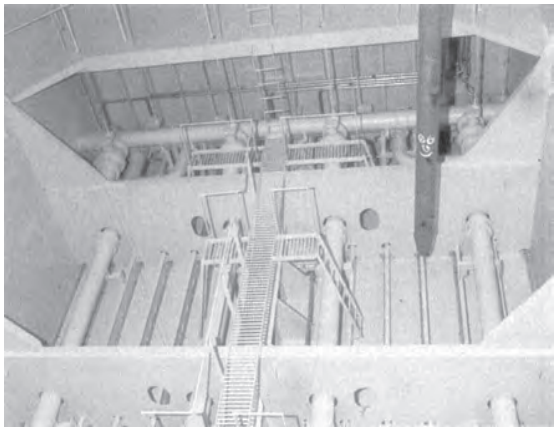


Figure 16. Liquid cargo storage tank.

Liquid Cargo Tank Coating

Coatings for product and chemical carrier tanks must protect the steel from cargo-imparted corrosion and protect the cargo from coating-related contamination **(Figure 16)**. Epoxy polyamines, epoxy phenolics, high-build solvent-free urethanes, and inorganic zincs are typically used; however, the actual choice of coating requires a close consultation between ship owner and coating manufacturer or consultant. The U.S. Navy has started using solvent-free, edge-retentive epoxy coatings on cargo tanks in an attempt to eliminate thin edge areas.

Factors that influence cargo tank coating selection include:

- Types and sequence of cargo
- Type of cleaning between loads
- Cargo temperature at loading
- Storage temperature
- Storage time



Figure 17. Corrosion with edge failure.

Freshwater Tank Coating

Potable water tank coatings must protect the steel without imparting a taste to the water and meet the regulations of the countries in which they will be installed. In the United States, linings for potable water tanks must comply with ANSI/NSF Standard 61. Full curing with ample ventilation helps avoid contamination of potable water. While a variety of coatings, including coal-tar and cement, have been used in the past, a two- or three-coat epoxy polyamide or epoxy polyamine system tested and certified to meet ANSI/NSF Standard 61 is typical today.

Ballast Tank Coating

As vessels built in the early 1970s become more vulnerable to cracks and fractures that have led to serious structural failues, ballast tank maintenance has come under increased scrutiny. Water, including salt water at various levels and temperatures, is stored in these ship tanks to contribute to the "trim" and stability of the vessel. For this reason, ballast tanks form an almost perfect corrosion cell **(Figure 17).**

The International Maritime Organization (IMO) has

adopted several ballast tank regulations. Guidelines for selecting, applying, and maintaining the corrosion prevention systems in all oil tanker and bulk-carrier seawater ballast tanks are codified in the International Convention for the Safety of Life at Sea (SOLAS) Regulation II-1/14-1:

- The owner should select and maintain a system to ensure an adequate level of corrosion prevention.
- Coating manufacturers should provide evidence of product quality and ability to satisfy the owner's requirements.
- The shipyard and/or its sub-contractors should provide clear evidence of their experience in coating application. The coating standard, job specification, inspection, maintenance, and repair criteria should be agreed to by the shipyard and/or its subcontractors as well as the owner and manufacturer in consultation with the administration or an organization recognized by the administration, before the ship's construction.

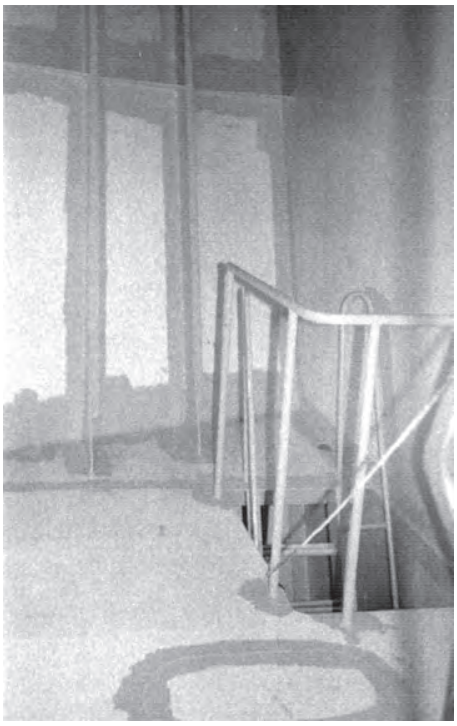


Figure 18. Strip coat.

New Construction. The newbuilding stage offers the ideal opportunity to invest in long-term protection and avoid the high cost of remedial work caused by poor preparation and ineffective coating. As a general rule, it will cost a minimum of ten times as much to repair a ballast tanks to the original standard than it would cost to apply a solid newbuilding system.

In coating ballast tanks, it is necessary to use light colors for better visibility during application and inspection. Stripe coatings should be applied to difficult areas such as edges, welding seams, and holes to meet the required DFT. Weld seams require stripe coating because they are more prone to corrode due to the dissimilar metals.

Clean weld "smoke" from the surface with a hydrocarbon solvent, remove weld splatter, and grind sharp edges on seams until smooth **(Figure 18).**

Table 1. Typical Coating Systems and Expected Lifetime under Normal Ballast Tank Conditions.

Coating type	No. of coats*	DFT mils/ microns	Lifetime (years)
Coal tar epoxy	1	6-8/150-200	5±3
Epoxy Mastic	2	4-6/100-150/coat	10±3
Epoxy Mastic	3	4-6/100-150/coat	15±3

* Assumes brush applied stripe coat on ares difficult to achieve required DFT.

Some vessel owners, including the U.S. Navy employ solvent-free, edge-retentive epoxies applied in two- or three-coat systems with stripe coats. Others are also using solvent-free, high-build "instant-set" urethanes. "Soft" single-package coatings appear to have fallen from favor over the past few years, and are not normally recommended if long-term corrosion protection is the goal. However, they make a fine temporary solution for filling dry voids. Another ballast tank lining system features a single 3-mil inorganic zinc coat with back-up anodes, which is useful in double-bottom vessels handling heated cargo.

Cathodic protection can extend the life of the ballast tank and its coating system but only works when the anodes are submerged, so it is not suitable as a standalone protection system. The design of a cathodic system in a ballast tank is based on:

- General arrangement, midship and longitudinal section plans, and capacity plans
- Tank type: ballast only, cargo-ballast, or segregated ballasts in tankers
- Wetted surface, including supports, pipes, and ladders
- Current density (should be evaluated by a corrosion engineer/ designer)
- Expected lifetime of anodes in years

• Condition of the tank coating and degree of deterioration
• Ballast period: percentage of total time in service and average ballast time in days.

Maintenance. Ballast tank maintenance can take several forms, depending on the tank's previous history, its current condition, and the vessel's operating situation. On a vessel that had a coating system applied during new construction, the tanks should be inspected at the end of the first year, and then every two years with repairs following the manufacturer's recommendations for the existing coating system **(Figures 19 and 20).**



Figure 19. Ballast tank before maintenance.

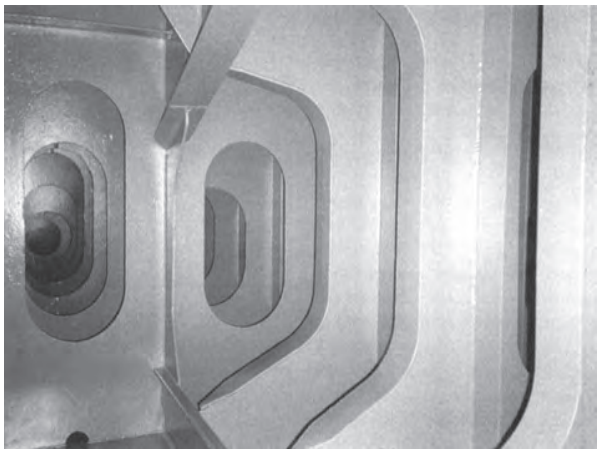


Figure 20. Ballast tank uncoated.

Tanks not coated during construction or exhibiting a complete system failure present very difficult and costly surface preparation challenges relating to heavy scale, deep pits, salt contamination, difficult accessibility, poor lighting, dampness, temperature extremes, and sweating. To remove the scale and salt, it may be necessary to power wash, hand clean, power wash again, abrasive blast and possibly power wash again. Another option is to use electrolytic descaling with magnesium strips but this only works when at least 70% of the paint has failed.

Electrolytic descaling removes only the rust, not the paint. It also requires the tanks to be full of seawater (not brackish) for 8 to 14 days in order for the electrolytic reaction to occur. The tank is then emptied and washed with freshwater as soon as possible to remove the rust scale, salt, and grayish jelly-like calcareous layers. Because this process can produce explosive gases the tanks have to be ventilated and additional safety precautions taken.

Soluble salt contamination testing must always take place with the contaminated tank rewashed until the soluble salt level is acceptable to the coating manufacturer and vessel owner. The lining system manufacturer must approve any chemicals used during this cleaning and decontamination process. Soluble salt left on the surface will cause blistering and paint failure. Once clean, the tank will have to be dried with dehumidifying equipment before the two- or three-coat surface-tolerant epoxy coating system is applied.

Coating Accommodation Areas

Coating systems used in public, or accommodation, areas of vessels should be bright, cleanable and, in most cases, have a "low-flame" spread.

New Construction

Since these spaces are enclosed, the coating system should be designed with potential maintenance application problems already in mind. Products with low-flash points and/or high solvent levels should be avoided. Water-based materials can be used, but require a great deal of fresh air flowing through the painted area so that the water in the film evaporates quickly. While the use of an inorganic zinc/epoxy/polyurethane coating system may appear at first to be a good choice, it is not always the most cost-effective system nor is it the easiest to repair or recoat. Typically, a long or medium oil alkyd or water-borne acrylic system will give the necessary protection in these areas, and is easy to clean and repair. A new coat can then be applied in the future to change the color or otherwise freshen the appearance. An alkyd coating

Table 2. Suggested Systems for Newbuilding in Interior Accommodation Areas.

No. of coats	Product Generic Type	Approximate DFT (See specific product)	Comments
2	Alkyd Primer	2 mils (50 µm)/coat	Typical, well proven system.
1	Alkyd Undercoat	2 mils (50 µm)	Easy to apply and economical.
1	Alkyd Topcoat	2 mils (50 µm)	
1	Acrylic Primer	2 - 3 mils (50 -75 µm)	Easier to clean than the alkyd.
1	Acrylic Primer	2 - 3 mils (50 -75 µm)	Higher cost.
1	Acrylic Topcoat	2 - 3 mils (50 -75 µm)	Better color stability.
1	Epoxy Mastic	6 - 8 mils (150 - 200 µm)	May be top coated with an acrylic for easier cleaning.
1	Epoxy Mastic	6 - 8 mils (150 - 200 µm)	Use in areas below gratings or that may be
1	Epoxy Mastic	6 - 8 mils (150 - 200 µm)	frequently wetted or immersed.

cannot be applied over an inorganic zinc pre-construction or standard primer. To do so will cause saponification and alkyd failure. Two 6 to 8 mil coats of a surface-tolerant epoxy system is another excellent choice for interior accomodation areas as well as for coating decks and other areas that may be exposed to physical abuse or frequent wetting from splash or spillage.

Engine and Machinery Spaces. Engine rooms are frequently painted white to provide a high level of reflected light. The coating used must resist lubricants, fuels, and cleaning solvents as well as abrasion from tools, rolling drums, and moving equipment. High temperatures can yellow paint and shorten the expected life of many products. For these reasons, it is typical to find several different coating systems in an engine room.

Bulkheads and overhead spaces should be coated with a two- or three-coat epoxy system. If the epoxy is not a high gloss, add a third coat of alkyd or acrylic. When initial economy factors in the coating selection, a three- or four-coat alkyd system is another option, although more maintenance and physical damage can be expected.

Paint deck areas with a three-coat epoxy that includes a non-skid additive between the second and third coats. In areas with a very high level of physical abuse consider using a glass-fiber reinforced epoxy coating. Most standard epoxies are not recommended on surfaces that exceed about 200°F (93°C) on a regular basis so another coating must be chosen for certain types of equipment. The coating selected for insulated carbon steel piping will vary with the equipment's temperature range and "cool-down" frequency. As always, share temperature information with the coating manufacturer to ensure the proper coating is selected.

Dry Void/Cofferdams Spaces. There are three things to keep in mind when designing and building a vessel that will have a dry void:

- Dry voids are not dry
- Steel corrodes in dry voids
- Mill scale will not protect steel very long



Figure 21. Dry void.

It is usually false economy to not blast and paint dry voids. In a recent drydocking of a 5-year-old dry cargo ocean barge, the steel repairs and painting to the "dry" double bottom cost over $900,000. Several bottom plates were so badly pitted that they had to be

Table 3. Suggested Systems for Newbuilding in Engine Rooms.

	No. of coats	Product Generic Type	Approximate DFT (See specific product)	Comments
Decks	3	Epoxy Polyamide or Epoxy Mastic	6 - 8 mils (150 - 200 µm) per coat	Add non-skid to second coat in traffic areas.
Bulkheads and Overheads	2 or 3	Epoxy Polyamide or Epoxy Mastic	6 - 8 mils (150 - 200 µm) per coat	Add an optional third coat of high gloss alkyd or acrylic if necessary.
	2 1 1	Long Oil Alkyd Primer Alkyd Topcoat Alkyd Undercoat	2 mils (50 µm)/coat 2 mils (50 µm)/coat 2 mils (50 µm)/coat	Typical, well proven system. Easy to apply and economical.
High Temperature	It should be noted that many "standard" paints will discolor and/or breakdown at continuous temperatures above 200°F (93°C). It is recommended that when the temperature of the substrate is going to be close to or higher than that of a "high temperature" rated coating, such as an epoxy phenolic or some acrylics, a single coat of inorganic zinc or silicone materials should be considered.			
Insulated Carbon Steel Pipe Operating up to 140°F (60°C)	1 1	High Build Epoxy Primer High Build Epoxy Finish	4 to 6 mils (100 - 150 µm) 4 to 6 mils (100 - 150 µm)	An amine-cured epoxy is recommended for chemical resistance.
Insulated Carbon Steel Pipe Operating up to 300°F (150°C)	2	Epoxy Phenolic	4 to 6 mils (100 - 150 µm) per coat	Should be recommended for this service.
Insulated Carbon Steel Pipe Operating between 250° (120°C) and 1,000°F (540°C)	1	Inorganic zinc silicate	3 mils (75 µm)	

replaced. The owner had saved approximately $300,000 by not blasting and painting the entire void area during new construction **(Figure 21).**

An alternative to the significant investment required for abrasive blasting and coating dry voids is to apply a non-hardening coating to minimally prepared surfaces. While this type of material (generally a soft oily or waxy product) can provide suitable protection from corrosion, it is temporary and must be continually inspected and repaired or replaced.

Topside structures, masts, and deck equipment. In today's new construction, many owners use a zinc/epoxy/polyurethane system for the superstructure. However, it is not the easiest system for shipboard crews to repair. Many years of marine coatings experience has shown that single-package systems, such as acrylics and alkyds, provide good and economical protection as finish coats.

Alkyd products will yellow and change color, generally in one year, which is not a problem if the vessel is painted every year. For longer lasting color and gloss, apply a water-borne acrylic or an alkyd modified with polyurethane or silicone as a finish coat. The U.S. Navy is currently using several special blends of silicone alkyds to reduce solar absorption and the appearance of rust bleed.

Maintenance

Maintenance must be based on the new construction system and follow the coating manufacturer's instructions. To test a coating system before maintenance, use "medium" pressure to wipe the surface with a fairly strong solvent, such as epoxy thinner, on a white rag about 20 to 30 times and then observe the rag's surface. Paint on the rag indicates the presence of a single-package material, such as an alkyd or a chlorinated product. The maintenance material should be the same. No paint on the rag is a good indicator of a solvent-resistant surface. Lightly sand glossy surfaces to remove the gloss and roughen the texture. Rust must be removed with a needle gun or sand paper rather than a power wire brush. Use a scraper to remove loose paint.

SSPC SP 1, SP 2, or SP 3 are helpful in defining the type of cleaning required. Areas with the substrate showing should have the existing coating system tapered back from the edge to the finish coat with at least an inch or two of each coat exposed. To keep the new coating from curling up at the edges of the interface, use a 100% solids epoxy penetrating sealer.

Underwater Hulls

On a steel vessel, the underwater hull coating system has to reduce the steel corrosion rate and prevent fouling by ocean organisms that will roughen the surface. On nonmetallic vessels, keeping the hull smooth is the primary requirement. Welding seams,

Table 4. Newbuilding of Topsides, Superstructures, Decks, Masts, and Equipment.

No. of coats	Product Generic Type	Approximate DFT (See specific product)	Comments
1	Inorganic zinc silicate	3 mils (75 µm)	Requires blast cleaning removal of ordinary shop primer to minimum SSPC-SP 10/NACE 2
1	Epoxy mist coat	1 to 2 mils (25 to 50 µm)	
1	High build epoxy	4 to 6 mils (100 to 150 µm)	
1	Polyurethane topcoat	2 to 3 mils (50 to 75 µm)	
2 or 3	Epoxy Polyamide or Epoxy Mastic	6 - 8 mils (150-200 µm) per coat	Add an optional third coat of high gloss alkyd or acrylic if desired.
2	Long Oil Alkyd Primer	2 mils (50 µm)/coat	Easy to apply and economical – However, has a short useful life.
1	Alkyd Undercoat	2 mils (50 µm)	
1	Alkyd Topcoat	2 mils (50 µm)	

valve openings, and bulging plates—surface irregularities that occur during the design process—are generally not changed once the steel vessel is built.

Corrosion, paint flaking, porosity caused by spent antifouling coatings, poor workmanship, external cathodic protection systems, mechanical damage, and fouling are all surface roughening problems that can be corrected during maintenance. A rough hull can slow a vessel considerably or require additional fuel to maintain optimal speeds. Thus controlling hull roughness impacts operating costs **(Figure 22).**

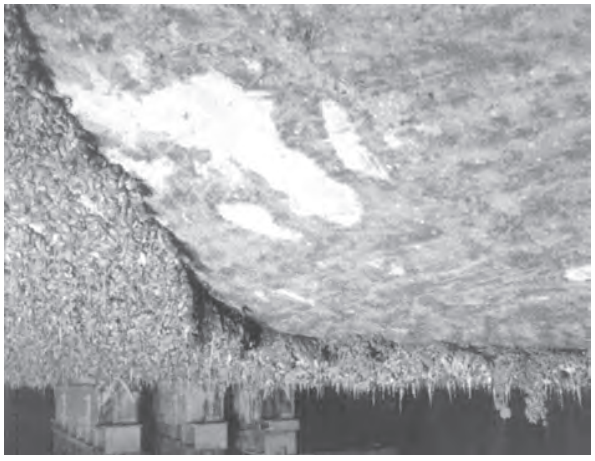


Figure 22. Roughend hull without antifouling agents.

Key Factors in Choosing an Underwater Hull Coating System

Select the hull coating system after consulting with a manufacturer or a consultant specializing in marine coatings. The entire system, anticorrosive and antifouling coats, should come from the same supplier, and the specification for number, type, and DFT of each coat followed exactly. A third-party inspection firm or a representative of the coating supplier's technical services department should be on-site full-time. Some of the issue to address with the coating supplier or consultant:

- Vessel speed
- Vessel trading area
- Drydocking interval and place
- Sailing duration per year
- Economic risk factors

The typical vessel speed will determine whether or not a self-polishing antifouling coating can be used. Slower moving vessels may benefit from a self-polishing antifouling coating. Since fouling problems differ throughout the world, a ship "trading" in areas that require it to move from warm to cold water regularly will require a different antifouling coating than one staying in mostly warm water.

Smaller vessels such as tugboats may be drydocked every year for regular inspection and repair. Less expensive, shorter-life antifouling coatings are typically used in these cases. The U.S. Navy has stated that they are anticipating a 10-year plus drydocking cycle on their ships and, as such, antifouling coatings applied in the future will be expected to provide 10 years of service. Presently, most antifouling coating manufacturers recommend a five-year maximum drydocking interval.

A ship that is often idle will require more frequent dry-dockings and a different type of antifouling coating than a ship that is at sea for most of its life. Self-polishing products work best when the water flowing over the hull removes layer after layer of the coating, continually exposing a fresh layer of antifouling.

Climatic and environmental factors are particularly important in choosing a dry dock location. The dry dock selected must be able to apply the most appropriate antifouling coating as required.

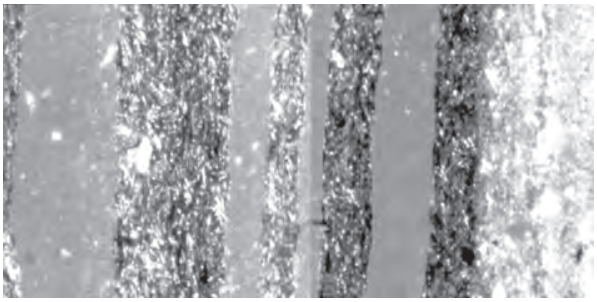


Figure 23. Sandwich coating.

Maintenance

The use of antifoulings creates unique maintenance problems. Some antifoulings lose the biocide, but leave the skeleton of the binder. Most single-package antifouling materials are not suitable as anticorrosive base coatings. This presents the challenge of repairing substrate damage and applying another coat of antifouling without removing the existing coating.

Sandwich coatings, layers of alternating anticorrosive and antifouling coatings, should be avoided if possible. On a small vessel, remove any remaining antifouling coating prior to repairing the anticorrosive layer and then reapply the antifouling material. If any usable antifouling material remains on a larger vessel, spot repair all damages then reapply just enough antifouling material to build the total film thickness back to the originally specified DFT **(Figure 23).**

Complete and inspect this repair carefully so that cracking, alligatoring, and eventual flaking is avoided. Only large, rough areas should be blast cleaned. Mechanically clean smaller areas to avoid damaging the good coating unnecessarily. Apply the anticorrosive coating as specified to the bare steel, with as little overlap as possible. Each touch-up coat should overlap slightly more until the total specified DFT is achieved **(Figures 24 and 25).**

Cleaning the area with fresh water before mechanical or abrasive blast cleaning prevents salt and other contaminants from ruining the surface. When salt is present between the substrate and the paint film, blisters and pits will form.

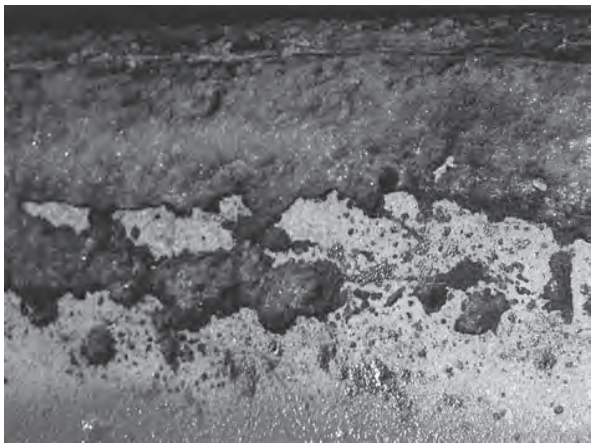


Figure 24. Severe corrosion.

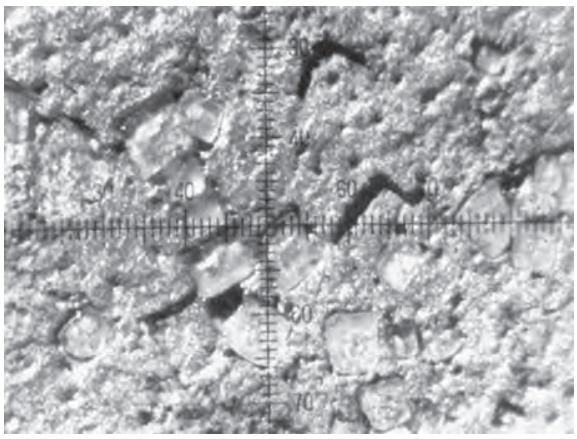


Figure 25. Salt crystals.

Antifoulings

Purpose

- To prevent or reduce microbiological growth
- To provide better fuel economy over the sailing period
- To prevent micro-organisms from penetrating coatings, thus extending corrosion protection

Composition

In their simplest forms, antifoulings consist of a binder, pigments, and solvent. The binder determines the nature of the antifouling protection. Pigments include the antifouling agents, or biocides, and various fillers. Solvents provide a workable body and impart application characteristics.

A chemical substance, the biocide is released at very low rates to kill micro-organisms or inhibit their growth. Cuprous oxide is one of the most common

antifouling biocides still used today. Organotin compounds, predominent during the 1960s and 1970s, are now severely restricted in many countries due to environmental concerns. The Convention on the Control of Harmful Anti-Fouling Systems, adopted by the International Maritime Organization on October 5, 2001, calls for the worldwide “phase out” of organotins by 2008.

Types

There are four choices in antifoulings: conventional, long-life, self-polishing, and fouling release. Conventional antifoulings, also known as soluble-matrix or ablative paints, use a rosin binder that slowly dissolves in seawater. When the coating is immersed in the seawater, biocide leaches out of the paint. This release rate soon falls to a level below which the fouling can be controlled. Effective life is generally short—approximately one year.

Long-life antifoulings, often referred to as insoluble-matrix paints, do not dissolve in seawater. The biocide leeches out of the film, leaving a porous skeleton on the surface. As the porous layer grows, the biocide release rate declines. Eventually, no more biocides can be released, and antifouling performance drops dramatically. Effective service life is up to 24 months, and a relatively porous layer remains on the surface to be removed prior to recoating.

Self-polishing antifoulings come in two classes: tributyltin (TBT) and tin-free. Because TBT will be banned in the very near future, it is not discussed in depth. Tin-free self-polishing products differ greatly from one another and from TBT products. TBT was not just a biocide, it was a part of the binder as well, and relied on hydrolysis. In some cases, contemportary manufacturers are using various blends of water-soluble and water- sensitive binders, along with copper and newer forms of biocides, in tin-free products. In essence, this is a refinement of conventional antifouling materials.

Another tin-free product is hydrolysable in that its binder reacts with the seawater, leading to a more stable reduction of paint thickness and a smoother hull, even on slow or stationary vessels. Hydrolysable materials may have a longer life that comes close to matching TBT products.

Fouling release products are another result of research into replacing TBT. These materials supply a smooth, non-stick surface to impede fouling. Unfortunately, current offerings are typically easy to damage and difficult to repair.

Boottopping Area Coating

Since the boottopping area (water line to rail) may be subject to severe mechanical damage from docking and undocking an inorganic zinc silicate primer and two coats of epoxy will allow an additional degree of protection. For a finish coat, duplicate that used topside.

Coating Aluminum Vessels

Aluminum vessels are coated to impart color and protect against fouling. Damage from dissimilar metal corrosion is a significant concern. Aluminum corrodes preferentially in contact with copper, carbon steel, and other common marine construction materials. If an antifouling coating containing copper has been selected, apply two coats of epoxy-based materials to insulate the aluminum hull from the copper. Figure 26 illustrates an aluminum window frame with a carbon steel insert that was exposed to salt water for about one year. Salt water trapped inside the frame in contact with the aluminum and steel destroyed the aluminum **(Figure 26).**



Figure 26. Salt water damaged aluminum.

Summary

Over the past twenty years, single-package alkyds, chlorinated rubber, and vinyl-based paints have been largely replaced by more complex epoxies, water-borne acrylics, and polyurethane-based materials. Experience, economics, and environmental regulations have influenced these changes.

Between 1990 and 1997, 99 bulk carriers

sank, leading to 654 deaths. Studies conducted by shipping classification societies, insurance companies, international maritime associations, and others in the marine field demonstrate that the most common cause of these catastrophies was structural failure due to a combination of corrosion, fatigue, and type of cargo hauled. Painting a ship when it is new and maintaining that paint over the service life of the vessel is critical.

Suggested Reading

Surface Preparation and Painting of Tanks and Closed Areas; SSPC: Pittsburgh, 2000.

Appleman, B. R.; Heisel, J.L. Technology: Improving the Quality of Preservation Work on U.S. Navy Ships. *Journal of Protective Coatings and Linings,* August 2001.

Thomas, E. D. Technology: The U.S. Navy's Advances in Coating of Ship Tanks. *Journal of Protective Coatings and Linings,* February 2001.

Smith, L. *Applicator Training Bulletin: What You Should Know About Applying Water-borne Coatings;* SSPC: Pittsburgh, 1992.

Kelleher K.; Meyer, D. *Applicator Training Bulletin: What You Should Know About Two-Pack Epoxies and Polyurethanes;* SSPC: Pittsburgh, 1992.

General Dynamics (Electric Boat). *Guidance Manual for the Application of High-Solids Coatings;* MARITECH/ASE Project 3-98-3 for NSRP Technical Panel SP-3, Surface Preparation and Coatings, December 2000.

Candries, M.; Anderson, D.; Atlar, M. Foul Release Systems and Dray. *Journal of Protective Coatings and Linings;* April 2001.

International Organization of Standardization Home Page. http://www.iso.ch (accessed April 2002).

Munger, Charles G. *Corrosion Prevention by Protective Coatings;* NACE: Houston, 1984.

Jotun Paints. Coating and Inspection Manual; Jotun: Sandefjord, Norway, 1997.

International Maritime Organization. Convention on the Control of Harmful Anti-Fouling Systems, adopted on October 5, 2001.

IMO and the Safety of Bulk Carriers. *Focus on IMO;* September 1999.

Appleman, Bernard R.; Fultz, Benjamin. Procedures and Techniques for Coating Interior of Ship Tanks. In *Proceedings of the Coatings for Asia Conference,* 1999, pp 279-286.

Appleman, Bernard R. Ventilation and Dehumidification of Ship Ballast Tanks for Blasting and Coating Work. *Journal of Protective Coatings and Linings;* April 2000, pp 43-50.

Askheim, Erik; Nakken, Olav; Haugland, Bjorne K. How and Why Corrosion Protection of Ballast Tanks Has Become the Business of Classification Societies. *Protective Coatings Europe;* June 1999, pp 48-52.

Askheim, Erik. Ballast Tanks and Cargo Holds in DNVs: Guidelines for Corrosion Protection of Ships. *Protective Coatings Europe;* June 1997, pp 26-36.

Cleland, J.H. Guidelines for Managing Ballast Tank Water. *Protective Coatings Europe;* February 1999, pp. 11-13, 85

Eliasson, Johnny; Frenzel, Lydia. On Service Life of Ballast Tank Coatings Over Waterjetted Surfaces. *Journal of Protective Coatings and Linings;* June 1999, pp 13-15.

Fultz, Ben. Study on Retaining Preconstruction Primers Under Standard Lining Systems for Ship Tanks. *Protective Coatings Europe;* April 1999, pp 36-44.

Hartland, Per. Inside View of Ballast Tanks. *Protective Coatings Europe;* January 2001, pp 59-62.

Jeffreys, Jeremy; Johnson, Jim; Mills, G.; Alveberg, Bjorn Erik. Problem Solving Forum: Limiting Chloride Content in Ballast Tanks. *Journal of Protective Coatings and Linings;* November 2000, pp 17, 18, 20, 22-24.

Research: Twenty-Year Study Released on Cleaning and Coating Ballast Tanks. *Journal of Protective Coatings and Linings;* August 2001, pp 71-72.

Kierkegaard, Henry. Using UHP Waterjetting for Coating Maintenance on Ships at Sea. *Journal of Protective Coatings and Linings;* January 2000, pp 38-47.

Knudsen, Rolf; Eliasson, Johnny; Boocock, Simon. Problem Solving Forum: Using Inorganic Zincs as Holding Primers. *Protective Coatings Europe;* November 1996, pp 4-6, 53.

Kuljian, Gordon; Kaznoff, Alexis. State-of-the-Art Procedures for Ensuring Optimum Coating Longevity in Navy Tank Coating Operations. In *Proceedings of SSPC '96,* pp 70-79.

Malfanti, Roberto. Achieving Cost-Effective Specifications for Ballast Tank Coatings. *Protective Coatings Europe;* October 1998, pp 32-38.

Moya, Jose L. News from the Field: Shipyard and Subcontractor Team Up for Major Ballast Tank Recoating Job. *Protective Coatings Europe;* August

2000, pp 9-12.
Osborne, Michael; Eliasson, Johnny. Tanker Structure Cooperative Forum: Guidelines for Ballast Tank Coating Systems and Surface Preparation. In *Proceedings of PCE 2000,* pp. 387-394.
Innovative Practice: Preparing Ballast Tanks by Electrolytic Descaling. *Protective Coatings Europe;* November 1997, pp 9, 11.
Peterson Builders, Inc.; Associated Coatings Consultants, Inc.; Naval Surface Warfare Center. New Surface Preparation and Coating Repairs Techniques in Ballast Tanks; NSRP 0471; 1996.
Richardt, W. Protecting Marine Newbuildings in Germany. *Protective Coatings Europe;* January 1998, pp 16-24.
Smart, John S.; Bryant, Deborah. Dehumidification for Ballast Tank Corrosion Control in a Tension Leg Platform. In *Proceedings of SSPC '99 ,* pp 225-241.
Applying Linings for Immersion Service: Tutorial at Increasing the Value of Coatings. In *Proceedings of SSPC '98.*
Towers, Rodney. Accelerated Corrosion in Cargo Tanks of Large, Double-Hulled Ships: Causes and Countermeasures. *Journal of Protective Coatings and Linings;* March 2000, pp 30-42.
U.S. Dept. of Navy, Carderock Div.; Naval Surface Warfare Center; National Steel and Shipbuilding Co. *Waste Water Treatment Technology Survey;* NSRP 0516; 1998.
Vold, Helge. Evaluating Protective Coatings for Ballast Tanks. *Protective Coatings Europe,* June 1997, pp 16-22.

Acknowledgements

The author and SSPC gratefully acknowledge John Tanner's peer review of this document.

About the Author

Earl Bowry
Earl Bowry has spent 25 years in the heavy-duty coatings industry employed by several different worldwide coatings and abrasives manufacturers. He has been a sales representative, a technical service engineer, a marketing manager, and a sales manager. He is currently employed as the technical support engineer for ocean shipping at Jotun Paints, Inc. North America. Mr. Bowry was the founding chair of the Chesapeake and Hampton Roads Chapters of SSPC and has served as chair of the NACE Virginia Chapter.

Chapter 7
Inspection

Kenneth A. Trimber and William D. Corbett

Introduction

The purpose of this chapter is to outline the inspections required to assure quality coating work. In addition, paint inspection equipment is described and summarized.

The Function of the Coating Inspector

Throughout this discussion the term "inspector" shall be used to indicate an individual or a group of individuals whose job it is to witness, report, and document coating work in a formal fashion. While painters themselves may conduct informal inspections, this will not be discussed. Instead inspectors providing a quality control (QC) function, or first line inspection of each aspect of the coating work will be described.

QC inspectors are specially trained contractor personnel or employees of a third-party hired by the contractor or owner to provide QC services. The quality assurance (QA) personnel working for the facility or company can also perform spot checks of work or any or all of the steps addressed herein.

The inspector's purpose is to verify that the requirements of the coating specification are met. This is analogous to that of a police officer: the inspector enforces the rules (specification) without exception even if these rules are deemed inadequate. An authorization to deviate from the specification is the responsibility of the "judge," usually the specification writer, contract administrator, or engineer in charge of the job. The inspector certainly may venture an opinion to the engineer and provide recommendations, but cannot unilaterally deviate from the specifications at the working level.

Besides specification enforcement, a QC coatings inspector provides thorough project documentation including a commentary on the type and adequacy of equipment at the job site, the rate of work progress, information regarding ambient conditions and controls, and verification that the surface preparation, coating application, coating thickness, and curing are as required. This is supplemented with any other information deemed to be of consequence to the quality and progress of the work.

The amount and type of QA inspection on behalf of the facility owner often varies according to the size of the project and the type of application contract. There are a number of types of contracts, but for simplicity two general categories, "fixed price" and "cost plus" will be addressed.

QA inspection under a "fixed price" application contract takes place to ensure that the contractor does not "cut corners" in order to hurry the job. While an evaluation of the equipment, work procedures, and sequence, etc. is important, the equipment and methods by which the contractor accomplishes the job are essentially at the contractor's discretion, provided the requirements of the specifications are met. When performing QA inspection services for a "cost plus" application contract, a knowledgeable inspector must be able to evaluate the contractor's equipment for adequacy and assess whether the rate of progress is reasonable.

Safety Considerations

Safety is paramount on any job. Coating inspectors should be aware of basic safety requirements and should have received personal protection training. If lighting, scaffolding, or equipment malfunctions present safety hazards, or appropriate protection from toxic substances or falls is not provided, the appropriate safety personnel should be notified. Paint application inherently presents dangers because the solvents used can be flammable and because many objects to be painted are relatively high or difficult to access. The inspector must be assured of the safety of these appurtenances before becoming involved.

Inspection Sequence

Inspection often begins with a pre-job conference where the ground rules are set. The inspector is responsible for witnessing, verifying, inspecting, and documenting the work at various

inspection points:

- Inspecting Pre-Surface Preparation
- Measuring Ambient Conditions and Surface Temperature
- Evaluating Compressor (Air Cleanliness) and Surface Preparation Equipment
- Determining Surface Preparation (Cleanliness and Profile)
- Inspecting Application Equipment
- Witnessing Coating Mixing
- Inspecting Coating Application Techniques
- Determining Wet and Dry Film Thickness
- Evaluating Cleanliness Between Coats
- Testing for Pinholes and Holidays
- Testing Adhesion
- Evaluating Cure

Inspecting Pre-Surface Preparation

Prior to surface preparation or other coating activities, it may be necessary to confirm that the work is ready to be prepared and painted. Heavy deposits of grease, soil, dust, dirt, cement splatter, and other contaminants must be removed, according to SSPC-SP 1, so that they are not redeposited onto freshly cleaned surfaces. This is particularly important when recycled abrasives are used so the abrasive itself does not become contaminated.

The specification may require that weld splatter be ground or otherwise removed and that sharp edges be rounded. Laminations in plate steel, if detected prior to blast cleaning, may have to be opened and, if deep enough, could require weld filling. If sufficient deterioration has occurred to the structure, replacing some structural members, “fish plating,” or other repair may be necessary. Responsibility for such repair should be specified in procurement documents. Although this work is not ordinarily considered to be part of the coating contract, the inspector should confirm that it has been performed before the surface preparation and painting work. As a prelude to most painting operations, taping and masking is used to protect adjoining surfaces not to be painted. The NACE Visual Comparator for Surface Finishing of Welds Prior to Coating, as referenced by NACE RP 0178, may be used to inspect lap and butt welds, primarily for immersion service lining systems.

If the work involves maintenance painting, a determination of the percentage of rusting in an area may be helpful. Assessments can be made in accordance with SSPC-Vis 2, *Standard Method of Evaluating Degree of Rusting on Painted Steel Surfaces.*

Perhaps the best method of determining coating compatibility is a test patch application of the new coating over the old, a few months or more in advance of production painting. The test patch is then evaluated for adhesion, and examined for signs of wrinkling, lifting, or other evidence of incompatibility.

Details regarding overcoating and test patch assessments can be found in SSPC TU 3, *Overcoating,* and ASTM D5064, *Practice for Conducting a Patch Test to Assess Coating Compatibility.*

Measurement Of Ambient Conditions

It is implicit that surface preparation and coating work be done only under suitable ambient conditions of temperature, humidity, and dew point. For most catalyzed coatings, specific minimum temperatures must be met. Many inorganic zinc-rich coatings (ethyl silicate), or moisture-cure urethanes require minimum humidity levels as well. The inspector should be cognizant of weather forecasts (particularly if coating work is to be done outdoors) and the temperature and humidity restrictions of the specific coating material(s) being applied to the surfaces.

Other ambient conditions that might affect painting operations should be noted such as potential industrial or chemical airborne contamination, water spray downwind from a cooling tower, leaking steam or chemical lines, and contamination from normal plant or adjacent operations.

Often, heating or dehumidification equipment is used to control (and maintain) ambient conditions for painting operations within tanks or contained areas. Ideally, a heater should be indirect fired so it does not contaminate the surface with products of combustion. Ventilation, if required, should provide for sufficient air flow and adequate ventilation of all areas where work is being performed. Most solvents are heavier than air; thus, the dangers of explosion and flammability are frequently the greatest in low-lying areas. Control of airborne contaminants such as dust and abrasive must also be effective in order to prevent contamination of the painted surfaces or unacceptable worker exposures.

While much of the above is inspected visually or with specially designed equipment for determining

solvent concentrations, the ambient conditions of air temperature, relative humidity, and dew point for surface preparation and painting quality are determined using instrumentation. This includes psychrometers **(Figure 1 and 2)** or instruments that give direct read-out recordings of humidity **(Figure 3)** and dew point. Measurements with these instruments are taken before the work begins each day and periodically throughout the day. A suggested minimum frequency is every four hours, or sooner if weather conditions appear to be worsening.

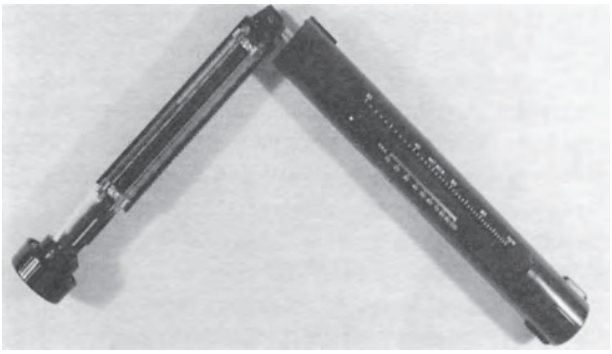


Figure 1. Sling psychrometer used for measuring wet and dry bulb temperatures in order to establish relative humidity and dew point. The instrument is spun in the air to reach termperature stabilization.

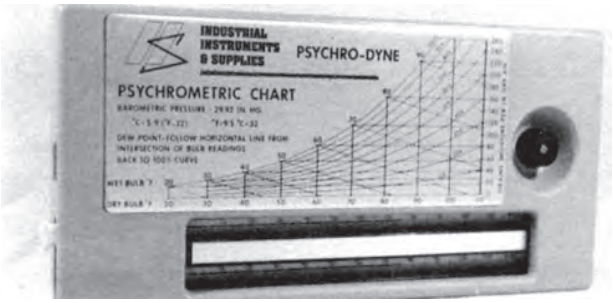


Figure 2. An electric psychrometer uses a fan to draw air across therrmometer bulbs, providing the wet and dry bulb temperature readings.

The psychrometer consists of two identical tube thermometers, one of which is covered with a wick or sock that is saturated with water. The covered thermometer is called the “wet bulb” and the other is the “dry bulb.” The dry bulb gives the ambient air temperature while the wet bulb temperature provides results from the latent heat loss of water evaporation from the wetted sock. The faster the rate of water evaporation, the lower the humidity and dew point. There are generally two types of psychrometers: the sling psychrometer, shown in Figure 1, and the fan or motor-driven psychrometer, shown in Figure 2. Electronic psychrometers are also gaining in popularity.

When using the sling psychrometer as detailed in ASTM E 337, the wet bulb sock is saturated with water, the instrument whirled rapidly for approximately 20 seconds, and a reading of the wet bulb quickly taken. The cycle is repeated (spinning/reading without additional wetting) until the wet bulb temperature stabilizes. Stabilization occurs when three consecutive readings of the wet bulb remain the same. At this time both the dry and wet bulb temperatures are recorded.

When using the fan-operated psychrometer, the wet bulb sock is saturated with water and the fan is started. Approximately two minutes are required for stabilization, and one need only observe the wet bulb thermometer and record both temperatures when the wet bulb temperature remains unchanged.

When the instruments are used in air temperatures less than freezing—32˚F (0˚C), the accuracy of the readings is questionable. The wet bulb thermometer will drop below 32˚F (0˚C) to a certain point (e.g., 27˚F [-2.7˚C]), then “heat up” rapidly to the freezing point. Quite often when using a sling psychrometer, this will take place as the instrument is whirled; therefore, a wet bulb temperature of 32˚F (0˚C) may always be obtained. When using the motor-driven psychrometer, one can observe the wet bulb temperature drop below freezing, then rise rapidly to 32˚F (0˚C). However, the low value may still be incorrect. Thus if the temperature is below 32˚F (0˚C), the ambient conditions will have to be established by other means. This could be accomplished by obtaining the dew point and relative humidity on a direct read-out instrument using more sophisticated equipment **(Figure 3).** Alternatively, the tube psychrometers can be supplimented with inexpensive direct reading humidity indicators. The psychrometer would be used only to determine the ambient temperature (dry bulb). These two values (dry bulb and humidity) can then be used to determine the wet bulb and dew point temperatures by plotting out this information “in reverse” on charts or tables.

After the dry bulb and wet bulb temperatures are determined, a psychrometric chart or table is used to determine the relative humidity and dew point temperatures. Charts require plotting the dry bulb and

wet bulb temperatures on different lines and interpolating the relative humidity and dew point from their intersection.



Figure 3. A digital hygrothermometer gives instant readout of air temperature, relative humidity, and dewpoint.

The U.S. Department of Commerce Weather Bureau has created individual psychrometric tables for relative humidity and dew point. To use the tables, the wet bulb temperature is subtracted from the dry bulb temperature and the difference found along the top row of the table labeled "depression of the wet bulb thermometer." The dry bulb (air) temperature is found down the left column and the intersection of the two is either the humidity or the dew point, depending upon which table is used. The U.S. Department of Commerce NOAA-WSTA B-0-6E (5-72) Relative Humidity and Dew Point Table includes both sets of information on one table.

Dew point is defined as the temperature at which moisture will condense. Dew point is important in coating work because moisture condensation on the surface will cause freshly blast cleaned steel to rust, or a thin, often invisible film of moisture trapped between coats may cause premature coating failure. Accordingly, the industry has established a dew point/surface temperature safety factor. Surface preparation and coating application should not take place unless the dew point is 5°F (-15°C).

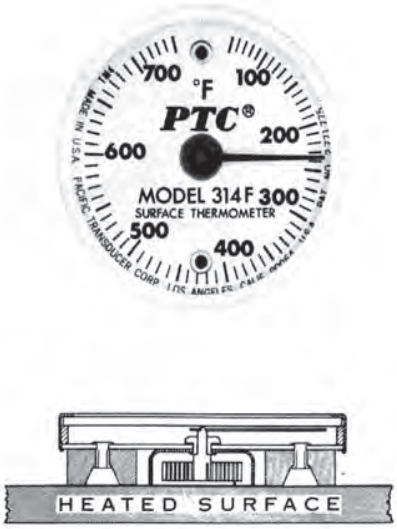


Figure 4. A surface temperature thermometer establishes the temperature of substrates during blast cleaning and painting.

Different field instruments are used for determining surface temperature. One of the most common is a surface temperature thermometer **(Figure 4),** which consists of a bimetallic sensing spring that is shielded from drafts. The instrument includes two magnets on the sensing side to attach to ferrous substrates. For non-ferrous surfaces, attach the thermometer using tape across the face of the gauge. A minimum of two minutes is required for temperature stabilization. Other field instruments for determining surface temperature are direct reading thermocouple/thermisters **(Figure 5a).** These instruments utilize a sensing probe that is touched to the surface, resulting in a direct temperature readout. Only a few seconds are required for a temperature reading to stabilize. Non-contact infrared (IR) thermometers are also available for use **(Figure 5b).** Accurate temperature readings can be obtained from a few inches to many feet away from the surface by simply pointing the IR beam at the surface. Some models contain a laser sighting.

With any of the instruments used for determining ambient conditions and surface temperatures, the readings should be taken at the actual locations of the work. For general readings where dew point is the concern, however, one should

consider the coldest point on the structure because a surface temperature/dew point relationship problem will occur there first. Air and surface temperature considerations are also important to ensure that coatings are not applied outside of their temperature limitations—in areas too cool or too warm. Accordingly, readings for this purpose should be made at the coolest or warmest areas.

Typical requirements for ambient painting conditions are given in SSPC-PA 1. Specific requirements are provided in the project specification and/or the coating manufacturer's product data sheets.



Figure 5a. Direct reading thermocouple/thermister.



Figure 5b. Non-contact infrared (IR) thermometer.

Evaluating Surface Preparation Equipment

The air compressor and other equipment used for blast cleaning and any hand or power tools should be inspected. The inspector need not have an extensive technical background on the equipment, but should have enough familiarity to verify its suitability.

Air Compressor and Air Cleanliness

When an air compressor is used for blast cleaning, power tool cleaning, or spraying equipment, the compressor should be appropriately sized and have a suitable volume ($ft.^3$/min.) to maintain the required air pressures. Abrasive blast cleaning equipment suppliers have charts and data available that are excellent aids for determining required sizes of compressors, air and abrasive lines, nozzles, and so forth.

The compressed air used for blast cleaning, blowdown, and air atomization for spray application should be checked for contaminants. Adequate moisture and oil traps should be used on all lines to assure that the air is sufficiently dry and oil-free in order to avoid interfering with the quality of the work.

A simple test for determining air cleanliness requires positioning an "absorbent collector" (clean white piece of blotter paper) within 24 inches of the air supply, downstream of moisture and oil separators.

ASTM cautions the tester to avoid personal contact with the air stream. Therefore, it is helpful to mount the paper on a rigid frame (e.g., 1/2-inch plywood) using duct tape. The air is permitted to blow on the blotter paper for a minimum of one minute followed by inspection for signs of moisture or oil contamination on the blotter. Obviously, if there is no discoloration on the blotter paper, the quality of the air is excellent, while streams of moisture and oil running down the sheet indicate unsatisfactory air.

Unfortunately, the point where good air becomes "bad" is difficult to determine. However, by using blotter paper (or a clean cloth), one can make judgments as to the air quality. Inspec the surface thoroughly for moisture or oil contamination after preparation or painting and correlate these results with the results of the blotter test.

In addition, the proper functioning of in-line moisture and oil traps can be evaluated on a comparative basis from the results of the blotter test. For work requiring that absolutely no moisture or oil be

permitted in the compressed air, oil-less compressors and sophisticated air drying equipment are available.

Blast Cleaning Machine

The blast cleaning machine mixes the abrasive with the air stream. The abrasive metering valve regulating the flow of abrasive into the air stream is perhaps one of the most overlooked but important considerations affecting the rate of production. Generally, too much abrasive is fed into the air stream, resulting in both decreased production and increased abrasive costs. The machine must be equipped for "dead man" capability so that it automatically shuts down if the nozzle is dropped [OSHA 29 CFR 1910.244(b)]. It should also be equipped with moisture and oil separators, or external separators should be provided. Since the tank of the blast cleaning machine is a pressure vessel, it should be constructed according to pressure vessel codes.

Abrasive

There are a wide variety of abrasives available for blast cleaning. The size, type, and hardness have a significant impact on the surface profile and speed of cleaning. Metallic shot and grit abrasives are commonly used for rotary wheel blast cleaning because they can be recycled. Iron and steel shot, grit, aluminum oxide, and non-traditional abrasives such as glass beads can be recycled and used in field operations as well, provided appropriate equipment is available to separate fines, paint, rust, and mill scale from the collected abrasive. Various slag abrasives are widely used in field applications, and in some cases, silica sand is still being used. However, its use as a blast cleaning abrasive is declining because of the potential silicosis hazards. Sand and slag abrasives are expendable and should not be recycled.

It is important that all abrasives be clean and free of moisture at the time of use. Abrasives should be stored off the ground and protected from the elements. Only expendable abrasives that have been washed at the manufacturing and packaging plant should be used. The washing should be done using fresh water only; if brackish water is used, chloride contamination of the cleaned surface can result, with subsequent rust bloom in humid environments as well as the potential for osmotic blistering of the coating film once in service.

Although there is no inspection apparatus for determining the cleanliness of the abrasive used, a visual inspection can be made to ensure that it is not damp or contaminated. When abrasive recycling systems are used, a simple test for the presence of oil or grease contamination can be conducted by dropping some of the abrasive (e.g., a handfull) into a small vial of water (e.g., 8 ounces) and shaking the vial vigorously. The top of the water is inspected for a film of grease or oil which will be present if the abrasive is contaminated. Dirt and dust in the abrasive can be assessed in the same manner. Small abrasive "fines" will be held by surface tension at the meniscus, and a dirty abrasive will color the water or cause turbidity. However, water-soluble contaminants such as salt will not be detected using this test. If water-soluble contaminants are present, a litmus paper test of the water in the vial will tell if they are acidic or alkaline. If neutral, a drop of 5% silver nitrate solution can be added to the water. The formation of a white precipitate will indicate the presence of chlorides. Alternatively, allow the water to evaporate and look for salt crystals, or use a chloride indicator strip to quantify the amount of chloride present in the water extract **(Figure 6).** Another field method for determining the presence of soluble salts in the abrasive involves the use of a conductivity meter to test a mixture of water



Figure 6. Testing for the presence chlorides.

and the abrasive. This test is described in ASTM D 4940. Commercially available kits specifically designed for the detection of chloride contamination on abrasive media and in wash water (used during pressure washing, waterjetting, or wet abrasive blast cleaning) can also be employed **(Figures 7a and 7b).**





Figures 7a and b. Commercial tests kits for detecting chloride contamination on abrasive media (a) and in wash water (b).

Forced Air and Abrasive Hoses

Sharp constrictions or bends in these lines should be eliminated, and they should be kept as short as possible to avoid friction and loss of pressure. For safety purposes, the couplings must be wired together to ensure secure closure and to prevent the connections from working loose and coming apart. Wire cables (whip checks) are also used to help maintain safety, in the event that the hoses come uncoupled during blast cleaning. Blast hoses must also be equipped with static wire grounding, as a considerable amount of friction is generated by abrasive flowing though the blast hose.

Blast Cleaning Nozzles And Nozzle Pressure

A great variety of nozzle sizes, types, and lengths are available for cleaning purposes. The specific nozzle chosen will depend upon the specific cleaning job. Venturi type nozzles provide a higher abrasive velocity and a larger blast pattern than straight barrel types of the same orifice size. In general, the longer the barrel and the larger the orifice, the faster the cleaning rate provided an ample volume of compressed air is available to maintain high pressures at the nozzle. Cracked nozzles and worn nozzles, even if not cracked, will reduce the rate of blast cleaning. As a rule of thumb, a nozzle that has been worn beyond 25% of its original inside diameter (I. D.) should not be used. A nozzle orifice gauge **(Figure 8)** is available for determining the orifice size after use. The number etched on the nozzle housing indicates the size when new (in sixteenths of an inch). For example, a No. 8 nozzle is equivalent to 1/2 inch inside diameter, when new.

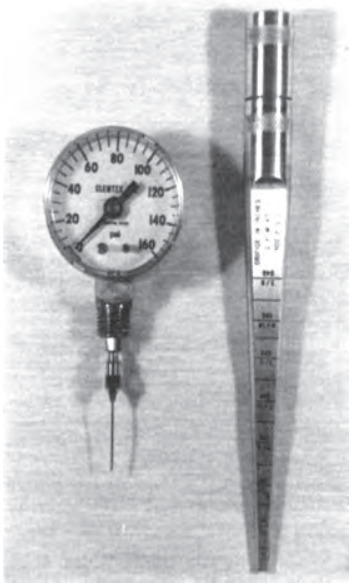


Figure 8. Nozzle orifice gauge (right) measures the nozzle orifice and indicates CFM of air required for the size. Hypodermic needle pressure gauge (left) measures air pressure at the nozzle when the needle is inserted through the blast hose.

The amount of air pressure at the blast nozzle is a determining factor in cleaning rate production. The optimum nozzle pressure is 90 to 100 psig for most

abrasives, although there are some exceptions. Optimum pressures when using steel grit, for example, may be 125 psig or even higher. The blast cleaning air pressure should be determined at the nozzle rather than at the gauge on the compressor because there will be pressure drops in the system due to hose length, bends, restrictions, air fed to the blast pot, moisture traps, and multiple blasters using the same compressed air source. Air pressure at the blast nozzle can be determined using a hypodermic needle air pressure gauge.

The gauge needle is inserted through the blast hose as close to the nozzle as is practical. The direction of needle placement should be toward the nozzle. Pressure readings are taken with the nozzle in operation (abrasive flowing). At the same time, all other pneumatic equipment using the same compressor system must be in operation, and multiple blasters must operate their nozzles simultaneously, in order to obtain an accurate measurement.

Rotary Wheel Blast Cleaning Equipment

Many fabricating shops and painting sites are equipped with rotary wheel blast cleaning equipment in order to efficiently prepare a surface for painting. The number of wheels directly affects the area that can be cleaned, and the type of structural shapes that can be cleaned.

Adjustments can be made to direct the abrasive stream from each wheel to the desired location in order to provide a uniform cleaning pattern. The speed through the machine determines the degree of cleaning; the slower the material goes through the machine, the greater the degree of cleaning.

Complex structural shapes are particularly hard to clean using automated equipment. The interior of box girders, enclosed shapes, and shielded members cannot be cleaned, unless cleaning is done prior to fabrication. In many instances, fabricators will employ handheld blast cleaning equipment in tandem with the automated equipment to reach the limited access areas.

Surface preparation methods such as vacuum blast cleaning, water blasting with and without abrasive injection, wet abrasive blast cleaning, and hand and power tool cleaning are discussed in other chapters of this book.

Determining Surface Preparation Cleanliness and Profile

Cleanliness

All surfaces should be inspected after surface preparation to ensure compliance with the specification. SSPC's surface preparation specifications describe hand and power tool cleaning, abrasive blast cleaning, waterjetting, etc., including the type and percentage of residues permitted to remain on the surface. It is important that this inspection be timely, in order to avoid any rusting of cleaned surfaces prior to applying the primer **(Figure 9).**



Figure 9. A selection of SSPC visual standards.

The written definitions for abrasive blast cleaned surfaces are supplemented by SSPC Vis1, which photographically depicts the surface appearance of various grades of blast cleaning over four initial mill scale and rust conditions on steel. The standards are visually compared with the prepared surface to determine the degree of cleanliness. ISO also has visual standards for evaluating surface cleanliness.

Agreement on the desired appearance of a cleaned surface using commercially available reference photographs is often difficult to achieve because of shadows and hues caused by the abrasive used, the pattern and degree of prior rusting, and numerous other factors unique to each project. As a result, job site standards are often developed to reach agreement on the appearance prior to beginning production work. Sections of the structure (or test panels of a similar nature) are prepared and all parties involved ultimately select the panels or areas that are representative of the desired end result. When

inspecting the quality of surface preparation, much of the effort should be spent on areas that are difficult to access such as the back sides or undersides of angles or supporting steel.

Cleanliness after surface preparation must also be examined. Residual traces of abrasive must be blown, swept, or vacuumed from the surface prior to primer application. It is also important to ensure that dust is removed from the surface prior to painting, particularly the “fine” film of dust-like spent abrasive often held to the blast cleaned surface by static electricity. Any scaffolding, staging, or support steel above the area to be coated must be blown down and cleaned to prevent abrasive and debris from dropping onto the freshly cleaned surface, or later contaminating the freshly primed surface. Adjacent blast cleaning and painting should not be perfomed concurrently unless permitted by the governing specification, and provided the blast cleaning operations are adequately isolated to prevent contamination of the freshly painted surfaces. The surface may also be inspected to determine if it is chemically clean and free of detrimental concentrations of soluble salts. This is discussed in a separate chapter of this book.

Profile

The surface profile, anchor pattern, or roughness is defined as the maximum average peak-to-valley depth (or valley-to-peak height) created during surface preparation. The terms are most commonly associated with abrasive blast cleaning and are the result of the impact of the abrasive onto the substrate. A white metal blast can have a 1, 2, 3, or 4 mil profile; likewise, a commercial blast can have a 1, 2, 3, or 4 mil profile. Specifying a certain blast cleanliness says nothing of the profile requirement. It must be addressed separately.

Surface profile is important because it increases the surface area to which the coatings can adhere, and provides a mechanical anchor to enhance coating adhesion. As a general rule, heavier coatings require a deeper surface profile than thinner coatings. Surface profile determinations are generally made in the field or shop using one of three instruments: a surface profile comparator, a depth micrometer, or replica tape. All three methods are described in ASTM D 4417. Magnetic measurements of surface profile have been attempted with little success. More sophisticated laboratory methods include a profilometer and a depth measuring microscope. SSPC’s *Surface Profile for Anti-Corrosion Paints* discusses a standardized method of measuring profile using a microscope.

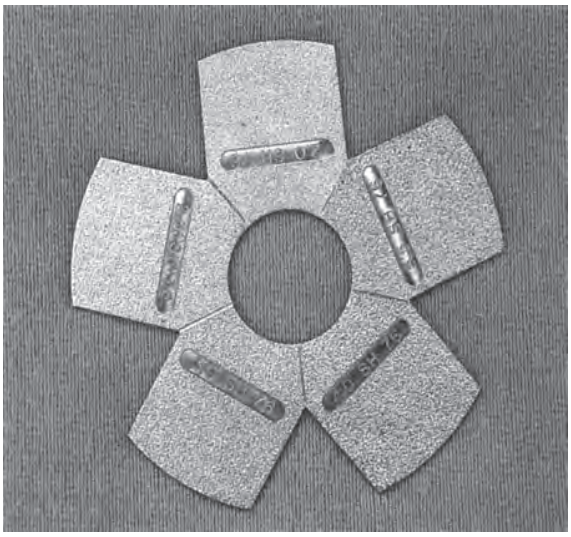


Figure 10. The surface profile comparator consists of a lighted magnifier and reference disk (shown) for visually comparing the anchor pattern of blast cleaned steel. Reference disks are available for sand, grit, or shot abrasives.

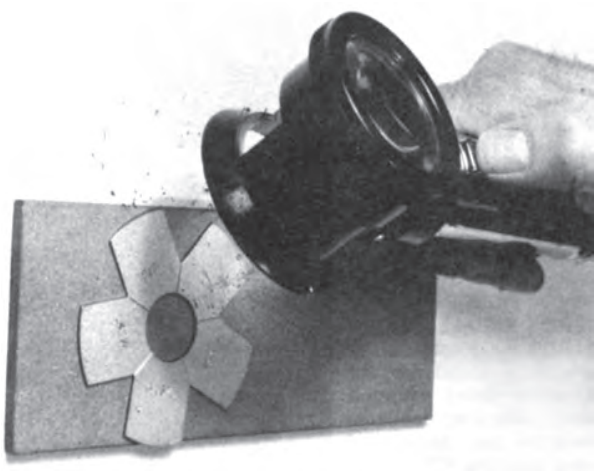


Figure 11. Surface comparator in use measuring surface profile.

The most common surface profile comparator is the Keane-Tator Surface Profile Comparator **(Figures 10 and 11),** which consists of a reference disc and a 5-power illuminated magnifier. The disc is held magnetically against the magnifier, through which

prepared surface and disc segments can be viewed simultaneously. The reference disc has five separate leaves or segments, each of which is assigned a number representative of the profile depth of the particular leaf. Each disc is a high purity nickel electroformed copy of a master. The master disc was measured microscopically at SSPC to establish its profile depth.

The reference disc is compared with the surface through the 5-power magnifier. The leaf or leaves that most closely approximate the roughness of the surface are considered to be the profile of that surface. For example, the profile may be 2 mils, or perhaps from 2 to 3 mils if the surface roughness appears to lie between the 2 and 3 mil leaves.

There are three reference discs available. The one to use for measurement depends upon the type of abrasive. Different abrasives generate a different surface profile appearance, although the peak-to-valley depths may be identical. For example, shot is round when compared with a more angular grit. In order to achieve similar profile depths, shot, by virtue of its shape, will generally result in greater lateral distances between the peaks than grit provides, resulting in a lower peak count per given area. The optical effect provides an illusion that the profile of the shot-blast cleaned surface is deeper than the grit-blast cleaned surface (because the peaks are wider apart), even when the depths are essentially identical. Therefore, it is critical that the correct reference disc be selected.

The designations for the three reference discs available with the instrument are: S for sand; G/S for metallic grit or slag; and SH for shot. The numbering system on each leaf consists of a number followed by a letter designation, then another number. The first number represents the profile depth of that leaf, the letter(s) represents the abrasive type used (sand, grit/slag, or shot), and the final number represents the year that the master disc was formed. For example, 1S70 indicates that that leaf was prepared to a 1 mil profile using sand as the abrasive and that the master disc was formed in 1970. The year that the master disc was formed is only significant if it were to be replaced at a later date. Another field instrument used for this purpose is a pit depth finder.

Surface profile depth can also be determined by using replica tape. Replica tape consists of compressible foam attached to a uniform 2 mil film of mylar. The tape is pressed onto the blast cleaned surface, foam side down, and the mylar rubbed vigorously with a blunt instrument, such as a swizzle stick or burnishing tool. The peaks and valleys of the profile conform to the compressible foam and the peaks will ultimately touch, but not alter the thickness of the mylar, as the mylar is non-compressible. The tape is removed and measured using a light spring-loaded micrometer, which provides a reading from the upper or outermost surface of the mylar to the high spots on the foam (corresponding with the valleys of the profile). The total micrometer reading is adjusted for the thickness of the mylar by subtracting 2 mils from the result to provide a direct reading of the maximum average profile. The tape is available in four ranges: “coarse” for profile measurements from 0.8 to 2.0 mils; “paint grade” for measurements from 1.3 to 3.3 mils; “x-coarse” for measurements from 1.5 to 4.5 mils; and “x-coarse plus” for measurements from 4 to approximately 6.5 mils.

The replica tape will retain the impression indefinitely, provided it is stored in a cool area with no pressure ever applied. Conceivably, replicas of profile depths could be kept on file permanently for future reference.

It is important that the inspector realize that each method has its limitations. For example, the comparator can be subjective, and persons using it could be biased by the results of others. The peaks of the profile may be too close together to permit the projecting pin of the surface profile gauge (depth micrometer) to reach the valleys, or the surface might be irregular or wavy, holding the base of the instrument slightly above the plane of the profile, giving erroneously high readings. Replica tape cannot be used for profile depths less than 0.8 mil nor exceeding 6.5 mils, and if there is any dirt or dust contamination on the surface, it will be picked up and incorrectly read as additional profile depth on a spring-loaded micrometer. Finally, it is important to realize that there may not be exact correlation among each of the above methods because each takes in a different peak count or surface area for its measurement. Therefore, it is advisable that all parties concerned agree upon the method that will be used to determine the surface profile and not deviate from it. Coating manufacturers will occasionally supply a profile reference coupon representative of the roughness necessary for their product or alternatively may specify

the use of a specific instrument. Oftentimes project specifications will dictate the method (and frequency) of surface profile measurements.

Inspecting Application Equipment

The inspector must also be familiar with the methods and equipment used for coatings application.

Spray Application Equipment

Spray equipment for traditional industrial coatings is classified as either air atomized or airless. With air atomization equipment, the paint is fed through the fluid line at relatively low pressures, and compressed air is directed at the fluid stream through an air cap to atomize it. Adjusting the fluid stream and air pressure enables the painter to adjust the spray pattern. Only the minimum pressures necessary to adequately atomize the paint should be used. The proper fluid tip and needle must be chosen, as well as an air cap design, all based on the coating manufacturer's recomendations. Because the compressed air mixes with the coating, filters must be used to ensure a clean air supply.

In airless spraying, hydraulic pressure (1000-3000 psi and higher) is used to atomize the paint through a small diameter spray tip, much in the same manner as water is dispersed into droplets when passing through a garden hose spray nozzle. For airless spray, variations in the spray pattern can be attained only by changing the spray tip (fluid orifice), although some adjustable tips are available. Choice of the appropriate tip, as well as variation in fluid pressure, can result in a wide range of spray patterns suitable for almost any application. As a general rule, airless spray tips have an identification number indicating the orifice size and spray pattern size. For example, a 4017 tip is 0.017 inch in size and produces an 8 inch spray patten (2x the first I.D. number) at a 12 inch distance from the spray tip to the surface to be coated.

The coating manufacturer's application instructions usually recommend the appropriate spray tips and air caps for air spray and spray tip sizes and fluid pressures for airless application. These are only recommendations and under certain conditions, other tip or air cap combinations may be more appropriate. Care should be taken when cleaning the tip and air caps as the orifices can be easily damaged.

The predominant malfunction of spray equipment is attributable to lack of cleanliness, both of the spray gun itself and of fluid lines. Paint chips or agglomerations and blast cleaning abrasive particles are of sufficient size to clog the small diameter orifices.

Additionally, cleanliness of mixing pots, spray pots, spray lines, spray guns, or other application equipment is necessary for good paint application. Dirty equipment can cause new paint to become contaminated with old. Dislodged particles can clog the spray gun, perhaps allowing the pot life to be exceeded, or even result in the deposition of incompatible traces of previously applied material in the new paint film. Cleanliness of all spray application equipment should be verified prior to mixing the paint to avoid problems with clogging or contamination.

Spray Pot

The spray pot should be clean and in good working order prior to use. Many types of paints, particularly zinc-rich primers, require the use of an agitated pot (one equipped with a stirring paddle) in order to keep the paint components in suspension. Air and fluid pressure gauges should be available and functional on conventional (air) spray pots. The pressure release valve should also be operative. The conventional pot should be equipped with diaphragm pressure regulators, making it possible to control both air and fluid pressure to the spray gun from the pot. A variation of conventional spray equipment, high-volume low-pressure (HVLP) spray guns, are typically equipped with a pressure regulator close to the spray gun with the atomization pressure maintained between 0.1 and 10 psi.

Mixing Paint Material

Mixing is perhaps one of the most important, yet one of the most underappreciated operations. Improper mixing or thinning can affect the coating's ability to perform. However, mixing is not always specified as an inspection "hold point" in painting contracts. Regardless, there should be some means to ensure that all components of a multi-component paint system have been added, that mixing is thorough and proper, and that any required induction times have been met. Leaking or damaged containers should not be used, particularly with catalyzed paints as some of the components necessary for complete cure may have leaked out or evaporated and proper proportioning may not be achievable. Containers with

illegible labels should not be used. Mixing should continue until the paint becomes smooth, homogeneous, and free of surface “swirls” or pigment lumps or agglomerations. Unless prohibited by the manufacturer, use mechanical stirrers. Some paints tend to settle out upon prolonged storage, so “boxing” is beneficial to ensure that all pigment settled on the bottom of the container is incorporated in the mixed paint.

When adding zinc dust to the vehicle of zinc-rich primers, it is good practice to sift the zinc dust through a screen into the liquid portion while mixing. This helps to reduce a problem when spraying two-component zinc-rich primers; that is, gun clogging caused by pigment agglomerations that are not properly dispersed. For such heavily pigmented coatings, it is also important that the spray pot agitator is operable to keep the zinc in suspension.



Figure 12. Zahn viscosity cup.

Only complete kits of multi-component paints should be mixed. If this cannot be done, the manufacturer must be consulted to ensure that partial mixing of their material is permitted. If allowed, it is imperative that the components be carefully measured using graduated containers or even scales. Most manufacturers now prohibit partial mixing of kits.

Thinners (if required) and should be well mixed into the paint material. The type and amount of thinner should be in accordance with the coating manufacturer’s recommendations. The inspector should record the amount of thinner used, as the addition of any thinner effectively reduces the volume solids content of the mixed paint and affects the target wet film thickness.

Measuring viscosity helps ensure that the proper amounts of thinner are used and that the thinning has not changed significantly from pot to pot. A common viscosity cup (Zahn), as shown in **Figure 12,** is simply a small cup of known volume with a precisely sized orifice in the bottom center.

Generally five orifice sizes are available and so numbered. The coating manufacturer can be consulted as to the orifice size to use for the material, and the time (in seconds) for the volume of properly thinned material held by the cup to pass through the orifice. For example, the manufacturer might stipulate that the material should be thinned such that it will pass through a No. 3 Zahn cup in 20-30 seconds at a given liquid paint temperature.

The clean cup is fully immersed in the coating material and withdrawn quickly. A timer is started at the precise moment that the top of the cup leaves the level of the liquid. The material will flow steadily through the orifice. When the solid stream first breaks at the base of the cup, the timer is stopped instantly. It is important to hold the cup 1 or 2 inches above the surface of the liquid so that it remains in the solvent atmosphere and away from drafts. The amount of thinner in the mixed paint is adjusted accordingly so that volume of paint held by the cup will flow through the orifice within the stipulated time range. The viscosity of some high-build thixotropic coatings cannot be measured with the Zahn cup, but other viscometers can be used. In this case, the coating manufacturer should be contacted for a recommendation.

Viscosity measurements are of value for quick field determinations of thinning and will reveal if significant changes in the viscosity occurred from pot to pot of material. While the paint applicator is generally the best judge of the proper amount of thinner to add to ensure the application of a smooth wet coat without runs or sags, the coating manufacturer’s maximum thinner amount should never be exceeded. The coating, at application, must also comply with VOC regulations. Adding a thinner

effectively increases the quantity of solvent emissions into the atmosphere. Restrictions on the type and amount of solvent emissions vary from area to area, and local air quality regulations must be followed. As a result, VOC regulations may prohibit adding thinners to a coating, even though the manufacturer recommends it.

Coating Application

The actual application of the coating is the most visible aspect of the painting project, and is equally as important as surface preparation. Accordingly, the coating inspector should be familiar with various application techniques.

When spraying with air atomized (conventional or HVLP) equipment, the spray gun should typically be held from 6 to 10 inches from the surface and maintained perpendicular to the surface throughout the stroke. For airless application, the distance should be from 12 to 18 inches. At the end of each pass, the gun trigger should be released. Each spray pass should overlap the previous one by 50%, and where possible, a cross-hatch technique should be used. This requires a duplicate series of passes 90° to the first series to ensure complete and uniform coverage.

In brush application, the brush should be dipped approximately two-thirds of its bristle length into the coating. The bristle tips should be brushed lightly against the side of the container to prevent dripping, maintaining as fully loaded a brush as possible. Brushing is more effective than spraying for working paint into depressed irregularities, pits, or crevices, and is effective for striping welds and around rivets, bolt heads, and nuts. However, care should be taken when striping edges to ensure that the coating is not brushed out too thin and actually pulled away from the surface.

Other application methods include plural-component spray, rolling, using mitts or pads, dipping, electrostatic spraying, powder coating (using fluidized bed or electrostatic spray), and roller coating using automated facilities for flat sheets. Each has its own specific technique as described elsewhere in this book.

Besides ensuring proper application technique, additional care is necessary when inspecting coating work where atmospheric contamination is present. Often water washing between coats or application of the topcoat within a minimum time interval is necessary. Otherwise, contaminants often invisible to the unaided eye may be coated over, leading to reduced coating life or premature coating failure.

Deficient and excessive coating thicknesses in multicoat systems should be observed. In cases where a topcoat is applied over a generically similar (e.g., non-rust inhibitive) primer, deficient primer thickness can be “built up” by additional topcoat thickness. However, where the primer contains rust inhibitors or is a different generic type, an additional coat of the primer or previously applied coating must be used before the topcoat can be applied.

Another common practice is to use coatings of a different color, or to tint each coat. This is an excellent aid to the applicator and inspector to ensure that complete coverage is achieved. Upper thickness limits are also specified in some cases. When paint thickness exceeds that specified, the excess should be removed by grinding or sanding, as appropriate. After this, reapply a thin coat to seal irregularities. Excessive or unsightly runs, sags, drips, and other film deficiencies should be brushed out during application or removed after drying. This again is done by grinding or sanding. In some cases, complete removal of the excessive coating (by abrasive blast cleaning) is required.

Determining Wet Film Thickness

Wet film thickness readings are used to aid the painter (and in some cases the inspector) in determining how much material to apply in order to achieve the specified dry film thickness. Wet film thicknesses on steel and most other metallic substrates are considered “guideline” thicknesses, with the dry film thickness being the thickness of record. However, when coating concrete or nonmetallic substrates, the wet film thickness is often used as the accepted value.

The wet film thickness gauge is generally a standard “notch” configuration **(Figure 13),** although circular dial gauges are also available. The notch gauge consists of two end points on the same plane with progressively deeper notched steps in between. Each step is designated by a number representing the distance in mils (or microns) between the step and the plane created by the two end points. The instrument is pressed firmly into the wet film perpendicular to the substrate and withdrawn. In every case, the two end

points will be wetted by the coating material. The wet film thickness is considered as being between the last wetted step and the next adjacent higher dry one. For example, if the “3 mil’ step is wetted and the “4 mil” step is dry, the wet film thickness is between 3 and 4 mils. If none of the steps or all of the steps in between the end points are wetted, it is necessary to turn the gauge to a different face, as the wet film thickness is outside of that particular range.

When using this instrument, it is necessary to stay away from any surface irregularities that could distort the readings. If determinations are being made on curved surfaces, it is important that the gauge be used along the length of the curve rather than across its width, as the curve itself could cause irregular wetting. The gauge must also be cleaned thoroughly after each use to ensure the accuracy of future measurements.

Wet film thickness gauges are of value only if the applicator knows how heavy a wet film to apply. The wet film thickness/dry film thickness ratio is based on the percent solids by volume of the specific material being applied.

The theory of doubling the desired dry film thickness to determine the wet film to be applied is only correct if the solids by volume of the coating material is 50% and no field thinner is added. The solids by volume of the coating material is information readily available from the manufacturer and is commonly included in their product data sheets. The basic formula is:

Dry Film Thickness = Wet Film Thickness X % Solids By Volume

Because the dry film target is known and the wet film target is the unknown value, a more workable formula showing the required wet film thickness for the desired dry film thickness is:

$$\text{Wet FilmThickness} = \frac{\text{Desired Dry Film Thickness}}{\text{\% Solids by Volume}}$$

The above formula is accurate provided the solids by volume of material is accurate. The percentage will change, however, if any thinner is added to the coating. When thinner is added, the total volume of the material is increased without any corresponding increase in the amount of solids. Therefore, the thinned material will result in a lower percentage of solids by volume. Thus, when comparing thinned versus unthinned material in order to achieve a comparable dry film thickness, a heavier wet film application of the thinned material will be required. This formula, which incorporates the “adjusted” solids by volume should be used to determine the required wet film thickness when the coating is thinned:

$$\text{WFT} = \frac{\text{Desired Dry Film Thickness}}{\dfrac{\text{\% Solids by Volume}}{(100\% + \text{\% Thinner Added})}}$$

For example, assume a coating contains 78% solids by volume and is to be applied in one coat to a dry film thickness of 8 mils. Without thinner added, the required wet film thickness is determined:

$$\text{WFT} = \frac{8}{0.78} = 10.25 \text{ mils}$$

If the coating in the previous example is thinned 20%, the adjusted wet film is calculated as:

$$\text{WFT} = \frac{8}{\dfrac{0.78}{1.2}} = \frac{8}{(0.65)} = 12.3 \text{ mils}$$

Thus, without thinning, 10.25 wet mils are required to obtain 8 mils dry. After thinning, the solids by volume drops from 78% to 65% and the required wet film thickness increases by 2 mils.

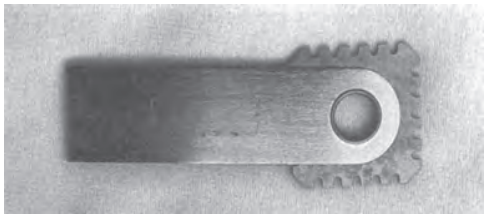


Figure 13. “Notch” wet film thickness gauge.

Because the use of the wet film thickness gauge is dependent on the solids by volume, and the solids by volume is considered to be the “in can” percentage, it is essential that wet film thickness readings be taken as soon as a film is applied to the

surface. Actually, during spray application, some of the solvents will already have evaporated by the time the material that has left the gun reaches the surface, thus changing the percent of solids by volume slightly. For practical applications when measuring wet film thickness, this change is not very significant. However, the longer one waits before taking a reading, the less accurate that reading becomes. For highly pigmented coatings (such as zinc-rich), or very fast drying coatings, wet film thickness readings may be unreliable.

Determining Dry Film Thickness

Dry film thickness readings on steel substrates are commonly obtained non-destructively using magnetic gauges. For non-ferrous metallic substrates, eddy current equipment is used. Calibrate magnetic thickness gauges in accordance with SSPC-PA 2, *Method for Measurement of Dry Paint Thickness with Magnetic Gages.* Although the standard is written for magnetic gauges, many of the principles of operation and calibration apply to eddy current instruments as well.

Determining the thickness of each coat in a multicoat system should be an inspection "hold point." When using magnetic gauges to measure multi-coat systems, the average of the first coat must be determined prior to applying the second coat. Readings taken after the second coat is applied will obviously be the cumulative thickness of the two coats combined, and the specific thickness of the second coat can only be determined by subtracting the average thickness obtained from the first coat reading. The second coat thickness cannot be determined precisely, however, because it is highly unlikely that specific readings taken on the second coat will be over an area of the first coat that is coincidentally the first coat average. Therefore, with magnetic gauges, unless precise locations are measured for each coat, it is nearly impossible to specifically determine the thicknesses of coats applied after the first. For example, if the specification requires 2-4 mils of primer, 4-6 mils of intermediate coat, and 2-3 mils of topcoat, the inspector should ensure the coating thickness is between 2 and 4 mils for the first coat, 6-10 mils for the primer and intermediate coat combined, and 8-13 mils for all three coats combined.

It is often a good idea, where practical, to provide a means to indicate coating thickness in areas where it is either thin or thick, so appropriate repair can be done. Possible methods are brush application of a contrasting color of the same paint, compatible felt tip marking pens, chalk or other material that can be readily removed, or graphic plotting and notations on charts and records.

Thickness readings are taken to provide reasonable assurance that the specified or desired dry film thickness has been achieved. However, it is not possible to measure every square inch of the surface. SSPC-PA 2 states that when using magnetic gauges, five separate spot measurements should be made over every 100 $ft.^2$ in area. Each spot measurement consists of an average of three gauge readings next to one another. The average of the five spot measurements must be within the specified thickness, while the spot measurements (average of three gauge readings) are permitted to underrun or overrun the specified thickness by 20% (i.e., must be no less than 80% of the specified minimum thickness, nor any greater than 120% of the specified maximum thickness for each coat).

The single gauge readings making up the spot measurement can underrun or overrun by a greater amount. For example, a specification calls for 10 to 12 mils. The five spot measurements (each a cluster of three gauge readings) are: Spot 1 (10,11,12; average 11); Spot 2 (7, 8, 9; average 8); Spot 3 (12, 12, 12; average 12); Spot 4 (7,12,11; average 10); Spot 5 (12, 13, 11; average 12). This measured area would be acceptable because the average of the five spots is 10.6 mils and within specification. According to SSPC-PA 2, unless otherwise specified, the 8 mil spot measurement would be acceptable because "no single spot measurement . . . shall be less than 80% of the specified thickness" (8 mils is exactly 80%), and the 7 mil reading is acceptable because "single gauge readings . . . may underrun by a greater amount."

Dry film thickness instruments fall into four basic categories: magnetic pull-off, magnetic-constant pressure probe, eddy current-constant pressure probe, and destructive. Each of the four categories is addressed separately.

Magnetic Pull-Off Gauges

The Mikrotest **(Figure 14)**, PosiTest, or Elcometer 211 magnetic pull-off gauges consist of a lever running through the center of a scale dial that houses a helical spring. The scale dial is located at the

fulcrum point of the lever. One end of the spring is attached to the lever and the other end to the scale dial. One side of the lever contains a permanent magnet while the opposite end contains a counterbalance **(Figures 15 and 16).**



Figure 14. Mikrotest magnetic pull-off gauge.

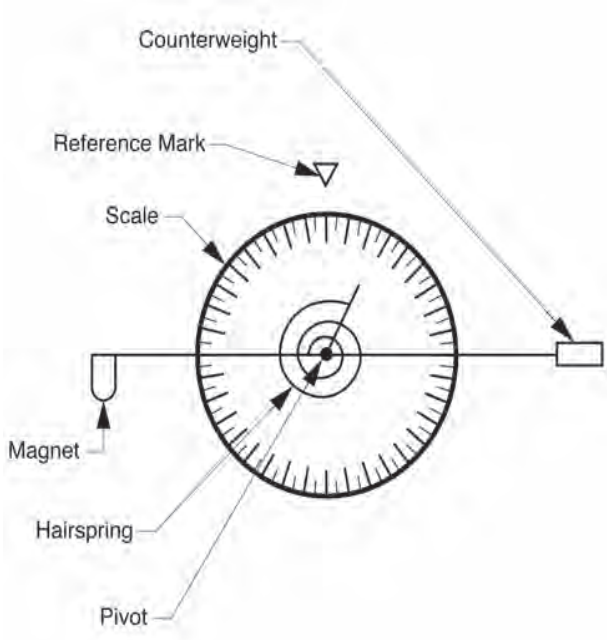


Figure 15. Principle of magnetic pull-off gauge.

To operate, the scale dial is turned counterclockwise and the magnet brought into direct contact with the metal substrate (through the coating or non-magnetic barrier). Next, the scale ring is turned clockwise (manually or automatically), increasing the spring tension, which applies a pulling force onto the magnet. Ultimately, the spring tension overcomes the attraction of the magnet to the substrate, lifting the magnet from the surface. The spring tension is calibrated so that the point where the magnet breaks contact with the surface can be equated to the distance of the magnet from the surface. This distance is read directly from the scale dial or digital read-out in mils (or microns). The calibrated spring tension is an inverse logarithmic relationship of the distance between the magnet and the substrate (i.e., the greater the spring tension required to remove the magnet, the thinner the coating).

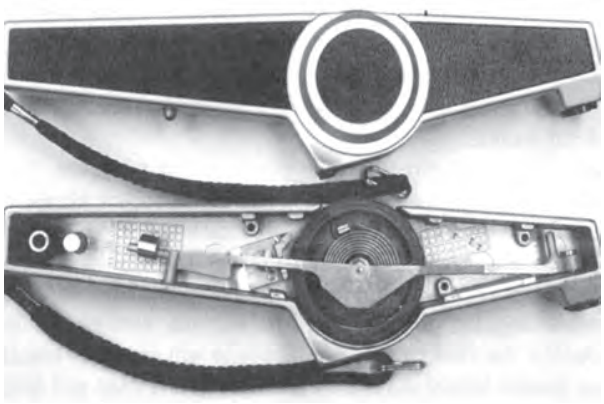


Figure 16. Inside of Mikrotest magnetic pull-off gauge with components corresponding to schematic in previous figure.

Note that the thickness reading shown on the gauge when the magnet breaks contact with the surface represents the gap between the magnet and the substrate. This gap is considered to be the coating thickness. However, it could also be comprised of voids, rust, embedded contaminates, etc. Therefore, one must include a thorough visual inspection during the work to ensure that the coating is applied over a clean surface and does not become contaminated during drying. Also, coating thickness gauges measure galvanizing as coating thickness, as they are not capable of distinguishing one layer from another (galvanizing is non-magnetic). Therefore, if the inspector only wants to measure only the “coating” thickness, baseline measurements of the galvanizing must be obtained prior to coating application, then subtracted from the gauge readings to obtain coating thickness values exclusive of galvanizing.

The Mikrotest, PosiTest, and Elcometer 211 gauges should be calibrated, or at least have their

calibration verified prior to, during, and after each use to ensure that they are measuring accurately. SSPC-PA 2 defines the pull-off instruments as Type 1 gauges. Calibration test blocks similar to those supplied by the National Institute of Standards and Technology (NIST), chrome and copper plated steel, are used to verify the accuracy of Type 1 gauges. The use of plastic shims is not recommended. It is essential that the instrument is verified for accuracy in the desired thickness range of use. If a coating is being measured in the thickness range of 2 to 4 mils, calibration should be verified in that range rather than at 20 mils.

Calibration with NIST plates requires that the gauge reading be matched against the readings on the plates. Next, a series of gauge readings on the bare, uncoated substrate is obtained after blast cleaning (or other surface preparation). The instrument will generally read between 1/10 and 2/10 of a mil up to 1 mil or more over the bare steel. Therefore, any coating thickness readings taken must be corrected by this base metal reading, or BMR in order to determine the coating thickness above the peaks of the profile. Adjust subsequent thickness readings by subtracting the BMR. For example, if the instrument is calibrated to a 4 mil NIST Standard, and a 0.5 mil BMR is measured, a paint thickness reading of 3.5 mils indicates that the true coating thickness above the peaks of the surface profile is actually only 3 mils. The BMR does not represent surface profile depth. Rather, it represents the effect of the surface profile on a paint thickness gauge. It is very important that the inspector not subtract the surface profile measurement from the coating thickness, as the thickness will be reported as being too low. Using this example, if the surface profile measured with the Keane-Tator Comparator is 2 mils, and this were subtracted from the thickness reading, it would be assumed that the coating thickness was 1.5 mils, rather than the true 3 mils.

Another type of magnetic pull-off gauge, based on a similar principle is the pencil pull-off gauge **(Figure 17).** Basically, the instrument housing is similar to a large pencil with a magnet at the bottom. An extension spring is attached to the magnet and to the top of the instrument housing. The instrument is held perpendicular to the surface and the magnet brought into contact with the substrate. As the housing is lifted, the magnet remains attached to the substrate until the spring tension overcomes the attraction of the magnet, popping it from the surface. The tension on the spring required to lift the magnet is read from the scale in mils or microns **(Figure 18).** This instrument cannot be adjusted, although calibration should be verified. In this case, however, a calibration correction curve is necessary if the instrument does not read correctly on the standards. The preferred method for verifying calibration is the use of calibration test blocks (e.g., NIST). Pencil-style gauges provide a quick check of coating thickness, but for most of these gauges, considerable judgment is involved in determining the point at which the magnet breaks from the surface, as most do not retain the measurement once the magnet is detached.

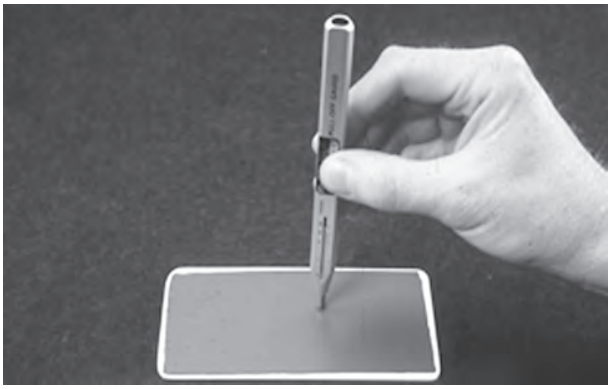


Figure 17. Pencil pull-off gauge.

Special precautions are necessary when using any instrument that involves a magnet. First, the magnet is exposed and therefore susceptible to attracting iron filings, or steel shot and grit particles. The magnet must be cleaned of any contaminants during use, or the contaminant will incorrectly be read as coating thickness. This is extremely important in shop work where grinding operations are common. Iron filings attach to the exposed magnet often requiring that the magnet and coating surface be cleaned before each thickness reading. If the instrument is used on a soft film, allowing the magnet to sink into the surface, a thinner coating thickness will be recorded. This is because the coating itself may be tacky, holding the magnet beyond the point where the spring should have lifted it from the surface, or the coating under the depression caused by the magnet actually will be thinner. In this case, place a plastic shim on top of the surface to prevent the magnet from deforming the coating and subtract the shim thickness from any subsequent readings. In addition, if there are

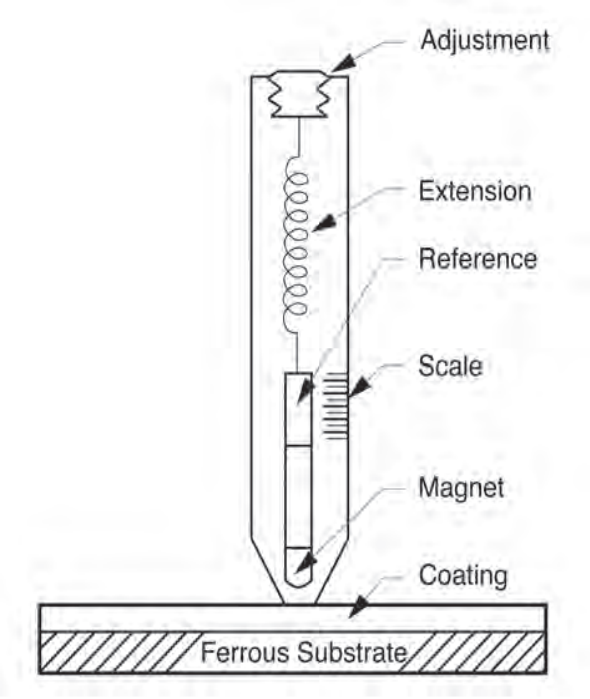


Figure 18. Principle of pencil pull-off gauge.

any vibrations in the area of instrument use, they could cause the magnet to be detatched from the surface prematurely, giving an erroneously high thickness reading. Finally, residual magnetism in the structure on which the coating is measured can have an adverse effect on the readings.

Scale dial instruments have an additional "human error" problem during use. It is easy to continue to turn the dial beyond the point that the magnet has lifted from the surface giving an incorrect thickness reading. It is imperative then that the dial be stopped as soon as the magnet lifts from the surface. Automatic versions of the Mikrotest have addressed this problem by incorporating a self-winding mechanism that automatically retracts the thumb wheel.

Constant Pressure Probe Gauges

SSPC-PA 2 describes constant pressure probe gauges as "Type 2" gauges. They include the Elcometer 456 **(Figure 19),** Positector 6000 **(Figure 20),** QuaNix 2200 **(Figure 21),** QuaNix Keyless **(Figure 22),** QuaNix 1500 **(Figure 23),** eXacto **(Figure 24),** Minitest 4100 **(Figure 25),** Elcometer 355 **(Figure 26)**. Type 2 gauges also must be verified



Figure 19. Elcometer 456.



Figure 20. Positector 6000.

for calibration prior to use. Calibration verification is accomplished using the non-magnetic shim method described here or the NIST calibration plates described previously. When calibrating using the plastic shim method, verify the shim thickness with a micrometer. Hold the shim firmly on the bare cleaned substrate and measure it with the instrument. If the instrument does not read the shim thickness, adjust the gauge or address the discrepancy according to the manufacturer's instructions, keeping in mind that some gauges cannot be field calibrated. Check the calibration by using shims of lesser and greater thickness to determine the range of accuracy. The



Figure 21. QuaNix 2200.



Figure 22. QuaNix Keyless.



Figure 23. QuaNix 1500.



Figure 24. eXacto.



Figure 25. Minitest 4100.



Figure 26. Elcometer 355.

instrument is now ready to measure thicknesses within that range over the same substrate and surface preparation. If a section of the bare substrate is unavailable, clean small steel test panels (e.g., 1/8X4X6 inches) to obtain the same or a similar anchor pattern and cleanliness, protect them from corrosion using a rust-inhibitive paper or other suitable means, and use the panels for calibration. The instrument will correctly record the thickness of the coating material. Any effect of surface roughness is calibrated into the instrument because it was adjusted over the bare steel, thus eliminating the need for a BMR correction factor.

These gauges experience some of the same problems as pull-off gauges: lower than actual thickness readings on soft or tacky films and difficulty in keeping the magnet clean. In addition, SSPC-PA 2 cautions the user to stay at least 1 inch in from all edges, unless the gauge has been specifically calibrated for these locations.



Figure 27. PosiTest 100 ultrasonic gauge.

Eddy Current Gauges

Eddy current instruments—PosiTector 6000N and the QuaNix Keyless, among many others—measure the thickness of non-conductive coatings on non-ferrous metal substrates. The probe is energized by alternating current, inducing eddy currents in the metal. These currents create opposing alternating magnetic fields within the metal, modifying the electrical characteristics of the probe coil. The extent of these changes is determined by the distance of the probe from the substrate and is shown on a display as coating thickness. Eddy current instruments are calibrated using the plastic shim method. Most gauge manufacturers supply gauges that will measure coating thickness on both ferrous and non-ferrous metal surfaces.

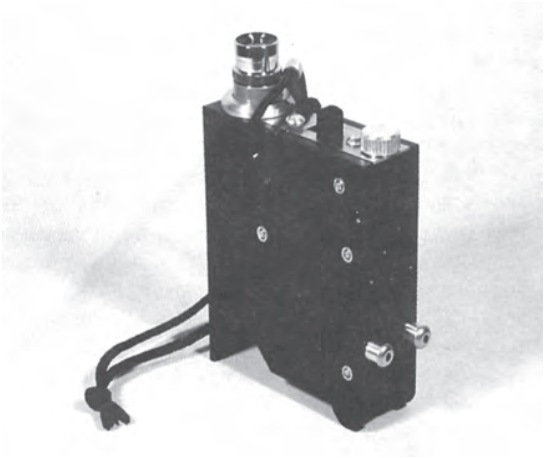


Figure 28. Tooke scratch gauge for determining dry film thickness by cutting a cross-section through the film and viewing it under magnification.



Figure 29. Modified Tooke gauge with all three cutting tips mounted on the instrument body and three bulbs to improve lighting.

Ultrasonic Coating Thickness Gauges

Coating thickness measurements over non-ferrous, nonmetallic surfaces such as concrete and

wood can be obtained non-destructively using a coating thickness gauge that operates on an ultrasonic principle. The PosiTest 100 **(Figure 27)** can measure total coating thickness on these surfaces, and in some cases can distinguish coating layers. A gel or couplant must be applied to the probe prior to measurement, and must be wiped from the coated surface to prevent contamination when applying subsequent coats.

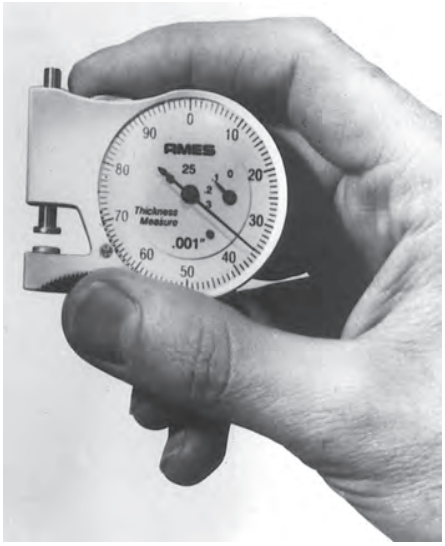


Figure 30. A hand-held, spring-loaded micrometer useful for measuring the thickness of coating chips.

Destructive Coating Thickness Instruments

Destructive thickness testing includes the use of the Tooke, or paint inspection, gauge (PIG) **(Figures 28 and 29),** micrometers **(Figure 30),** or microscopes **(Figure 31).** The Tooke gauge consists of a 50X microscope that is used to look at scribes in the coating made by precision cutting tips supplied with the instrument. The principle of the Tooke gauge is basic trigonometry. By making a cut through the coating at a known angle and viewing perpendicular to that cut, the actual coating thickness can be determined by measuring the width of the cut from a scale in the eyepiece of the microscope. The instrument can be used for determining the thickness of underlying coats in multicoat systems and eliminates many of the drawbacks of the magnetic instruments caused by magnetic fields, proximity to edges, irregular surfaces, magnetic effect of the substrate, profile, and so forth. The instrument can be used on coating thicknesses up to 50 mils provided the coating is not too brittle or elastic for a smooth cut.



Figure 31. Pocket-sized 30X microscope with integral light source.

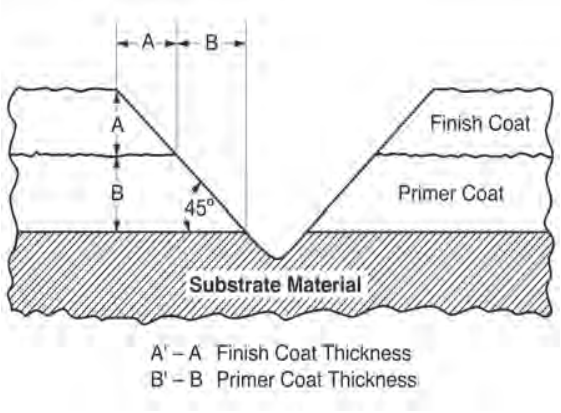


Figure 32. Measurement principle of Tooke gauge.

Cutting tips of different angles are available. They are designated as either 1X, 2X, or 10X. The tip used determines the thickness equivalent for each line or division in the microscope eyepiece. The number of divisions corresponding with the coating is divided by the number of the tip used. Therefore, 1 division when using the 1X tip is equivalent to 1/1 or 1 mil; 1 division with the 2X tip is 1/2 or .5 mil; and 1 division with the 10X tip is 1/10 of 1 mil (0.1). Thus, if the coating cross-section covers 7 divisions and the 2X tip is used,

the thickness is 7/2 or 3.5 mils **(Figures 32 and 33).**

Another means of destructively measuring coating thickness is to remove a sample of the coating from the substrate and measure the thickness using a standard micrometer. The coating chips could also be returned to a laboratory for microscopic thickness determinations. The Tooke gauge may also be used for this purpose. When viewing the edge (cross section) of a disbonded chip through the Tooke gauge lens, each division of the microscope is equivalent to 1.0 mil.

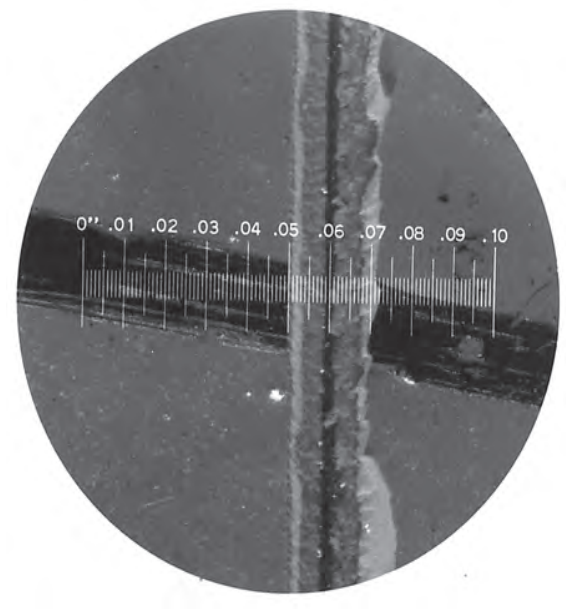


Figure 33. View through Tooke gauge microscope. The interface of the coating/substrate is one division to the left of .06 on the scale. Coating thickness is measured from this point on the left ending at the black bench mark at .05.

Cleanliness Between Coats

Where more than one coat is to be applied, an important inspection "hold point" is determining surface cleanliness immediately prior to applying the next coat. In addition to dirt and dust, dry spray or overspray can cause overcoat problems.

All contaminants should removed because their presence can result in reduced adhesion between coats and coating film porosity, rendering the coating less resistant to the effects of the service environment. The surface should also be inspected for any contamination from the environment (e.g., residue from chemical facilities, salt, etc.)

Pinhole and Holiday Detection

After all coats of paint have been applied, the inspector should verify that the appropriate clean-up is done, and that any abrasions, nicks, or scrapes are repaired. Often holiday, pinhole, or spark testing is used to find nicks, scrapes, and pinholes in the coating film, particularly if the coating is intended for immersion service. A "holiday" is a skip or missed area on the structure. Holiday testing may be required after application of either the next to last, or the last coat of paint. When performed between coats, however, there is the risk of spreading contamination that could influence the performance of the subsequently applied coat. Usually when such testing is specified, it is done before final cure has occurred so that any repair will successfully bond to the underlying coat.



Figure 34. Tinker-Rasor low-voltage wet sponge holiday detector used for finding pinholes and holidays in non-conductive paint films up to 20 mils thick when applied to conductive substrates.

Pinhole and holiday detectors fall into three categories: low-voltage wet sponge **(Figures 34 and 35),** DC high-voltage **(Figures 36 and 37),** and AC electrostatic types.

The low voltage wet sponge holiday detectors are used for locating discontinuities in nonconductive



Figure 35. Using a low-voltage wet sponge holiday detector to locate discontinuities in non-conductive coatings applied to conductive metal substrates.

coatings applied to conductive metal surfaces. The low voltage detector is suitable for use on coatings up to 20 mils. The basic unit consists of the detector itself, a ground cable, and a sponge electrode. The ground cable is firmly attached to the bare substrate and the sponge electrode is saturated with tap water. The electrode (wetted sponge) is moved across the entire surface, the water permitting a small current to flow through the pinholes down to the substrate. Once the current reaches the substrate, the circuit is completed to the detector unit and an audible signal can be heard indicating that a pinhole or discontinuity is present. When coatings are in the range of 0 to 20 mils, a non-sudsing wetting agent (such as Eastman Kodak Photo-Flo) may be added to the water to increase the wetting properties. If the coating system is found to be greater than 20 mils, high-voltage holiday detection equipment should be used.

High-voltage detectors consist of a testing unit capable of producing various voltage outputs, a ground cable, and an electrode made of conductive materials such as neoprene, brass, or steel. High-



Figure 36. Spy high-voltage holiday detector for uncovering flaws in thick coating systems. Voltages are available up to 22,000 volts DC. A spark jumps from the electrode through the coating at deficient areas.



Figure 37. D.E. Stearns high-voltage holiday detector used for non-conductive coatings applied to conductive substrates.

voltage units are available up to 35,000 volts and are used for nonconductive coatings applied to conductive substrates. The ground wire is firmly attached to a section of the bare substrate and the electrode is passed over the entire surface. A spark will jump from the electrode through the air gap down to the substrate at pinholes, holidays, or missed areas, simultaneously triggering audible and/or visual signaling device on the unit. It is important to use only the voltage level recommended by the coating manufacturer for the coating thickness. Otherwise, damage to “good” coating could occur. A rule of thumb is to apply

100–125 volts per mil of coating.

For exterior pipeline work, many times the ground wire of the holiday detector is permitted to drag across the earth provided the pipe itself is grounded to the earth. However, the preferred method of testing is to attach the ground wire directly to the substrate whenever possible.

When testing conductive linings applied over steel substrates (i.e., conductive rubber linings), the AC Tesla coil electrostatic tester is generally used. It has a variable voltage output (preferably, the voltage is indicated) but does not require the use of a ground wire.

The unit constantly emits a blue corona, but emits a white spark whenever it passes over a break in the lining. Note that surface contaminants or dampness may also cause a color change or spark; therefore, it is advisable to clean and retest questionable areas to confirm that a holiday or pinhole is truly present.

Field Adhesion Testing

Occasionally, there is a need to test coating adhesion after application. In flame spray and electric arc metallizing, adhesion testing is common. The different types of adhesion testing methods used range from a simple penknife to more elaborate testing units. A penknife generally requires a subjective evaluation of the coating adhesion based on some previous experience. Generally, one cuts through the coating and probes at it with the knife blade, trying to lift it from the surface to ascertain whether or not the adhesion is adequate. ASTM D 6677 describes this method with a rating scale.

A more common field method for adhesion testing is the tape and knife test as described in ASTM D 3359, *Measuring Adhesion by Tape Test.* This testing consists of cutting an "X" or a number of small "squares" through the coating down to the substrate. Tape is rubbed vigorously onto the scribed area and removed firmly and quickly. The test area is evaluated according to the amount of coating removed. The "X" cut (Method A) is used for coatings in excess of 5 mils and the "cross-cut" (Method B) is used for coatings less than 5 mils, although the cross-cut can be used for heavier coatings if the spacing between cuts is adjusted. The distance between the parallel knife cuts for Method B is based on the thickness of the coating being tested (0–2 mils = 1 mm spacing; 2–5 mils = 2 mm spacing). Although not addressed in the ASTM standard, spacing of 5 mm is common for coatings heavier than 5 mils.

There are also instruments available for testing the tensile (pull-off) adhesion strength of coatings. They apply a value to the adhesion strength in pounds per square inch (psi), kilopascals (kPA), or megapascals (mPA), thus eliminating some of the subjectivity of the other tests. Instruments for tensile testing include mechanical, pneumatic, and hydraulic adhesion testers **(Figure 38).** The tensile adhesion test kits consist of the test unit itself and aluminum or stainless steel pull stubs. The pull stubs are cemented to the coating surface with adhesive. After the adhesive has cured, the test instrument is attached to the pull stub. It applies a pulling force on the stub, ultimately breaking it from the surface. The point of the break is read from the scale on the instrument, then converted to psi, kPA, or mPA. This method is described in ASTM D 4541.



Figure 38. Tensile adhesion test kit.

Not only is the numerical value of importance when using this method, but also the type of break. For example, there is a significant difference in the test results if one finds a clean break to the substrate or between coats, compared to finding a cohesive break within a coat. Adhesive failure may also occur. This then establishes that the coating tensile adhesion strength is at least as good as that pressure that broke the adhesive. Attaching a second set of pull stubs may be necessary, depending on the value obtained.

It is generally recommended that two-component epoxy adhesives are used instead of single-component fast drying cyanoacrylates. When testing zinc-rich coatings, for example, it has been found that the thin cyanoacrylates may have a tendency to penetrate and bond the zinc particles together, resulting in a much higher tensile pull than

should be expected. In other cases, the adhesive appears to soften and cause premature coating system failure. Adhesives that cure by UV light are also available and show promise for conducting tests within minutes of attaching the pull stub.

Evaluating Cure

The applied coating film must be allowed to cure for a given length of time prior to being placed into service. This cure time is generally shown on the manufacturer's product information sheet. Alternately, forced-heat curing may be used to reduce the time between final curing and service.

Determining the cure is generally difficult. When most coatings are suitably cured, rubbing them with sandpaper will produce a fine dust. If the sandpaper gums up, depending upon the coating, it may not be thoroughly cured. Certain phenol-containing coatings may discolor upon heating—and the cure of phenolic tank lining coatings is often determined by comparing their color with color reference coupons supplied by the coating manufacturer.

Pencil hardness (ASTM D 3363) is recommended by some coating manufacturers as a method for determining cure, and ASTM D 4752 describes a solvent rub test (using methyl ethyl ketone or MEK) for characterizing the cure of ethyl silicate inorganic zinc-rich primers. ASTM D 5402 describes a similar solvent rub test for use on organic coatings and ASTM D 1640 describes another cure test.

Because a coating is "dry" or hard does not necessarily mean that it is cured. In fact, for most coatings, hardness is not synonymous with cure. The only coating types for which this is true are solvent-deposited coatings, such as chlorinated rubbers and vinyls. Even then, residual retained solvents (and moisture in water-borne coatings), under certain atmospheric conditions of temperature and/or humidity may take a long time to escape from the paint film. Final film properties require satisfactory solvent evaporation. In some cases, this evaporation process may take as long as two or three weeks or more, depending on the prevailing conditions.

Conclusions

There are a wide variety of inspection instruments available to help ensure the adequacy of the ambient conditions, surface preparation, wet and dry film thicknesses, and final coating continuity and integrity. The instruments all have advantages and limitations, but the overriding factor in their successful use is the knowledge and ability of the individual using them.

It is important that the instruments be cared for, calibrated, and used properly. However, inspection using instrumentation is only part of the total process. It must be combined with good common sense and visual inspections of misses, skips, runs, sags, surface contaminants, overspray, dry spray, and any other defects that may be objectionable for the intended service. Finally, all of the results of any inspection should be thoroughly documented (in writing) to prove that the specified requirements have been met. Future maintenance or the removal and maintenance of a failed coating system may be dependent on the factual reporting of every phase of the work.

Acknowledgements

The authors and SSPC gratefully acknowledge Steve Pinney's peer review of this document.

About the Authors

Kenneth A. Trimber

Kenneth A. Trimber is the president of KTA-Tator, Inc. He has more than 25 years of experience in the industrial painting field, is a past president of the SSPC board of governors and chair of the SSPC committees on surface preparation and visual standards and the task group on containment. He is also past chair of ASTM D1 on paints and related coatings, materials, and applications. Mr. Trimber authored *The Industrial Lead Paint Removal Handbook* and coauthored Volume 2 of the *Project Design Handbook.* He is a principal instructor for SSPC's Supervisor/Competent Person for Deleading Projects Course (C-3) and the NHI/FHWA courses Bridge Coatings Inspection and Hazardous Bridge Coatings: Design and management of Maintenance and Removal Operations. An SSPC protective coatings specialist (PCS) and NACE certificated coatings inspector, he is certified at level III coating inspection capability in accordance with ANSI N45.2.6 and an NBR nuclear coatings specialist. He is also past technical editor of the *Journal of Protective Coatings and Linings.*

William D. Corbett

Bill Corbett is the corporate products manager for KTA-Tator, Inc. An SSPC protective coatings specialist (PCS) and NACE certificated coatings inspector, he is a principal instructor for the NHI/FHWA courses Bridge Coatings Inspection and Hazardous Bridge Coatings: Design and Management of Maintenance and Removal Operations. Mr. Corbett is certified at level I nuclear coatings inspection capability and has authored or coauthored many industry publications including a chapter of SSPC's *The Inspection of Coatings and Linings.*

Chapter 8
Safety and Health in the Protective Coatings Industry

Daniel P. Adley and Stanford T. Liang

Introduction

In 1999, 5.7 million U.S. workers became ill or were injured on the job. This total includes both minor discomfort and serious injury. Roughly 6 people out of every 100 were affected. Of course, some industries are more dangerous than others. In the painting and paperhanging industry, the rate was somewhat lower than average—4.9 per hundred—while the injury rate for shipbuilding and repairing was 20.2 per hundred. By contrast, the rate in the financial industry was only 1.8 per hundred. No breakdown for the painting industry alone is available.

Workers in the painting industry have to be alert to the possibility of falling from scaffolds, being struck by material falling from above, or becoming caught in or electrocuted by machinery. They also need to be aware of occupational illnesses that may result from coating and coating removal operations. Exposure to lead pigments and silica in abrasives can cause serious and even fatal illness. Various solvents affect the nervous system and are identified as known or possible carcinogens.

About 5,344 workers were killed on the job in 2000, or 4.3 per 100,000 full-time workers. According to the Bureau of Labor Statistics, although fatalities are not available for the painting industry alone, the incidence is not much higher than this national average. These figures suggest that it is in the best interest of everyone engaged in the painting and coating trades—employers, employees, managers, and suppliers—to take health and safety issues quite seriously.

Cost Benefits from Safety

Of course, no company wants to see workers hurt or killed, but there are also external incentives to safety, particularly the costs of incidents when workers are injured on the job. Lost work-time also decreases worker productivity and lowers morale. Many facility owners and general contractors are pre-qualifying contractors based on their safety records, and companies cannot afford to present the image of safety being anything but a top priority.

Workers compensation and health care costs are becoming more of a drain on all businesses, particularly on small companies, and any costs that can be avoided will benefit these firms. While the workers compensation system has traditionally precluded a worker suing an employer for workplace injury, various exceptions have been granted by the courts, and more can be expected to follow. For instance, because several different entities are often involved in a painting job, an injured worker employed by a contractor may bring suit against a third party, such as the specifier. An effective safety program may help to reduce these types of costs.

Role of OSHA, NIOSH, and Other Organizations and Safety Professionals

In 1970, Congress passed the Occupational Safety and Health Act, which created the Occupational Safety and Health Administration (OSHA), a division of the Department of Labor. OSHA is responsible for developing and enforcing mandatory job safety and health standards. OSHA receives assistance from the National Institute for Occupational Safety and Health (NIOSH), a complementary agency established under the Act as a branch of the Department of Health and Human Services. NIOSH conducts research on safety and health issues and provides technical assistance to OSHA.

Safety and health organizations, such as the American Industrial Hygiene Association, the American Conference of Governmental Industrial Hygienists, the American Society of Safety Engineers, and the National Safety Council provide information to help managers and health and safety professionals to stay abreast of developments in this rapidly changing field. Professional organizations for the painting and coating trades, such as the Society for Protective Coatings, the International Brotherhood of Painters and Allied Trades, the National Paint and Coatings Association, and the Painting and Decorating Contractors of America, provide industry specific information.

Why Owners and Specifiers Need to be Aware of Safety and Health

Owners and specifiers have a stake in ensuring that the contractors they employ have the capability to comply with health and safety regulations. Many painting specifications require the successful bidder to comply with all applicable safety regulations during a contract. In order to comply, a contractor must know what materials employees may be exposed to and what federal, state, and local regulations require. The contractor must also be familiar with various approaches to compliance, including engineering, work practice and administrative controls, air and personnel monitoring, and the proper use of personal protective equipment (PPE).

A contractor who does not have the expertise to keep abreast of safety regulations and to comply with them may be subject to regulatory fines and civil and criminal liabilities. The owner who hires such a contractor runs the risk of being included in legal actions against the contractor. For instance, according to OSHA guidance to inspectors, when one employer is not meeting the requirements to inform employees of workplace chemical hazards at a multi-employer work site, the other employers may be cited also.

Contractors who do not make health and safety a priority often suffer reduced productivity and lower worker morale. An owner may also be affected by unnecessary work stoppages and slow downs, as well as unfavorable publicity as a result of a serious accident, or a pattern of occupational injury and illness, at a work site.

Contracting firms who value employees and practice safety on each job will reap many benefits, not only for themselves, but also for the owners who hire them. Good safety performance reduces lost work hours, which, in turn, reduces the contractor's insurance costs while increasing productivity. A contractor with lower insurance costs can do the job at less cost to the owner—everyone benefits.

Responsibilities of Employers, Employees, Inspectors, Consultants, and Engineers

Conscientious painting contractors have written safety programs based on all safety standards applicable to the industry, and make every effort to routinely train their employees to comply with the written program. Many progressive firms have active safety committees, which include management and worker representatives, and continuously refine their safety programs and refer suggestions for improvement to upper management.

A truly professional contractor evaluates the hazards of each job undertaken before any equipment is brought on site, and develops a plan to control the hazards expected during each phase of the job. For example, the project manager may hold a pre-job safety meeting with workers and supervisors, and follow up with weekly "tool box" meetings with workers to ensure that expected hazards are being controlled and unexpected hazards are recognized as they develop. Daily job site safety inspections by the person responsible for safety and health are also advisable. Workers who consistently violate safety regulations should be suspended and, in some cases, terminated.

Owners and specifiers can reduce the odds of contractor safety violations by pre-qualifying contractors before they are allowed to submit a bid. OSHA's regulation on process safety management (PSM) requires owners in the chemical process industry to evaluate the safety records of contractors before they are hired. Although other sections of the industry are not required to do this, it is a good way for them to protect themselves. Examples of indicators to measure a firm's safety performance include the contractor's workers compensation experience modification rate (EMR), total cases and lost workday incident rates, and serious and willful OSHA citations.

In addition to pre-qualifying contractors, owners and specifiers should routinely outline in their specifications the safety responsibilities of the contractor and enforce the safety and health section of the specification just as stringently as the quality assurance sections. Owners can also require the low bidder to submit a site-specific safety and health plan that the owner must approve before awarding a contract.

Hazardous Operations in the Protective Coatings Industry

Fire Hazards and Explosions

Most solvent-thinned paints and paint solvents are highly flammable and extremely dangerous when they, or especially their vapors, are exposed to open flames, sparks, or very high temperatures. In a confined area, a fire or explosion could result unless

proper precautions are taken. A certified industrial hygienist or certified safety professional should be consulted for advice about safe working conditions, particularly in confined spaces.



Figure 1. Paint vapors can be flammable if adequate ventilation is not provided.

Because of the flammability of solvent-thinned paints, precautions need to be taken when handling these types of coating systems. Two examples of solvent-thinned paints include:

• **Two-Component Paints:** Two-component paints should never be mixed in large quantities, generally no more than five gallons at a time. They usually create heat because they react immediately upon mixing. The larger the volume mixed, the higher the temperature. The temperature may become high enough to create a hazard.

• **Oil Paints and Specialty Coatings:** Waste or wiping rags soaked with paints based on linseed oil may catch fire spontaneously if left lying around, especially during warm weather. Spillage of peroxide catalysts used in polyester laminates and other similar chemicals can cause combustion.

Most paint solvents are volatile and will flash in the presence of a flame or an electric spark. Usually, the faster the solvent evaporates, the lower its flash point. Therefore, solvent-thinned brushing or rolling paints, which dry relatively slowly, will contain solvents with a flash point of about 105°F (41°C) or somewhat higher. A solvent-thinned spray paint that requires fast evaporating solvents may contain solvents that flash as low as 30°F (1°C). A spray gun, which applies a pint to many quarts of paint per minute under high pressure, will produce a greater volume of solvent vapor than brushes or rolled paint. Therefore, all spray equipment must be grounded to prevent accidental ignition by static electricity. This includes containers. Painters should bond their empty bucket to the bulk drum while filling it, and the drum should be properly grounded.

Pure solvent vapors are heavier than air and tend to move along the ground when in confined areas. Thus, all flames near the area must be extinguished. Solvent vapors must be mechanically exhausted from all enclosed areas with the ventilation designed for efficient airflow. Explosion-proof lighting must be used. All electric motors should be turned off.

The following precautions will help prevent the possibility of fires.

• Store solvents in Underwriter's Laboratory (UL) listed containers.

• Prohibit smoking wherever solvent-thinned paint is stored, mixed, or used. Allow no other sources of ignition, such as electric coffee pots, hot plates, or other such appliances to be used in the area.

• Provide adequate ventilation in all working areas to prevent a build-up of explosive concentrations of solvent vapor. Properly calibrated direct reading detection instruments should be used to monitor confined areas or closed spaces to be sure vapor concentrations are maintained below explosive limits.

•Use nonmetallic ladders in confined areas or within 10 ft. (3.05 m) of exposed electric wiring.

• Use non-sparking tools to clean metal surfaces where fire hazards are present.

• Extinguish all sources of flame in the area. Turn off all gas valves and open all electrical switches if working in confined areas or near electrical equipment.

• Be sure that all equipment, motors, and lights in the area are grounded, and consider using only explosion-proof lighting.

• Keep fire extinguishers nearby. Be sure that they are of the proper type, as follows:

Class A—Paper, wood, rubbish, where water is effective;
Class B—Burning liquids, where smothering action is required;
Class C—Electrical equipment, where the extinguishing agent must be non-conductive.

• Keep pails of sand or similar absorbent materials near dispensing pumps and spigots to absorb any

spills. Replace all leaking containers.
• Clean up before, during, and immediately after painting operations. Wet down sweepings, rags, and waste with water and store in closed metal containers. Dispose of daily.
• Always clean up paint or solvent spills immediately.

Health Hazards

A variety of paint ingredients or chemicals may be harmful to the human body. For instance, some chemicals may cause irritation sensitization, central nervous system effects, or systemic effects. Most people can withstand chemical exposures for short periods of time at low doses; however, some people are immediately sensitive to some ingredients and almost everyone will be affected to some degree if exposed for a sufficient period of time. Continued exposure may cause the body to become sensitized so that subsequent contact may result in an aggravated reaction, especially for anyone with a chronic illness.

Types and Components of Paints. The term paint is commonly used to identify a range of products including conventional paints, varnishes, enamels, and lacquers. Conventional paint is an inorganic pigment dispersed in a vehicle consisting of a binder and solvent, with selected fillers and additives. Varnish is a non-pigmented product based on oil and resin in a solvent that dries first by the evaporation of the solvent and then by the oxidation and polymerization of the resin binder. A pigmented varnish is called an enamel. Lacquers are coatings that are commonly based on a cellulose ester in a solvent that dries by evaporation, leaving a film that can be re-dissolved in the original solver.

•Alkyd Paints: Employ metal soaps of organic acids to catalyze the oxidation of the drying component. Because lead soaps are commonly used, lead is a potential hazard in any drying oil-type paint (alkyd, epoxy ester, oleoresin, and urethane-oil). Lead used as an oxidation catalyst may comprise 0.5–1.0% of the paint solids by weight. (For more information, see the section Hazards of Pigments and Other Additives.)

• **Liquid Epoxy Resins and Curing Agents:** Are primarily used in solvent-borne and waterborne two-component epoxy paints. These liquid resins are modified by the addition of reactive diluents (glycidyl ethers) that are themselves irritants to the skin, the eyes, and the respiratory tract.

•Aliphatic and Aromatic Polyamines, Polyamine Adducts, and Polyamides: Are used as curing agents in two-component epoxy coating systems. The aliphatic amines are potent irritants and sensitizers; the aromatic amines are somewhat less potent. The polyamide resins are relatively harmless. Acid anhydrides and formaldehyde resins are used as cross-linking agents in powder coatings and baking enamels. The acid anhydrides are irritants and sensitizers. Formaldehyde is a strong irritant and is also considered a human carcinogen.

• **Epoxy Resins:** Are commonly reacted with fatty acids to produce epoxy esters. Because coatings produced with these resins contain no un-reacted epoxy groups, no hazard exists.

• **Urethane Resins:** Organic isocyanates are the principal hazard associated with urethane coatings. Isocyanates can cause severe irritation to the conjunctiva, as well as respiratory distress. They react with various protein functional groups and should be capable of forming antigens. A typical response to isocyanate inhalation, either as a vapor or an aerosol, is the manifestation of an asthma-like syndrome, characterized by a feeling of chest constriction and difficult breathing, sometimes accompanied by a dry, irritating cough. A small percentage of the population may become sensitized to isocyanates, whereupon the above symptoms are produced on exposure to even low airborne concentrations. The toxicity can be minimized, however, by avoiding use of smaller molecular weight species.

Hazards of Solvents and Thinners. Most solvents are toxic to some degree, depending upon the exposure. Solvents may enter or affect the body in three ways. The most frequent way solvents affect the body is through skin contact. When a solvent is allowed to contact the skin, even for a short period of time, it will start to damage the skin or cause dermatitis (a reddening and swelling of the skin). The second route of entry of solvents into the body is by breathing, or inhalation. Once solvents are inhaled, the vapors can pass from the lungs directly to the blood. The solvent

may irritate the respiratory tract and/or cause adverse health effects to other body systems by being transferred through the blood stream. The third route of entry of solvents into the body is by ingestion. Ingestion of solvents may affect the gastrointestinal tract as well as other body organs. The following precautions should be used while working with toxic solvents:

• Properly label, seal, and store all toxic solvents when not in use.
• Adequately ventilate all areas where solvents are used or stored.
• Wear the proper respirator and eye protection.
• If a solvent gets splashed into the eye, immediately flush the eye with water for a minimum of fifteen minutes and seek medical attention.
• Wear the appropriate gloves and clothing when handling solvents.
• Practice good personal hygiene after handling any solvents.
• Consult the Material Safety Data Sheet (MSDS) to determine the toxicity of the material that is in use and the specified protective equipment needed when using the material.
• If permissible exposure limits are exceeded, as determined through air monitoring conducted by an industrial hygienist, then engineering control and respiratory protection becomes necessary.

Prevention of Health Hazards. The following precautions should help reduce potential hazards. They describe a common sense approach to avoiding contact:

• Identify and seal all toxic and dermatitic materials when not in use.
• Adequately ventilate all painting areas. Provide general exhaust ventilation in the form of blowers and fans supplying fresh outside air to the work area where necessary, and use National Institute for Occupational Safety and Health/Mine Safety and Health Administration approved respiratory protection equipment if the vapors cause irritation or intoxication.
• When surface preparation involves removal of old paint films, take care to minimize dusting to protect workers from the dust and to properly dispose of coating residues in accordance with applicable state and federal regulations.
• Wear goggles and the proper respirator when spray painting or performing any operation where an abnormal amount of vapor or dust is formed.
• Wear appropriate gloves and clothing when handling dermatitic materials. Change and clean work clothing daily.
• Avoid touching any part of the body when handling dermatitic materials. Wash hands, face, and arms thoroughly before eating and at the end of the day. Try to shower at or near the job site. Change clothing before leaving. Toxicants can be transferred easily.
• Paint removers containing solvents are often toxic. They should be used only with ventilation controls and/or respiratory protection.

Hazards of Pigments and Other Additives. Heavy metal pigments are another paint component that may be toxic to the human body. The most common contain lead, chromium, and oxides of iron, titanium, and zinc. Precautions such as ventilation, respirators, hygiene facilities, and personal protective clothing should be implemented when applying or removing paints containing these pigments. The substitution of hazardous pigments with non-hazardous pigments is the best method of controlling future occupational health hazards.

The removal of paints containing heavy metal pigments without control measures greatly increases an employee's chances of developing heavy metal poisoning. Airborne pigments such as lead may enter the body by inhalation and ingestion. Exposure to lead may affect each person differently. Even before symptoms appear, lead may cause unseen injury to the body. During early stages of lead poisoning, mild symptoms may be overlooked as everyday medical complaints, including: loss of appetite, trouble sleeping, irritability, fatigue, headache, joint and muscle aches, metallic taste, lack of concentration, and moodiness. Brief but intense exposure or prolonged overexposure may result in severe damage to the blood-forming, nervous, kidney, and reproductive systems. Some noticeable medical problems include: stomach pains, wrist or foot drop, high blood pressure, nausea, anemia, constipation or diarrhea, tremors, convulsions, or seizures.

Silica (both crystalline and amorphous) and the silicates clay, diatomaceous earth, mica, and talc are widely used as extender pigments. With the exception of clay, all have been demonstrated to produce fibrosis of the lung. A preliminary study of the health hazards in the painting trades suggested that "mixed dust pneumoconiosis" is common among

painters. While extender pigments are used in substantial quantities in some paint formulations, these materials may be at least partially locked up by encapsulation in the resinous binder.

The chronic hazards posed by organic pigments are largely unknown. Many of the pigments are based on dyestuffs; the dyestuff is combined with an inorganic compound to produce an insoluble pigment. The dyestuffs have been studied more extensively than the pigments, and several have been implicated as carcinogenic. In paint, the biological availability of these materials is probably limited by the insolubility of the pigments and their partial encapsulation in the paint resin matrix. Fat and/or water-soluble dyes are used in some wood stains, increasing the potential hazard.

Activators and catalysts found in some coatings, such as mercury compounds, can be very harmful if proper protective clothing and respiratory protection is not used.



Figure 2. Eye and respiratory protection are needed for spray painting.

Hazards of Surface Preparation Materials. Blast cleaning can turn paint, rust, and substrate surfaces into a dust cloud consisting of many airborne particles, some too small for the naked eye to see. Whether or not any of the airborne dust particles are a potential health hazard depends on the size of the dust particles, the toxicity of the materials in the dust, and the amount of dust breathed into the lungs. To determine the toxicity of the dust, refer to the MSDS for the abrasive in use, then identify the chemical makeup of the coating being removed and the substrate or object being cleaned. To control workers' exposures to potentially toxic dust, a well-designed ventilation system should be installed. Respirators and proper protective equipment should also be used to ensure adequate protection.

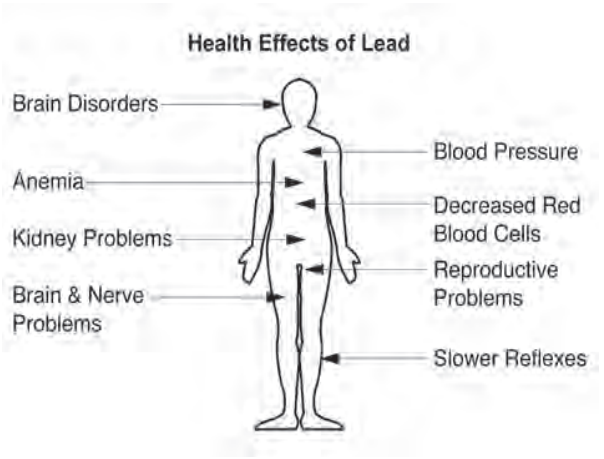


Figure 3. Health effects of lead.

Abrasive fines used to remove paint coatings that contain lead, cadmium, chromates, zinc, or nickel should be treated as hazardous unless testing can prove otherwise. In addition, abrasives may contain small amounts of toxic heavy metals such as lead, copper, arsenic, cadmium, and beryllium. Respiratory devices and protective clothing should be worn when working with abrasive fines. Of particular concern is the presence of silica (quartz) in sands and other mineral abrasives.

Chronic or acute short-term exposure to silica dust can cause a debilitating disease known as silicosis. Air-supplied respirators, operated in accordance with the OSHA Respiratory Protection Standard 1926.103, can protect blasters from this hazard. However, because of poor maintenance of respiratory equipment and poor hygiene, many workers have been exposed to and injured by excessive levels of silica. NIOSH recommended as early as 1974 that abrasive blasting be restricted to abrasive with a maximum of 1% silica content. In a Hazard Alert, NIOSH described specific health hazards from silica, and cited several case histories where blast cleaners

had died from this condition. NIOSH also identified inadequate engineering controls, inadequate respiratory protection, and failure to conduct adequate medical surveillance programs as contributing to the development of silicosis. NIOSH recommends a series of preventative measures, including substitution of alternative abrasives, air monitoring, use of containment structures, personal hygiene, protective clothing, respiratory protection, medical monitoring, posting of warning signs, and worker training.

The Texas Department of Health also issued an advisory on the hazards of using silica abrasives to the oil and gas pipe coating industry. Both documents strongly recommend observing the OSHA PEL (Permissible Exposure Limit). The PEL is based on an 8-hour time-weighted average and is calculated using a formula that requires an analytical laboratory to determine the percentage of crystalline silica in respirable dust collected during worker exposure-monitoring.

Chemical strippers are used to soften the existing coating for removal by scraping and/or flushing. Chemical strippers eliminate airborne hazards, but proper protective clothing such as coveralls, gloves, and glasses should be worn to prevent skin and eye irritation. Caustic compounds in some chemical strippers can cause burns if not immediately washed off the skin and can cause eyes, nose, and throat irritation upon inhalation. Solvent-based strippers are also available. Health hazards may vary from irritation and central nervous system depression, possible with substances such as xylene, to the possibility of carcinogens affecting humans, as with methylene chloride. Methylene chloride is also regulated by an OSHA standard as a carcinogen. Use of methylene chloride should be avoided whenever possible. Chemical strippers containing solvents may require use of respiratory protective devices. Refer to SSPC Technology Update (TU 6), *Chemical Stripping of Organic Coatings from Steel Surfaces* for additional information on the safe use of chemical strippers.

Acids and alkalis commonly found in “wash primers” and chemical strippers (e.g., sodium hydroxide and phosphoric acid) are highly corrosive, and appropriate measures should be instituted concerning storage, handling, waste disposal, ventilation, personal protection, and first aid.

A pre-job analysis of the surface materials should be conducted to determine whether the coating contains hazardous materials. If the coating contains potentially hazardous constituents then respiratory and protective clothing should be worn while working with the removed material.

All spills should be cleaned up immediately and workers should wash immediately if their skin comes into contact with a hazardous substance. If a solvent chemical gets splashed into the eye, immediately flush the eye with water for a minimum of fifteen minutes and seek medical attention. Wear the appropriate gloves and clothing when handling spills. Practice good personal hygiene after handling any spills. Consult the MSDS to determine the toxicity of the material that is in use, and the specific protective equipment needed when using the material. Store and dispose of all oily or solvent wetted rags in metal containers with tightly sealed lids. Respiratory protection should be worn if the spill creates a hazardous atmosphere, or the MSDS indicates it is necessary.

Paint Application

Paint products are used widely in industry to provide a surface coating for protection against corrosion, for appearance, as electrical insulation, and for a number of special purposes. Common methods of application include airless spray, conventional spray (air atomizing), and electrostatic spray.

Because airless spray systems operate at high pressure, special attention must be given to them to ensure safety during operation. A tip guard and trigger lock must be present on airless spray guns. Fluid sprayed from the gun is propelled with sufficient force to penetrate skin and cause serious damage. In the event of injection, special treatment by a physician is required. The attending physician should be advised of the material’s ingredients (an MSDS would be helpful) and of the nature of the injection (high pressure). The entire system is pressurized so that hose ruptures or leaks at fittings can result in dangerous high-pressure spray.

Some important safety practices to help avoid these hazards include:

• Never point the gun at anyone.

• Do not make adjustments to the equipment setup, such as changing nozzles or fittings, without first shutting off the pump and releasing the system pressure.

• Always make sure the fluid hose is in good condition before spraying; kinks or abrasion can develop into a

rupture. Store the hose in a dry area.

• Do not use standard hardware on an airless system; only high-pressure fittings can be used. A high-pressure hose is required for fluid flow. The hose must never be bent or kinked in less than a 4-inch (102-mm) radius.

• Ground airless spray equipment to prevent static sparking. If extension cords are used, make sure that they have a ground wire and that the ground is connected.

• Do not spray solvent through the nozzle tip, because this can cause a build-up of static electricity and an explosion or fire. Take the tip off before spraying solvent through the system.

• Secure the blast hose at a point no more than 10 ft. (30.5 m) from the operator.

• Conduct hydrostatic tests at least once, and preferably twice, a year. Check all valves, including safety valves, daily.

The conventional, or air atomizing, spray gun is widely used due to its versatility, its low cost, and because it creates a high-quality finish. In this method, cold pressed air provides the energy to atomize the finish. The atomization is produced by an air nozzle. Two types of nozzles are used: external mix and internal mix. In the external mix nozzle, the coating and the compressed air exit from separate orifices and are mixed outside the nozzle. The jet atomizes and shapes the spray fan. Internal mix nozzles combine the compressed air and finishing materials in a chamber inside the nozzle. The atomized mixture is shaped by the geometry of the chamber opening. Regardless of which paint method is used, most industrial spray paint operations require exhaust ventilation, the use of air-supplied respirators, protective clothing, and adequate washing facilities.

In electrostatic spraying, an electrical charge is applied to the atomized coating particles, either by the creation of an ionized zone within the spray area, or by imparting a charge to the fluid stream prior to its release from the spray gun head. The charged, atomized paint particles are attracted the conductive object being finished by the electrostatic potential between the paint and the object.

The level of exposure to the paint is determined by the overspray and rebound that occurs during spraying. Effective ventilation controls should be in place, and protective clothing and respiratory protection should be worn while using this painting method. All electrostatic equipment must be properly grounded.

When using a compressor during any of these three application methods, never overload it. Place the compressor in an open and level area in a remote location because it requires a good supply of clean, fresh air in order to properly operate. It should also be grounded before being started. Allow a reasonable amount of time for it to warm up before building up pressure in the receiving tank and never tamper with preset safety valves.



Figure 4. Airless spray systems exert considerable force and can cause serious injury if not handled carefully.

Gauges should be kept clean and visible at all times. Workers need to see the gauges to tell whether all air pressure has been released before disconnecting any couplings or opening any lids. The gauges are also used to ensure that the compressor is operating safely.

Do not add fuel to a gasoline-powered compressor when it is hot or running. The fuel can easily ignite, causing a fire or explosion. All re-fueling of the compressor should be done in the morning before start-up. The compressor should be kept tuned-up and out of confined spaces. If compressors are used to supply breathing air for respirators they must be equipped with carbon monoxide monitor and filter systems capable of providing Grade D air.

Surface Preparation

Abrasive Blast Cleaning. Without proper precautions, the high pressures used in blast cleaning can cause injuries. Injections of water beneath the skin should be treated as seriously as any other chemical injection. In

addition, abrasive material may cause harm at high or even moderate pressures, and continuous exposure to the dust may result in lung disease.



Figure 5. Specialized protective equipment is required for abrasive blast cleaning.

Protective equipment is essential to protect the abrasive blaster and fellow workers from the hazards of the job. At a minimum, a continuous flow respirator with helmet and wide angle, clear vision lens must be used by the abrasive blaster. The helmet must fit completely over the head and neck to the shoulders. The helmet should be equipped with a constant supply of clean air (Grade D or better) of not less than 6 $ft.^3$ (.168 m^3) per minute. The air-line should be equipped with air-purifying filters, pressure regulator gauge, relief valve, air-flow control valve and a NIOSH/MSHA approved blasting respirator. The abrasive blaster should also be equipped with appropriate work gloves, coveralls, and other clothing.

The blaster must use a "dead-man" control valve on the blasting nozzle to cut off the air and abrasive stream when the pressure on the control is released. The hoses for the blasting equipment must be equipped with a static dissipating tube or be lined with carbon black. This prevents shock from static electricity build-up. Such a shock could cause the operator to fall if working on an elevated surface.

Before starting any abrasive blasting operation, thoroughly examine the condition of hoses, hose fittings, couplings, and unions. Any of the above showing wear must be replaced to prevent sudden parting and whipping under pressure.

Hand and Power Tools. Common hand tools used for hand tool cleaning are sandpaper, non-woven abrasive pads, wire brushes, chipping hammers, scrapers, and chisels. Prolonged use of chipping hammers and chisels may cause trauma to the hands, wrists, and elbows. Use of shock absorbing gloves and/or wrist supports or ergonomically designed tools may be advisable.

Common power tools are pneumatically driven hammers or rotary hammers, needle guns, roto peens, rotary grinders, sanders, or wire brushing tools. It is important to have a proper equipment setup when using power tools. Follow the manufacturer's instructions for the tool being used.

Power tools can be dangerous, and safety precautions must be taken when operating them. Protective equipment must be worn. In addition to a hardhat and eye protection, work gloves should be worn. Power tool cleaning may be very noisy, and it is therefore very important to use adequate hearing protection. Respiratory protection and coveralls are advisable whenever hand or power tools are used to remove paint, and are required for removal of lead-based paints.

If electrically driven (rather than air-powered) tools are used, they must be adequately grounded or double insulated, and used in a dry atmosphere to avoid the possibility of shock. Ground Fault Circuit Interrupters (GFCI) should be used with all electric cords and tools. In confined spaces and other areas where there may be a danger of explosion, power tool cleaning should not be conducted because of the possibility of sparking.

The operator must be certain that the tools in use are checked and safe. Make sure that the abrasive media is attached securely and tightened. Tools should not be operated above maximum operating speed or run at all unless in contact with the work surface. Manufacturer's directions should always be strictly followed.

Waterjetting. Although water itself is relatively safe, the extremely high pressure often used for waterjetting can be hazardous. Prior to waterjetting, employees should examine the condition of the hoses, hose fittings, couplings, and unions. All equipment showing

wear should be replaced to prevent sudden parting and whipping under pressure.

Waterjetting hoses should be secured to the staging at the working level, leaving only enough free hose so the hose weight can be properly and safely handled by the blaster. Any electrical equipment in the area of operations that presents a hazard to the operator should be de-energized, shielded, or otherwise made safe. Operators should wear appropriate waterproof clothing, head, eye, and hearing protection during all waterjetting operations.

When waterjetting operations are conducted in confined spaces, the blaster should be in constant communication with the stand-by person. Employees should take precautions to protect the water blasting equipment from freezing in cold weather and signs should be posted to advise others in the area when water blasting operations are being performed. As always, injection of water beneath the skin should be treated as seriously as any other chemical injection, and a physician should be consulted.

Welding, Cutting, or Heating. All welding, cutting, or heating on surfaces with preservative coatings should be performed according to OSHA standard 29 CFR 1926.354, Welding, Cutting, and Heating in Way of Preservative Coatings. Before welding, cutting, or heating, the potential toxicity and flammability of preservatives should be evaluated. All surfaces covered with toxic coatings require the use of protective clothing and a respirator that is capable of filtering out the emissions generated during surface cleaning. Means for fire protection and proper ventilation should also be provided during welding, cutting, or heating.

Pressure Pots. Sandblast pots and related blast machinery should be built to standards set by the American Society of Mechanical Engineers (ASME) or National Board Code. Pots not meeting these requirements must not be used. The ASME code means that everything has been done to make the vessel as safe as possible. The code prohibits any field welding on blast machines. Blast pressures should stay within the manufacturer's blast machine ratings.

Pot tenders and others working near abrasive blasting operations may need to be equipped with respirators, gloves, hard hats, and safety glasses. Most abrasive blasting operations produce noise levels in excess of 90 decibels, therefore hearing protection devices (ear plugs or earmuffs) should also be worn.

Never force the lid off the sandblast pot. If the lid is difficult to open, stop and check the air pressure. The pot must be depressurized before opening the pot lid, or before any changes to hose couplings or repairs of any kind are allowed. A blast machine should never be moved while it contains abrasives. Abrasive blasting machines that will be towed on a highway should be equipped with properly operating brakes, taillights, fenders, and side reflectors.

Access and Rigging

Ladders. Use the following procedures in storing, setting up, and using ladders:

- Use safety shoes.
- Store ladders off the ground in a warm, dry arc protected from the weather.
- Protect wood ladders with a clear finish so that defects are visible.
- Inspect ladders daily during use. Keep them clean and free of oil or grease.
- Use ladders that can be carried and erected by two workers.
- Use a stepladder that is less than 12 ft. (4 m) high.
- Ladders should be fully opened with a locking device.
- Do not stand on the top step. One worker should hold a ladder if the worker climbing the ladder will be more than 8 ft. (2 m) from the ground.
- Avoid placing ladders in front of doorways, unless the door is blocked.
- Only one worker should work on a ladder at a time.
- Do not use a ladder as a horizontal scaffold member.
- The ladder should extend at least 3 ft. (.92 m) above the point of support and should be tied off when accessing unusually high levels.

Fall Hazards. Falls from heights are a significant hazard faced by painters and blasters in day-to-day work. Because falls are a routine hazard, there is a tendency to ignore some of the precautions necessary when working on elevated surfaces, but safety cannot be taken for granted. The hazards of high work subject employees to possible injury and death, and an employer to possible OSHA citations and fines.

The primary means for protecting workers from hazards of falls from heights is the use of a standard guardrail consisting of top rail, intermediate rail, and toeboard. Guardrails and toeboards should

be installed on all open sides and ends of platforms to give maximum protection. The OSHA standard pertaining to this protection is 29 CFR 1926.502(b), which refers specifically to work on floors, platforms, and runways. Other OSHA standards that discuss the use of guardrails are 1926.451(g), pertaining to scaffold arrangements, and 1926.550(9), pertaining to suspended personnel platforms.



Figure 6. Failure to use proper access equipment can lead to falls, a common source of injury in coating operations.

Guardrails and toeboards cannot be used in all fall hazard situations. When guardrails are neither practical nor feasible, use a secondary means of fall protection, or personal fall arrest equipment. Personal fall arrest equipment consists of a safety harness connected by a lanyard to an anchorage. Federal regulations prohibit the use of body belts as part of a personal fall arrest system. Use of body belts, even when properly worn, can cause severe internal injuries or suffocation in an arrested fall. OSHA regulates the use of personal fall arrest systems in 29 CFR 1926.502(d).

While personal fall arrest equipment can be anchored directly to a structure, personal fall equipment is typically attached to a lifeline system. There are three basic types of lifelines: horizontal, vertical, and retractable.

Horizontal lifelines consist of a fiber or wire rope suspended between two fixed anchorages. The safety harness is connected directly to the horizontal lifeline via a lanyard. OSHA requires that horizontal lifelines be designed, installed, and used under the supervision of a qualified person. An evaluation of the horizontal lifeline should be performed to verify that it maintains a safety factor of two, as required by OSHA. Horizontal lifelines should be used for multiple tie-offs only after the qualified person determines the maximum number of workers who can use the lifeline.

The vertical lifeline or dropline is a rope system used with a harness. The harness is attached to a lanyard and rope-grabbing device. The rope-grabbing device is attached to a lifeline that must have a minimum breaking strength of 5,000 pounds (2,270 kg). The rope-grabbing device should be installed and used in accordance with the manufacturer's manual. Improper use or installation (e.g., installing the rope-grab upside down) can result in failure. Only one worker at a time is permitted to be connected to a vertical lifeline.

A retractable lifeline is a device with an integral line that moves upward or downward with the worker, preventing slack from developing. This lifeline is connected directly to the safety harness. Retracting lifelines have a centrifugal locking or braking system to prevent further decent in the event of a fall. Retractable lifelines must be kept overhead as much as possible. As the worker moves horizontally away from the anchor point, the severity of a "swing fall" in the event of an arrested fall increases. A "swing fall" is pendulum like motion that can occur in an arrested fall. During a "swing fall," collisions with obstructions in the path of travel can occur with as much destructive energy as by hitting the ground in a vertical fall. Retractable lifelines should not be used with horizontal lifelines unless the manufacturer approves such use. Improper connection of a retractable lifeline to a horizontal lifeline can result in failure of the lifeline's locking mechanism during an arrested fall.

Anchorages for direct connection of lanyards or connection of lifelines must be independent of any anchorage used to support or suspend platforms. Anchorages must be capable of supporting at least 5,000 pounds (2,220 kg) per employee attached or be used and designed as follows: (1) as part of a complete fall arrest system, which maintains a safety factor of at least two; and (2) under the supervision of a qualified person.

Shock-absorbing lanyards should be used unless lanyards are connected to equipment that limits free fall distance to 2 ft. (.61 m). The free fall distance is the distance traveled in an arrested fall until the fall protection device begins to slow decent. An example of a device that limits the free fall distance to 2 ft. (.61 m) is the retractable lifeline.

Lanyards are only to be connected to the D-ring on the back of the harness approximately between the worker's shoulder blades. Harnesses may have D-rings at other locations for connecting other types of fall protection equipment (e.g., D-rings at waist level for connection to positioning systems, such as belts). Use of the incorrect D-ring for lanyards can result in severe injury or death. Lanyards must also be equipped with the correct attachment device (e.g., snaphook) for connection to the anchorage (e.g., lifeline).

OSHA requires the use of locking snaphooks to prevent "roll out" where the snaphook keeper is accidentally depressed in an arrested fall, resulting in disengagement. Snaphooks cannot be connected to objects that are not compatibly shaped (e.g., the keeper of the snaphook is unable to close after attachment to the anchorage). When snaphooks are not able to be directly connected to the anchorage, the use of anchorage connection devices (e.g., cross arm strap, carabiner) should be investigated. Snaphooks should not be connected directly to horizontal lifelines unless it is of a locking type and unless the manufacturer recommends such use.

Personal fall arrest systems must be rigged so that workers will not free fall more than 6 ft., (1.83 m) nor contact a lower level. The amount of clearance beneath the anchor point needed to meet this requirement is determined by the free fall distance (6 ft. [1.83 m] if a six foot lanyard is used), the deceleration distance (3.5 ft. [1.07 m] if the lanyard is equipped with a shock absorber), and the length of the worker's body suspended beneath the D-ring on the back of the harness (about 5 ft. [1.53 m]).

A safety factor of about 4 ft. should also be included in the amount of clearance required to allow for D-ring slide and stretching in lifelines and webbing in the harness and lanyard. This safety factor may have to be increased for horizontal lifelines depending on the amount of sag permitted by the qualified person. Where there is insufficient clearance beneath the anchor point, use of a retractable lifeline should be investigated. These devices limit free fall to 2 ft. (.61 m), making use of a shock absorber unnecessary and eliminating the deceleration distance of 3.5 ft. (1.07 m). Other options to reduce the amount of clearance needed include use of a shorter lanyard or simply moving the anchor point to a higher location. Keeping free fall distances to less than 6 ft. (1.83 m) is accomplished by using lanyards that are 6 ft. (1.83 m) or less in length (or by using a retractable lifeline) and by maintaining the anchor point location above the D-ring on the back of the harness.

OSHA requires employers who rely on personal fall arrest systems to have pre-planned rescue procedures in the event of a fall. As an alternative to developing rescue procedures, employers can provide employees with equipment that allows for self-rescue. An example of a self-rescue device is a retractable lanyard with a controlled decent mechanism that permits employees to lower themselves to the ground after arrested falls. Since improper installation, use, and maintenance of fall protection can result in serious injury and death, workers must be trained when exposed to fall hazards. OSHA training requirements are addressed under 29 CFR 1926.503. Training should also include information in the manufacturer's manual for personal fall arrest equipment used by workers.

Sometimes personal fall arrest systems, guardrails, or other conventional protective equipment may be impractical or not feasible for the work method. In these situations, personnel safety nets can be installed under and around the work area. Personnel safety nets are typically used in bridge work and long-term structural projects where workers are exposed to significant fall hazards.

Personnel safety nets must be manufactured and tested in accordance with all pertaining ANSI standards and OSHA standard requirements. They should bear a label displaying the manufacturer's name, date of manufacture, and proof of load testing. Every net should also carry a serial number so that records can be kept of details such as repairs, inspections, and load test results. OSHA's requirements for safety nets can be found in 29 CFR 1926.502 (c).

Aerial Lifts. OSHA regulates aerial lifts under 29 CFR 1926.453. According to the OSHA standard, aerial lifts include the following vehicle mounted aerial devices used to elevate personnel to job sites above

the ground:

- Extensible boom platforms
- Articulating boom platforms
- Vertical towers
- A combination of any such devices

These requirements are specifically applicable to extensible boom and articulating boom platforms:

- Only authorized persons shall operate an aerial lift.
- Belting off (i.e., connecting personal fall arrest equipment) to an adjacent pole, structure, or equipment while working from an aerial lift shall not be permitted.
- Employees shall always stand firmly on the floor of the basket and shall not sit or climb on the edge of the basket or use planks, ladders, or other devices for a work position.
- Boom and basket limits specified by the manufacturer shall not be exceeded.
- The brakes shall be set and when outriggers are used they shall be positioned on pads or a solid surface. Wheel chocks shall be installed before using an aerial lift on an incline, provided that they can be safely installed.
- An aerial lift truck shall not be moved when the boom is elevated in a working position with workers in the basket, except for equipment that is specifically designed for this type of operation in accordance with 29 CFR 1926.453 (a)(1) and (a)(2).
- Articulating boom and extensible boom platforms that are primarily designed as personnel carriers shall have both upper and lower controls. Upper controls shall be in or beside the platform within easy reach of the operator. Lower controls shall provide for overriding the upper controls. Controls shall be plainly marked as to their function. Lower level controls shall not be operated unless permission has been obtained from the employee in the lift, except in case of emergency.
- Climbers (i.e., spurs or spikes attached to the shoe) shall not be worn while performing work from an aerial lift.
- The insulated portion of an aerial lift shall not be altered in any manner that might reduce its insulating value.
- Before moving an aerial lift for travel, the boom(s) shall be inspected to see that it is properly cradled and outriggers are in the stowed position, except when the requirement described above is met for moving the aerial lift when the boom is elevated.

Many injuries and fatalities associated with the use of aerial lifts are due to falls. Typical causes of falls from aerial lifts include mechanical failures in the hydraulic system that cause the basket to tip, operating the aerial lift on an incline causing the unit to tip over, falling while climbing out of the basket onto a scaffold or other elevated work surface, or falling out of the basket while standing on the guardrail or makeshift platform (e.g., board suspended from the guard rails or a bucket).

OSHA requires personal fall arrest equipment for all occupants in an aerial lift. In lieu of personal fall arrest, which protects occupants if they fall from the aerial lift, OSHA permits occupants to be provided with a restraint system as an alternative. A restraint system may consist of a body belt (note this exception for the use of body belts with “restraint systems” only), or a harness and lanyard that must be short enough to prevent the occupants from leaving the basket. Lanyards used in restraint systems for aerial lifts typically must be less than 4 ft. (1.22 m) long.

Only if scissor lifts are equipped with standard guardrails does OSHA permit, in a letter of interpretation dated August 8, 1995, an exemption to the requirement to provide occupants with personal fall arrest or restraint systems. OSHA stated in this letter that this exemption does not apply if guardrails are removed or are not effective. The use of personal fall arrest for scissor lift occupants should also be considered if there is the possibility that occupants may climb out of the platform or (improperly) stand on guardrails while working from these platforms.

In two letters of interpretation dated January 25, 1988 and September 5, 1998, OSHA addressed control measures for fall hazards when workers transfer between elevated work surfaces and aerial lifts. These letters state that employees should attach their lanyards to an attachment point on the fixed structure (e.g., bridge) before exiting the basket. A vertical lifeline is given as an example of a means of attachment. Any lifelines, including their anchorages, used for connection of personal fall arrest must meet the requirement of 29 CFR 1926.502 (d).

OSHA warns, in the September 5, 1998, interpretation letter, that attachment of personal fall arrest equipment to the aerial lift basket may be inappropriate if the manufacturer of the lift cannot certify that the lift will not tip over if a person, tied off to the lift, fell from a position on top of the basket guardrail. The use

of dual lanyards should also be considered to allow workers to be tied off at all times when disconnecting their lanyards from the aerial lift basket and connecting them to a lifeline suspended from the structure.

The manufacturer's manual must be consulted before operating an aerial lift on an inclined surface. The limits in the manual for an acceptable incline surface must not be exceeded. Many newer aerial lifts are equipped with devices that prevent operation if the aerial lift is tilted beyond acceptable limits.

Confined Spaces. OSHA's Permit-Required Confined Space Standard 1910.146 defines a confined space as a "space the is large enough and so configured that an employee can bodily enter and perform assigned work; and has limited or restricted means for entry or exit (e.g., tanks, vessels, silos, storage bins, hoppers, vaults and pits are spaces that may have limited means of entry); and is not designed for continuous occupancy."

The confined space standard states the minimal requirements for safe entry, continuous work in, and exit from tanks and other confined spaces. A confined space program should include training in:

- The duties of a standby person
- Use of ventilating equipment
- Isolation of systems
- Atmospheric testing
- Confined space entry limits
- The use/purpose of an entry permit

Understanding OSHA

General Duty Clause

Although OSHA has developed a number of industry- and substance-specific standards, the general duty clause takes a very broad view of worker health and safety. It requires employers to furnish to their workers "employment and a place of employment which are free from recognized hazards that are causing or likely to cause death or serious physical harm." OSHA can use this clause to cite an employer when conditions it believes to be unsafe do not violate specific OSHA regulations.

The Regulatory Process

Some OSHA standards have been mandated by Congress. They may also be initiated by the agency in response to petitions from other parties including NIOSH, state and local governments, groups that develop voluntary industrial standards or labor representatives. Once the need for a new standard has been identified, OSHA Advisory Committees, which include representatives of management, labor, and state agencies, develop recommendations.

In the very early stages of the process, OSHA may request additional information needed for the development of a standard by publishing an "Advance Notice of Proposed Rulemaking" in the *Federal Register,* a daily record of federal business. When a first draft of the proposed regulations has been completed, a "Notice of Proposed Rulemaking" must appear in the Federal Register. Interested parties must then have at least 30 days to comment on the way proposed regulations will impact them. Following this comment period, the final regulations are published in the Federal Register, and incorporated into the Code of Federal Regulations, a permanent record of government regulations organized by subject.

Those who feel they will be adversely affected by a standard may request a judicial review. Employers who cannot meet the standard, or believe an exception should be made in their cases because their facilities or methods are "at least as effective," can request a temporary or permanent variance.

When new or particularly hazardous conditions warrant, OSHA may develop emergency standards, which take effect immediately. Once these standards have been published in the Federal Register, they are also subject to comment and review before they are published as permanent standards.

Enforcement and Interpretation

Every establishment covered by the Occupational Health and Safety Act is subject to inspection by OSHA compliance safety and health officers. Inspections are generally conducted without advance notice, though OSHA is required to obtain a warrant if an employer does not consent. OSHA gives highest priority to workplaces:

- Where there is imminent danger of death or serious physical harm
- Where fatal accidents, or accidents that hospitalized more than five employees, have occurred
- When employees complain of alleged violations and request an inspection
- When specific industries, occupations, or materials

Table 1. Possible Fines for OSHA Violations.

Type of Violation	Criteria for Type of Violation	Possible Penalty
Other than Serious Violation	Probably would not cause death or serious physical harm	Penalty is discretionary and may range from $50 to $70,000 for each violation, depending on a show of good faith
Serious Violation	Substantial probability of death or serious physical harm; Employer knows or should have known about the violation	Penalty is mandatory and up to $7,000 for each violation
Willful Violation	Employer knows about the hazard or violation, and makes no reasonable effort to correct it	Penalties range from $5,000 to $70,000 for each violation
Willful Violation Resulting in Death	—	Fines up to $25,000 for an individual and $500,000 for a corporation; Possible 6-month jail term
Repeat Violation	Upon reinspection, a substantially similar violation is found	Up to $70,000 for each violation
Failure to Correct Violation	A violation for a final citation has not been corrected by the prescribed abatement date	Up to $70,000 for each day past the abatement date the violation continues

are associated with high rates of illness or injury

If OSHA discovers violations during an inspection, the employer will receive a citation, which details the violation and includes information about penalties and a schedule for compliance. Penalties may depend on the seriousness of the violation, knowledge of the violation, and a show of cooperation or good faith. Serious penalties are also possible for repeat violations and failure to correct previous violations. Employers may want to schedule an informal meeting with OSHA's area director, who is authorized to enter into settlement agreements that revise citations and penalties.

The employer may also contest both a citation and associated penalties within 15 days. The written Notice of Contest will be evaluated by the Occupational Safety and Health Review Commission. Unfavorable decisions can be appealed at this level and to the U.S. Court of Appeals.

Painting contractors are considered part of the construction industry for OSHA record-keeping purposes. These businesses are most frequently cited for failure to comply with the Lead Standard. They are also frequently cited for respiratory protection, scaffolding (i.e., general requirements, manually propelled ladder stands and scaffolds, and training), hazard communication, and fall protection.

Consultation Assistance

OSHA provides a Consultation Service that can help employers evaluate and improve their compliance. The service was developed with small employers in mind. Although the program is funded by OSHA, it is entirely voluntary. No penalties are issued, and OSHA enforcement compliance officers do not see the results.

State officials or university staff often operate the Consultation Service. They may point out weaknesses in an employer's health and safety program and provide the training and technical assistance needed to resolve any problems. Firms that participate in the program receive a limited one-year exemption from OSHA inspection.

OSHA's Voluntary Protection Programs encourage employers to take their health and safety programs beyond the letter of the law and provide recognition for those who accept the challenge. The Star, Merit, and Demonstration Programs are cooperative programs, and participants are volunteers. These firms also receive limited exemptions from inspection.

Local OSHA offices can also provide publications, speakers, audiovisual materials, and technical advice. OSHA provides funds to nonprofit organizations to conduct workplace training and education. A number of private firms and universities also offer OSHA compliance training.

Components of OSHA Compliance

Company safety and health programs should be designed to be used in conjunction with the current copy of the OSHA *Construction Industry Standards 29 CFR 1926*, and the *General Industry Standards 29 CFR 1910.* OSHA states in *29 CFR 1926.20 General Safety and Health Provisions:* "It shall be the responsibility of the employer to initiate and maintain such programs as may be necessary to comply with this

part" (part refers to all of 29 CFR 1926).

The purpose of an OSHA Compliance Program is to establish and maintain policies, programs, and procedures that are necessary to comply with all applicable OSHA standards, and to establish and maintain an effective program to prevent accidents, injuries, and illnesses.

The components of an OSHA Compliance Program should include:

• Policy statement establishing goals and commitment of management and the means for communicating these to all employees

• Delegation of responsibilities for implementing the program

• Methods for identifying hazards and hazardous activities and for controlling them

• Commitment to ongoing training and education of all supervisors and employees on all aspects of job safety and health

• Proper reporting, record-keeping, and investigation of all accidents, injuries, and illnesses

• Methods and procedures for complying with specific OSHA standards

• Periodic review of the program with revisions made as necessary



Figure 7. Workers may be required to wear hearing protection under OSHA's Occupational Noise Exposure Standard.

Organization and Hierarchy of OSHA Standards

The *OSHA General Industry Standards 29 CFR 1910* contains several standards applicable to the protective coatings industry. When a construction industry standard (29 CFR 1926) is not applicable or is non-existent, the *General Industry Standard (29 CFR 1910) Protective Coatings* may be enforced. Some common aspects of the protective coatings industry and their related General Industry standards include the following:

• **Abrasive Blasting:** No specific standard applies to blasting in the field, but many aspects of blasting operations fall under other applicable standards.

• **Noise/Hearing Conservation:** Noise protection should be provided, and a Hearing Conservation Program should be in place and be in compliance with OSHA standard *29 CFR 1910.95, Occupational Noise Exposure.*

• **Respiratory Protection:** The selection, issue, use, inspection, cleaning, storage, and repair of respirators should comply with the *OSHA Respiratory Protection Standard, 29 CFR 1926.103.* See section III F for more information on choosing respirators.

• **Confined Spaces:** Practices and procedures used to protect employees from the hazards of entry into permit required confined spaces should comply with *OSHA Standard, 1910.146, Permit-Required Confined Spaces.*

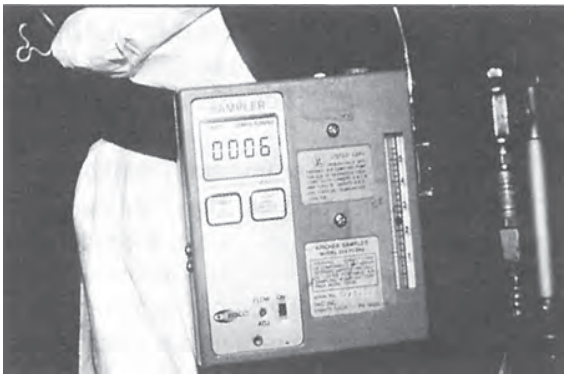


Figure 8. In order to test the level of air contaminants, a vacuum pump on the worker's belt is used to pull air through a specialized filter placed in the worker's breathing zone.

Construction Industry Standard Relating to Industrial Protective Coating Operations

The *Construction Industry Standards, 29 CFR 1926,* contain many standards that apply to industrial protective coating operations. Some of the common standards that apply to the construction industry include:

• **Hand Tools and Power and Pneumatic Tools:** All hand, power, and pneumatic tools should be equipped, inspected, guarded, used, and maintained according

to the manufacturer's specifications and limitations and OSHA standards *29 CFR 1926.300-305, Tools–Hand and Power.*

• **Compressed Air:** There is no existing OSHA standard for compressed air. However, there are standards set by the American Society of Mechanical Engineers (ASME).

• **Electrical:** All electrical systems and equipment should be designed and installed according to OSHA standards *29 CFR 1926.402-408, Installation Safety Requirements,* and the most current edition of *NFPA 70, National Electric Code.* All employees performing work on electrical equipment or systems should comply with the work practices in OSHA standards *29 CFR 1926.416-417, Safety-Related Work Practices.*

• **Eye and Face:** Eye and face protection should be provided when machines or operations present potential eye or face injury from physical and chemical hazards as required by *OSHA Standard 29 CFR 1926.102, Eye and Face Protection.* Eye and face protection equipment required by OSHA should meet the requirements specified in *American National Standards Institute Z87.1, Practice for Occupational and Educational Eye and Face Protection.*

• **Fire Protection/Flammable, Combustible Liquids:** Fire protection should be developed for all company activities according to OSHA standard *29 CFR 1926.150, Fire Protection.* This should include providing, maintaining, inspecting, and testing fire suppression systems and portable fire extinguishers, as required by this OSHA standard. The fire prevention requirements, specified in OSHA standard *29 CFR 1926.151, Fire Prevention,* should be implemented for all jobs.

The storage, handling, use, and fire protection requirements for flammable and combustible liquids and their containers should be in compliance with OSHA standard *29 CFR 1926.152, Flammable and Combustible Liquids.*

• **Exposure to Gases, Vapors, Dusts, Mists, and Fumes:** Employee inhalation, ingestion, skin absorption, or contact with any material or substance at a concentration above the permissible exposure limit (PEL) specified in OSHA standard *29 CFR 1926.55, Gases, Vapors, Fumes, Dusts, and Mists* is prohibited.

Generally, OSHA requires employers to minimize employee exposure to air contaminants as much as possible through the use of engineering controls such as enclosure or confinement of an operation, ventilation, or substitution of less toxic materials. Only when acceptable levels of exposure cannot be achieved through these approaches (as is often the case in coating operations) may employers use respiratory protective devices to comply with these standards.

• **Housekeeping:** During the workday, work areas, passageways, and stairs in and around buildings or other structures must be kept clear of debris according to *OSHA Standard 1926.25, Housekeeping.*

• **Ladders and Scaffolding:** Stairways and ladders must be designed, constructed, and used according to the manufacturers' specifications and limitations and OSHA standards CFR 1926.1050 through 29 CFR 1926. 1060. Job-made ladders must conform to the design and construction specifications of these OSHA standards. The design, construction, load-bearing capabilities, platform guarding, and use of all scaffolding must comply with OSHA standard, *29 CFR 1926.450-454, Scaffolding.*

• **Personal Protective Equipment for head, foot, and body:** Hard hats must be used where there is a possible danger of head injury from impact, from falling objects, or from electrical burns as required by OSHA standard *29 CFR 1926.100, Head Protection.* Helmets and hardhats for the protection of employees against impact and penetration of falling and flying objects should meet the specification contained in *American National Standards Institute, Z89.1, Safety Requirements for Industrial Head Protection.* Helmets for the head protection of employee exposed to high voltage electrical shock and burns should meet the specifications contained in American National Standards Institute Z89.

Where the potential for serious foot injury exists, safety-toe footwear for employees should be required and meet the requirements specified in *American National Standard for Personnel Protection–Protective Footwear, Z41.* Employees working with chemicals or materials that can cause damage to the skin or that can be absorbed should be provided

Table 2. Task-Related Triggers Under the Construction Industry Lead Standard.

Workers engaged in the tasks listed must be protected as specified before air monitoring results are back and throughout the task unless monitoring results show that lower levels of protection are sufficient [29 CFR 1926.62(d)].

Presumed Exposures for Specific Tasks		
50 µg/m^3-500 µg/m^3	50 µg/m^3-2,500 µg/m^3	>2,500 µg/m^3
Specific Tasks		
Manual Demolition Manual Scraping Manual Sanding Heat Gun Applications General Clean-up Power tool cleaning with dust collection systems Spray Painting Any other task where employer has reason to believe task could exceed PEL	Power tool cleaning without dust collection systems Clean-up of dry expandable abrasives Movement and removal of abrasive blasting enclosures Use of lead-containing mortar Lead Burning Rivet Busting	Abrasive Blasting Welding, cutting and torch burning
Protective Measures *[A complete list of options for respiratory protection appears in the Interim Final Rule's Table on Respiratory Protection, 1926.62(f).]*		
Protective Clothing and Equipment Change Areas Hand Washing Facilities Training Initial Medical Surveillance: blood sampling and analysis Respirators with protection factor of 10, such as a half mask air-purifying respirator with high-efficiency filters or operated in demand (negative pressure) mode	Protective Clothing and Equipment Change Areas Hand Washing Facilities Training Initial Medical Surveillance: blood sampling and analysis Respirators with protection factor of 25-50, such as a powered air-purifying respirator with loose fitting helmet or hood and high efficiency filters, or full facepiece air-purifying respirator with high-efficient filters	Protective Clothing and Equipment Change Areas Hand Washing Facilities Training Initial Medical Surveillance: blood sampling and analysis Respirators with protection factor of above 50, such as a full facepiece supplied-air respirator operated in positive pressure mode (assigned a protection factor of 2,000 in new rule)

appropriate protective clothing.

The selection, issue, use, inspection, cleaning, storage, and repair of respirators must comply with the OSHA Respiratory Protection Standard, 29 CFR 1926.103. See section III F for more information on choosing respirators.

Standards for Lead and Lead Removal

The *Construction Industry Lead Standard, 1926.62* provides the practices and procedures for protecting employees exposed to lead on the job. All construction work excluded from coverage in the *General Industry Standard for Lead* by 29 CFR 1910.1025(a)(2) is covered by this standard. Construction work is defined as work for construction, alteration and/or repair, including painting and decorating. Lead paint removal and maintenance activities would be covered by the *CFR 1926.62, Lead Standard.* All other non-construction work is covered by the *General Industry Standard 1910.1025.* Protective measures required under the Construction Industry Lead Standard are shown in **Table 2.**

Choosing Respiratory Protection Devices

It is likely that workers will be required to wear some type of respiratory protection during most coating and surface preparation operations, particularly when removing lead paint using techniques such as powered hand tools and vacuum blasting, due to the very low levels of exposure required to trigger mandatory use (5 mg/m^3). In a containment structure in which abrasive blasting is occurring, workers will always be required to wear respiratory protective equipment, even if a well designed ventilation system is being used. It is also likely that most support personnel may be required to wear respirators in order to meet the permissible exposure limit. In general there are two basic types of respirators: air-purifying respirators and supplied-air respirators.

Air-purifying respirators remove particulates from the air in the worker's breathing zone by filtering it prior to the worker inhaling it. Air-purifying equipment has the advantage of being lighter and less restrictive as well as more economical than supplied-air respirators.

Supplied-air respirators supply breathing air from outside the work environment. Supplied-air respirators protect workers from simultaneous exposure to multiple contaminants, which is not uncommon in coating operations. High dust levels associated with

many surface preparation techniques may quickly overload the filtering systems on which air-purifying respirators are based, and air-purifying equipment may not be adequate to protect workers from high lead levels associated with containment systems.

Protection Factors. Various groups have established protection factors for respirators, including NIOSH, OSHA, ANSI, and others. In fact, there is quite a controversy over the level of protection afforded by different categories of respirators. In general, protection factor describes a degree of protection a given respirator will provide, versus some airborne concentration of contaminant outside the respirator. For instance, for the half-mask respirator equipped with HEPA filtration cartridge, a protection factor of 10 is assigned for lead. This means that the respirator can be worn in an atmosphere up to 10 times the PEL and still protect the worker so that the concentration of lead inside the mask is below the PEL. Assuming a PEL of 50 mg/m^3, this respirator can then be safely worn when airborne concentrations are up to 500 mg/m^3. Similarly, a protection factor of 50 is assigned for full-face respirators.

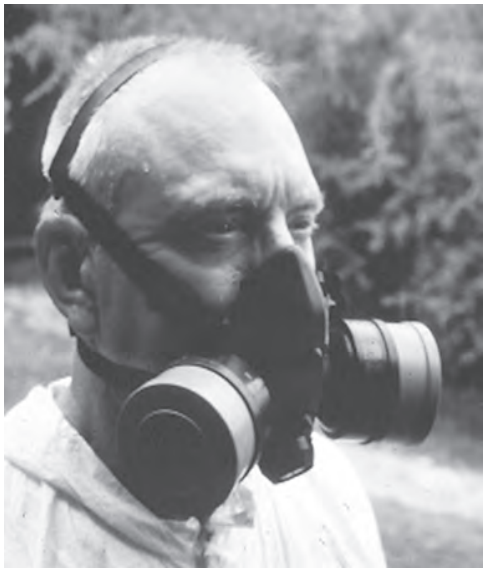


Figure 9. Air purifying respirators filter contaminants from the air workers breathe.

Powered air-purifying respirators (PAPR) highlight a variation on assigned protection factors. For lead, NIOSH has taken a very conservative posture and established a protection factor of only 50 for PAPRs, while OSHA and others have established protection factors of up to 1000.



Figure 10. Supplied air respirators deliver breathing air from outside the work environment.

Similar problems occur when looking at the standard respirator for blasting, the abrasive blasting hood. NIOSH's current position is to assign a protection factor of only 25. This same protection factor was incorporated into respirator protection factors assigned under the *OSHA Construction Industry Lead Standard.* However, since 1995 OSHA has issued letters of interpretation permitting specific models and makes of abrasive blasting helmets to be assigned a protection factor of 1,000. The protection factor assigned to these helmets is based upon using the helmets in accordance with the manufacturer's instruction manual and setting up the air-supplied system identical to the way the system was certified by NIOSH. It should be noted that these letters of interpretation only apply to enforcement of the *OSHA Construction Industry Lead Standard.* Other OSHA standards may assign different protection factors to the same respirator. For example, the *OSHA Cadmium Standard 29 CFR 1926.1127* assigns a protection factor of 25 to abrasive blasting helmets, which is the same as that recommended by NIOSH, while the *OSHA Arsenic Standard 29 CFR 1926.1118* assigns a protection factor of 2,000.

When OSHA published its recent revision to the *Respiratory Protection Standard 29 CFR 1926.103,* rulemaking to standardize protection factors was deferred until a later date. However, OSHA has provided employers with guidance in choosing a protection factor in the compliance directive for the *Respiratory Protection Standard CPL 2-0.120.* In this compliance directive, OSHA states that it will refer to

protection factors assigned by NIOSH, except in cases where protection factors have been published in substance-specific standards (e.g., cadmium) or are addressed by OSHA in separate letters of interpretation.

Breathing Air Requirements. With any of the supplied-air respirators, including abrasive blast hoods, it is essential that Grade D breathing air reach the respirator. ANSI Standard Z 86.1/Compressed Gas Association commodity specification G-7.1 for Grade D Air requires oxygen levels of 19.5–23.5%, no more than 5 mg/m^3 condensed hydrocarbon contamination, no more than 10 ppm carbon monoxide, no pronounced odor, and a maximum of 1,000 ppm carbon dioxide. Controls must be installed on compressors to achieve and verify compliance with these requirements, or special-built, dedicated breathing air compressors must be used. The control/filter systems of existing oil lubricated compressors must be equipped with a constant monitor for carbon monoxide or a heat-rise alarm with frequent measurement of in-line carbon monoxide. In addition, periodic samples from the air stream should be drawn, bottled, and sent to a laboratory to verify that each parameter of Grade D breathing air has been met.

Implementation of Safety and Health Problems

Establishing Worker Safety and Health Programs

A worker safety and health program should first establish and then maintain those policies, programs, and procedures necessary to comply with all applicable OSHA standards, while also effectively preventing accidents, injuries, and illnesses. After identifying the program components, it is important to dedicate the time to sit down with all company managers and supervisors to review the program and set specified goals for implementing its requirements. Have managers and supervisors do the same for all the employees. Encourage participation. Be honest and sincere. Continually ask for feedback and ways for improving the program. Let everyone know they will be consistently held accountable for fulfilling their responsibilities under the program. Let good performers know that they are doing a good job. At the same time, do not let poor or mediocre performance go unnoticed.

Monitor and maintain records relating to accidents, injuries, illnesses, medical examinations, training, fit testing, and exposure monitoring for the life of the company. Analyze the firm's total workers compensation costs over the years. Compare accident rates and evaluate changes in employee attitudes and work quality. Seek assistance from employees to get feedback on the success of the program.

Owner Evaluation and Monitoring of Contractor Programs

A representative of each facility owner should evaluate and monitor all contractor health and safety and OSHA compliance programs. These programs should be submitted, approved, and monitored by a qualified individual, such as a certified safety professional (CSP) or certified industrial hygienist (CIH). The program evaluations should be completed before any work begins. Monitoring should be conducted through job site visits and review of daily work logs.

OSHA Standard 1910.119 Process Safety Management of Highly Hazardous Chemicals contains the specific requirements and responsibilities for owner and contractor safety and health programs. This standard states that the owner is responsible for obtaining and evaluating information regarding contractor safety performance and programs.

A good example of a safety program that each contractor in the coatings industry should have is *OSHA 1910.146 Permit-Required Confined Spaces*. Under this standard, the contractor must develop a written permit space entry program that complies with the requirements of the standard. This program must be reviewed by the owner to verify that contractor safety procedures and practices are adequate and are being followed.

Maintaining a site injury and illness log, *OSHA Injury and Illness Records Form 300,* is another method employers must use to track work activities involving contract employees working on or adjacent to covered processes. Injury and illness logs of both the employer's employees and contract employees allow an employer to have full knowledge of process injury and illness experience. This log will also contain information that will be of use to those auditing process safety management compliance and those involved in incident investigations.

It is very important for owners to write OSHA compliance requirements into their contracts and

specifications. This will help ensure that the contractors are complying with the applicable OSHA standards.

About the Authors

Daniel P. Adley, CIH/CSP
Daniel P. Adley is vice president of operations for KTA-Tator, Inc. Mr. Adley has a BA in chemistry and an MS in industrial hygiene. He is a certified industrial hygienist and certified safety professional with over 25 years of diversified safety and health consulting experience. Mr. Adley is an active member of the SSPC, where he chairs Group Committee C.5 on environmental, health, and safety compliance and was the recipient of the 1994 Education Award and 1999 Technical Achievement Award. Mr. Adley was the technical editor of the first and second editions of the *Industrial Lead Paint Removal Handbook (Volume 1)*. He is co-author of Volume 2 of the *Handbook: Project Design*. He also served as a contributing safety editor for the *Journal of Protective Coatings and Linings*.

Stanford T. Liang, CIH
Stanford T. Liang is a certified industrial hygienist (CIH) with the EH&S group of KTA-Tator, Inc. Mr. Liang is also a certified environmental trainer and OSHA construction outreach program trainer. He has extensive experience performing industrial hygiene air monitoring, conducting job safety analysis, developing safety programs (including confined space entry, lockout/tagout, and emergency response plans), and presenting safety training and OSHA compliance audits. His experience with KTA has included updating a comprehensive safety and health program for 12 PDCA-member painting firms. Mr. Liang previously served as an assistant safety officer for the U.S. Navy. He is a member of the National Environmental Training Association, American Industrial Hygiene Association, and the American Academy of Industrial Hygiene.

Chapter 9.1
Air Quality Regulations

Bernard R. Appleman

General Overview of Activities and Regulations

National Ambient Air Quality Standards

The U.S. Congress passed the Clean Air Act in 1970 to protect and enhance the quality of the nation's air resources.[1] As a result of this act, EPA established the National Ambient Air Quality Standards (NAAQS) to promote public health and welfare. Under NAAQS, six primary pollutants were identified, for which EPA was to develop criteria allowing for an adequate margin of safety to protect public health:

- Lead
- Ozone
- Particulate matter (10 micrometers or less)
- Sulfur dioxide
- Nitrogen dioxide
- Carbon monoxide

Of most interest to the protective coatings industry are those criteria for ozone, lead, and particulates. NAAQS apply only to measured ambient levels (i.e., dust or vapors that remain suspended). Air emissions that deposit particles on the ground or adjacent properties are covered by CERCLA regulations discussed in Chapter 9.3.[2]

Clean Air Act Amendments of 1990

In 1990, Congress amended the Clean Air Act (CAAA).[3] CAAA set forth an ambitious program for reducing air pollution throughout the U.S. EPA identified four primary goals in implementing the 1990 CAAA: to bring all cities into health standards attainment; to cut air toxic emissions by 75%; to reduce sulfur dioxide emissions by 10 million tons; and to phase out all chlorofluorocarbons by 1995.[4, 5, 6]

The eleven titles that make up CAAA create a framework for achieving these goals. Reducing hazardous airborne emissions from coatings is but one target.

Hazardous Air Pollutants

As part of CAAA, Congress specifically added approximately 190 additional Hazardous Air Pollutants (HAPS) to the list of substances that required control. This list included many of the common solvents used in paints, such as xylene, toluene, and methyl ethyl ketone **(see Table 1)**. Previously, under the National Emission Standards for Hazardous Air Pollutants program, the EPA had been charged with regulating HAPS. However, there was no significant progress because of the requirement to apply health-based standards and because of the lack of specific targets.

Table 1. Hazardous Air Pollutants in Protective Coatings.

Chromium Compounds
Dimethyl Formamide
Dimethyl Phthalate
Epichlorohydrin (Chloro-2, 3-epoxypropahne)
Ethylene Glycol
Formaldehyde
Glycol Ethers
Hydrochloric Acid
Isophorone
Lead Compounds
Methanol
Methyl Chloroform (1, 1, 1, - Trichloroethane)
Methyl Ethyl Ketone (2-Butanone)
Methylene Chloride (Dichloromethane)
2 Nitropropane
Styrene
Toluene
Triethylamine
Xylenes (m, o, p or mixed)

The 190 substances listed are subject to controls using "maximum available control technology" (MACT). MACT is defined in part as "the maximum degree of reduction in emissions of the hazardous air pollutants..."[8] A new source (i.e., a new emitting facility) must achieve reductions equivalent to the best-performing similar source. Existing sources (the majority of facilities) are required under MACT to achieve the average reduction attained by the best 12% of similar sources (based on a minimum of 30 such sources). These standards are thus based on

technology rather than on health.

The facilities initially required to abide by MACT are stationary sources emitting more than ten tons [9 megagrams (Mg)] per year of any single HAP or 25 tons (23 Mg) per year total.Thus,a facility applying coatings containing 2 lbs/gal (240 g/L) of xylene would be limited to 20,000 gallons (76,000 L) per year.

CAAA also addresses the need to control HAPS from area sources. These are sources that are too small to be regulated as major sources (i.e., less than 10 tons [9 Mg] per year of a single HAP or 25 tons [23 Mg] per year total HAPS) but which collectively emit a substantial volume of HAPS.

It is important for the industry to coordinate the control of HAPS under MACT with the control of VOCs under other provisions of CAAA, (e.g., Control Technique Guidelines or National Rules). Recent activities to establish a combined HAP-VOC control strategy for the shipbuilding industry (marine coatings) are discussed below.

Ozone and VOC

Regulating Ozone

Ozone, a reactive form of molecular oxygen, is a major component of smog. The detrimental effects of ozone occur when it is found in the atmosphere (troposphere), where humans and other life forms exist. Here it affects human respiratory function at high ambient levels and can also damage life. In the upper atmosphere (stratosphere), however, ozone has a beneficial effect on health, helping to absorb solar radiation that could otherwise reach the earth and increase the risk of skin cancer and other diseases.

The coatings industry is involved in both aspects of the ozone problem. First, ground-level ozone is produced by the reaction of volatile organic compounds (VOCs) and nitrogen oxide. Almost all the organic solvents in coatings are classified as VOCs and are subject to regulation in the effort to control ground-level ozone.

Second, in an effort to protect the stratospheric ozone from depletion, EPA and other agencies have restricted use of certain halogenated components that interact with and deplete the ozone. These compounds include degreasing solvents and solvents used for dissolving resins and coatings.

In the early 1970s, EPA established 0.12 PPM as the maximum concentration of ozone consistent with human health. To be in compliance, a district or region must not exceed this level for more than one hour per year over a three-year period. Districts that meet this criterion are designated as “attainment areas;” those that do not are designated “non-attainment.” (**See Table 2.)**

In 1997, EPA announced a new regulation mandating a major reduction in the permissible level of ground level ozone.[9] The regulation was to phase out and replace the current one-hour standard of 0.12 PPM with a new eight-hour standard of 0.080 PPM. EPA had concluded that the 0.12-PPM standard did not adequately protect the public from adverse health effects. After an initial challenge in May 1999 by a coalition of industry groups the Supreme Court unanimously upheld these rules in April 2002.[10] The court directed EPA to revise its implementation plan. EPA is preparing further arguments to support its position on the inadequacy of the current rule. Once the new rule is implemented, many more air quality districts will be classified as non-attainment, based on current ozone levels.

Ozone is not a direct by-product of a painting operation, but, as indicated above, it is produced when VOCs react with nitrogen oxide under the influence of ultraviolet radiation. Therefore**,** regulating coating operations by requiring that the immediate vicinity of a coating application meet the 0.12-PPM ozone standard would not achieve air quality objectives. Rather, because VOCs are the precursors of ozone and are much more readily manageable, EPA and other regulatory agencies have elected to control the amount of VOCs in paint.

EPA Regulation of VOCs

EPA defines VOCs as “a group of chemicals that react in the atmosphere with nitrogen oxides in the presence of heat and sunlight to form ozone.” Not included are methane and other compounds determined by EPA to have negligible photochemical reactivity. Many solvents used in paints contain VOCs.

VOCs can be controlled in several ways. One approach (which has been used by EPA for certain industries) is to limit the total quantity of VOCs that can be emitted from a given facility for a unit of time (e.g., one ton of VOC per year). The second approach is to limit the amount or proportion of VOC permitted in a coating formulation. This method, widely employed by EPA and state agencies, is the most common and will

Table 2. Ozone Classifications of Major Metro Areas.

Metro Area	Number of Counties	Ozone Classification
Los Angeles, CA	4	Extreme
Chicago, IL	10	Severe
Baltimore, MD	6	Severe
Houston-Gavelston, TX	8	Severe
Milwaukee, WI	6	Severe
New York Metro Area (NY/NJ/CT)	24	Severe
Philadelphia-Wilmington-Trenton (PA, DE, NJ)	14	Severe
Sacramento, CA	6	Severe
Ventura, CA	1	Severe
Atlanta, GA	13	Serious
Baton Rouge, LA	5	Serious
Connecticut	6	Serious
DC/VA/MD	16	Serious
Dallas/Fort Worth	4	Serious
El Paso, TX	1	Serious
Phoenix, AZ	1	Serious
San Diego, CA	1	Serious
Santa Barbara, CA	8	Serious
San Joaquin Valley, CA	1	Serious
Springfield, MA	4	Serious
Beaumont-Port Authority, TX	3	Moderate
Cincinnati, OH	7	Moderate
Louisville, KY	5	Moderate
Manitowoc, WI	1	Moderate
Pittsburgh, PA	7	Moderate
St. Louis, MO	8	Moderate
San Francisco, CA	8	Moderate

be discussed in greater detail below. A third approach is to control the transfer efficiency of the coating application. This approach reduces the amount of coating material that evaporates, rather than landing on the substrate. It is probably the least used of the three approaches described.

EPA is authorized to regulate VOCs and HAPs directly by issuing a National Rule or indirectly by issuing a control technique guideline (CTG) for states to implement. Under a National Rule (e.g., for Architectural and Industrial Maintenance Coatings discussed below), each state must promulgate regulations that are at least as stringent as the EPA rule.

National rules are enforceable in all states and air quality districts. Under a CTG, states are required to develop implementation plans to control the emissions and EPA regional offices must approve these plans. CTGs are enforceable only in air quality districts that exceed the NAAQS standard for ozone (i.e., non-attainment).

Categories for Regulating VOCs and HAPS

EPA has classified VOC sources into two broad categories: mobile and stationary. Mobile sources include cars, trucks, and other vehicles. The VOCs produced by mobile sources are not relevant to the protective coatings industry. Within the stationary classification are numerous categories affecting all types of coatings. The categories most relevant for protective and marine coatings are:

- **Architectural coatings—**Coatings applied to structures in the field (including industrial maintenance coatings)
- **Miscellaneous metal parts and products (MMPP)—**Coatings applied to objects (e.g., bridge members, pipe sections, wires) in a fixed facility
- **Marine and ship building—**Coatings applied at shipyards

Other stationary sources of VOCs and HAPs include furniture, aerospace, and automotive coatings but these are outside the scope of this chapter.

VOCs from Shop-Applied Coatings

VOCs from pipe coating and steel fabricating and painting shops and other stationary facilities are regulated under a Control Technique Guideline designated the Miscellaneous Metal Parts and Products rule.

EPA issued this Control Technique Guideline in 1978 as a guidance document for states to control ozone in non-attainment areas.[11] The definitions and VOC levels for coatings are:

- **Air-dried coatings:** 3.5 lbs/gal. (420 g/L)—dried by the use of air or forced warm air at temperatures up to 194˚F (90˚C)
- **Clear coatings:** 4.3 lbs/gal. (520 g/L)—unpigmented or transparent coating, lacking color and opacity
- **Extreme performance coatings:** 3.5 lbs/gal. (420 g/L)—designed for harsh exposure or extreme environmental conditions
- **All other coatings:** 3.0 lbs/gal. (360 g/L)

Many states have established limits for the total amount of VOCs that can be emitted from a facility in a non-attainment area in a year, a month, a day, or an hour. The most common limits are for total emissions per year. There is a great spread among states with levels ranging from 2.5 tons (2.3 Mg) to 100 tons (91 Mg) per year.

Typical levels for daily emissions are 15 lbs. (6.8 kg) with a range of 5–100 lbs. (2.3–45 g) among the various states. Also, many states have adopted a maximum level of 3 lbs (1.4 kg) per hour. An application shop would have to install add-on controls to capture emissions in excess of these levels.

In the late 1990s, EPA started the process of revising the MMPP rules.[12, 13] Whereas the 1978 CTG had only addressed regulation of VOCs, the proposed revision of the MMPP rules will cover HAPs as well. The EPA statute for controlling HAPs (from 40 CFR 59) is known as the MACT rule (Maximum Available Control Technology). MACT is intended to represent the top 12% of the technology for controlling HAPs. EPA has surveyed shops that apply coatings in the U.S. to determine the level of control achieved by the top 12% and come up with formulas for determining HAPs limits that are based on this survey.[14,15] This approach assumes a relationship between the level of HAPs and the level of VOCs in two categories of coatings—general and high performance.

For HAPs under the MMPP rule, EPA has chosen a different way of defining the concentration. The units used are pounds of HAPs per gallon of solids, compared to the method of measuring VOCs in pounds of HAPs per gallon of paint. The proposed limits for existing and new sources for the general coatings category are shown in **Table 3**.[15]

Table 3. Proposed Limits for New and Existing Sources of HAPS for the General Coatings Industry.

Coating Category	HAPs Limit (lbs. HAPs/gal solids)	HAPs Limit (g HAPs/liter solids)	Approx. VOC* Equivalence (lb./gal)	Approx. VOC Equivalence (g/Liter)
Existing	2.6	312	3.3	396
New Source	1.9	228		

*MMPP: Miscellaneous Metal Parts and Products;
HAP: hazardous air pollutant; VOC: volatile organic compound

Based on these preliminary numbers, commonly used bridge coatings, such as inorganic zincs, epoxies, and polyurethanes, are expected to be able to meet the proposed levels. The major impact would be the reduction or elimination of some common thinners and solvents, such as MEK, xylene and toluene, and increased record-keeping requirements. Under the new rule, the paint application shops would need to maintain records not only of the total amount of solvents used, but also of the specific amounts of individual solvents. This rule is expected to be finalized in 2002 and to become effective in 2003.

VOCs from Architectural and Industrial Maintenance (AIM) Coatings Rule

Architectural coatings are generally defined as coatings applied to stationary structures and their appurtenances, to mobile homes, or to curbs. For architectural coatings, EPA issued a national rule in 1998 (40 CFR Part 59).[16] This rule established a number of subcategories for maximum VOCs levels in field-applied coatings. The level for industrial maintenance coatings is 450 grams per liter (g/L) or 3.75 pounds per gallon (lbs./gal.). Also of interest is the level for metallic-filled coatings—500 g/L or 4.17 lbs./gal. This category is defined as a coating with a minimum of 0.4 lbs./gal. (48 g/L) of a metallic pigment and includes zinc-rich coatings. A partial list of other coating categories of interest is presented in **Table 4.**

As a federal standard, the architectural and industrial maintenance (AIM) rule prevails in all states and air quality districts in the United States. State requirements must be at least as restrictive as the federal standard. To date, one air quality district in California has established more stringent VOC levels than EPA for industrial maintenance. The South Coast Air Quality Management District has imposed a maximum VOC for industrial maintenance coatings of 250 g/L (2.08 lbs./gal.) by 2002 and 100 g/L (0.83 lbs./gal) by 2007.[17] The California Air Resources Board (CARB) is recommending that other districts in the state adopt similar rules based on recent surveys of VOC emission levels.[18] A consortium of state and local regulatory agencies has recommended that EPA revise the AIM rule to be more in line with the new California regulation.[19] EPA has not indicated any intention of revisiting the AIM rule; consequently several states in the northeastern U.S. are considering issuing VOC rules that are also more stringent than the EPA AIM rules.

Table 4. Coatings and VOCs.

Coating Category	VOC (g/Liter)	VOC (lb./gal)
Flow Coatings	650	5.4
High Temperature Coatings	650	5.4
Impacted Immersion Coatings	780	6.5
Industrial Maintenance Coatings	450	3.8
Metallic Pigmented Coatings	500	4.2
Nuclear Coatings	450	3.8
Pretreatment Wash Primers	780	6.5
Repair and Maintenance Thermoplastic Coatings	650	5.4

Control of VOCs and HAPs From Marine Coating Operations

EPA issued a regulation for control of VOCs and HAPs from shipyards on December 15, 1995.[19] Shipyards are major sources of HAPs and regulations were required by November 15, 2000. In 1992, EPA surveyed shipbuilders and coating manufacturers to determine the current status of regulations and technology.[20, 21] Four coating types (epoxy, alkyd, inorganic zinc, and anti-fouling coatings) comprised 90% of the total coatings used for shipbuilding activities. Epoxy alone represented 60% of the volume for the shipyards

surveyed. The survey also identified xylene, toluene, and MEK as the three most commonly used HAPs. Others were MIBK, hexane, ethyl benzene, and glycol ethers.

The rule, designated National Emission Standards for Hazardous Air Pollutants (NESHAP) for Shipbuilding and Ship Repair (Surface Coating) Operations, addresses both HAPs and VOCs and prescribes the exact same limits for both.[22] In EPA parlance, VOCs are surrogates for HAPs. In other words, most VOC paint solvents used in shipyards are HAPs and all HAP solvents are VOCs, so one regulation is considered sufficient. The regulation includes VOC limits for 23 categories of coatings, as shown in **Table 5.**

Table 5. VOC Limits for 23 Coating Categories.

Coating Category	VOHAP limits [1] g/L (lbs./gal.) [2]
General use	340 (2.83)
Air Flask	340 (2.83)
Antenna	530 (4.42)
Antifoulant	400 (3.33)
Heat-resistant	420 (3.50)
High-gloss	420 (3.50)
High temperature	500 (4.17)
Inorganic zinc highbuild	340 (2.83)
Military exterior	340 (2.83)
Mist	610 (5.08)
Navigational aids	550 (4.58)
Nonskid	340 (2.83)
Nuclear	420 (3.50)
Organic zinc	360 (3.00)
Pretreatment wash primer	780 (6.50)
Repair and maintenance of thermoplastics	550 (4.58)
Rubber camouflage	340 (2.83)
Sealant for thermal spray aluminum	610 (5.08)
Special marking	490 (4.08)
Specialty interior	340 (2.83)
Tank Coat	610 (5.08)
Undersea weapons systems	340 (2.83)
Weld-through preconstruction primer	650 (5.42)

1 VOC (including exempt compounds listed as HAP) shall be used as a surrogate for VOHAP for compliance options 1-3.
2 coating (minus water and exempt compounds)

NESHAP describes four options to allow owners and operators flexibility in demonstrating compliance. The rule establishes higher VOC/HAP levels for certain coatings applied in cold weather (less than 40˚F [5˚C]). Also, any individual coating used at less than 53 gal (200 L) per year is exempt with a total exemption maximum of 264 gal. (1000 L).

State Approaches to Regulating VOCs

Not all states take the same approach to regulating VOC emissions from paints. For instance, states such as Oregon, North Carolina, and Maryland regulate emissions from shop painting operations in ozone non-attainment areas only. Others, such as Pennsylvania and Ohio, regulate VOC emissions from shop painting operations throughout the state, imposing stricter requirements on operations in ozone non-attainment areas. In 1998, California amended its Rule 1107 to limit one-component shop coatings to 2.3 lbs/gal (275 g/l) and multi-component shop coating to 2.8 lbs/gal (340 g/L).[23]

Compliance with VOC Rules

Reducing VOCs in Coatings. VOC regulations affect all painting operations, from formulation through application, performance, and service life. The principal approach for decreasing VOC emissions is by using coatings with reduced levels of VOCs. This is accomplished by employing higher solids, solvent-free (i.e., near 100 percent solids), water-borne, or powder coatings. Some of these new formulations may require special application equipment or specially trained applicators.

The coatings industry has committed tens of millions of dollars of resources to develop, evaluate, and manufacture VOC-compliant coatings. Many technical articles, seminars, and product announcements address this issue, which has come to dominate the technology.

Coatings chemists have thus been forced find substitutes for solvent-borne coatings with high VOC levels, and these substitutes have in some cases affected application properties—viscosity, for instance. Consequently, applicators have had to adjust to new equipment, methods**,** and restrictions for applying high solids, high viscosity coatings, and water-borne materials.

Performance properties of coatings have also been at issue because of the need to formulate materials with lower VOC levels. Unfortunately, there is little field data for the newer, lower VOC materials relative to the amount of data for older, solvent-borne

coatings. Hence, specifiers have had to select products without strong evidence for or against a product. Instead, they have had to rely on accelerated test data and on abbreviated field trials or manufacturers' claims. Users have found in some instances that the lower VOC products do not offer the chemical or weathering resistance or gloss retention of their solvent-borne counterparts. In other instances, however, the lower VOC products have performed as well as or better than solvent-borne coatings. A larger body of historical field data is needed to minimize problems with selection of low VOC products for regulatory compliance. SSPC Guide 10 provides recommended procedures for qualifying and selecting VOC-compliant coating systems and for preparing specifications.[24]

Exempt Solvents. EPA has exempted several solvents based on the agency's determination that they are not photo-chemically reactive. Exempt solvents that have been used for coatings included methyl acetate, methyl ethyl ketone (MEK), parachlorobenzotrifluoride (PCBTF), 1,1,1, - trichloroethane (TCE), and methylene chloride. For each of these solvents there are some advantages and limitations.[25, 26, 27] Methyl acetate has very good solubility properties but a very high evaporation rate that could result in dry spray. It also has a very low flash point and a tendency to hydrolyze. MEK is a strong polar solvent that can be used with numerous resins such as epoxy. However, it also has a very fast evaporation rate and low flash point. Because of the latter, it is not suitable for tanks interiors and other confined spaces in industrial plants or other locations. PCBTF is considered a good solvent for alkyds**,** polyesters**,** and other coating resins and has excellent properties as a diluent, along with a moderate evaporation rate. It is more expensive than the standard solvents for those resins. The EPA was expected to classify tertiary butyl acetate as an exempt solvent in 2002. Tertiary butyl acetate has a low-to-moderate evaporation rate, moderate flash point, and low toxicity. It is a suitable solvent for alkyds, epoxies, polyurethanes**,** and other common resins.

TCE and methylene chloride are good solvents for certain alkyd and other resins. However, there is a strong international effort to ban the use of chlorofluorocarbons in coatings because they contribute to the destruction of the ozone in the upper atmosphere (stratosphere). The solvent TCE is listed as a Class I substance, i.e., among the most ozone-depleting substances. Starting in May 1993, any coating containing this material was required to carry a warning label stating that the product contains a substance that harms public health and the environment by destroying stratospheric ozone. In addition, production was to be phased down by the year 2000 to 20% of its 1990 levels.

Alternate Approaches for Compliance

A third approach for compliance with VOC regulations is use of pollution abatement equipment that captures emissions. This approach is suited almost exclusively to shop painting operations because abatement equipment typically is not portable. Even for fixed-site facilities, such as steel fabrication and rail car paint application shops, the capital costs are often extremely high.

A fourth means of reducing VOC emissions is improving the efficiency of the application process. Using conventional air spray systems, much of the coating may not reach the intended surface, but instead be lost to the atmosphere because of wind, irregular surfaces, or poor applicator skill. Electrostatic spray or high-volume low-pressure spray equipment can significantly increase the transfer efficiency. In addition, better applicator training could also reduce the amount of paint and VOC lost during application.

Methods of Measuring VOCs

The quantity of VOCs or HAPs in a coating can be defined as:

- Mass of VOCs per volume of coating (g/L or lbs./gal.)
- Mass of VOCs per volume of solids (g/L or lbs./gal.)

Measurement based on grams of VOCs per liter of paint. The most widely used method for measuring VOCs is the former (g/L) in which any water or exempt solvents must be excluded from the volume. The standard method is EPA Method 24.[28] The procedure for determining VOC content is also described in ASTM D 3960.[29]

The procedure consists of these steps:

- Determine the percent volatiles by weight in coating
- Determine the density of the coating
- Determine the water content (percent weight) of the coating
- Compute the VOC

The standard equations are:

$$VOC = \frac{(V_W)(D_C)}{100} \quad (1)$$

$$VOC = \frac{(V_W - W_W)(D_C)}{100 - (W_W)(D_C/D_W)} \quad (2)$$

Where:

VOC = VOC content in g/L of coating less water and exempt solvent
W_O = Weight percent of organic volatiles ($V_W - W_W$)
W_W = Weight percent of water
V_W = Volume percent of water (W_W)(D_D/D_W)
D_C = Density of coating g/L at 25°C
D_W = Density of water, g/L at 25°C (0.997 x 10^3)

Equation 1 is for a solvent-borne coating that does not contain water or exempt solvent and equation 2 for a coating containing both solvents and water (but no exempt solvents).

There have been several concerns or problems with using the EPA and ASTM test methods. These are summarized below.

Baking of Multi-Component Air-Dried Coatings. Originally, the EPA and ASTM methods determined the volatiles using ASTM D 2369, which requires heating a sample at 110˚C for one hour.[29] One problem that arose was that the multi-component coatings were not fully cured before being baked. As a consequence, some of the unreacted low molecular weight species were volatilized and measured as VOCs although under air-drying conditions they would become part of the film (i.e., non-volatile). There was also concern that at 110˚C, some film additives, such as plasticizers, might also become volatilized, which would give artificially high readings of the VOC content. In 1992, EPA and ASTM agreed to allow the test specimens to stand at room temperature for up to 24 hours to allow the coatings to cure prior to baking.[31]

Low-Solids, Water-Borne Coatings. Several coating manufacturers have pointed out that EPA Method 24 is not well suited to measuring the VOC content of low-solids water-borne coatings. This can be understood by examining Equation 2 for a low solids water-borne coating. Both the numerator and the denominator become very small, as the ratio of D_c/D_w approaches 1 and the W_w (weight percent of water) approaches 100. There are inherent inaccuracies in dividing one very small number by another very small number.

Non-Linearity of VOC Levels. Because of the way VOC is defined (i.e., as mass of volatiles divided by volume of coating less water), the VOC content does not provide a linear measure of the difference in VOC emitted from different coatings. A linear measure of the VOC emission or release rate is provided by the quantity, “mass of VOC per volume of solids” (i.e., lbs. of VOC per gallon of solids [g VOC per liter of solids]). As noted in ASTM D 3960, “thus, a coating with VOC content of 3 lbs. of VOC per gallon (360 g/L) would release about 85% less VOC than emitted from a coating with 6 lbs. of VOC per gallon (720 g/L) of coating.”

Inability to Compute “Actual” VOC Emitted. Because the volume of the water is subtracted from the volume of the paint, it is often difficult to compute the actual amount of VOC emitted for a gallon of paint. Consider the following hypothetical example of a coating with 240 cc of water, 300 cc of organic solvent, and 460 cc of resin to constitute 1 liter of coating (1000 cc). Using assumed densities of 1.0 for water, 0.75 for the solvent, and 0.9 for the resin the VOC content is computed as 296 g/L **(Table 6)**. However, from an emissions inventory viewpoint, each liter of coating that is applied (e.g., at an application shop) emits 225 grams (300 cc). This situation can be confusing and can require several calculations to accurately compute total VOC emissions.

Table 6. Analysis of VOC Emissions.

Component	Density	Volume	(%)	Weight	(%)
Water	1.0	240 cc	(24)	240 g	(27.3)
Solvent	0.75	300 cc	(30)	225 g	(25.6)
Resin	0.9	460 cc	(46)	414 g	(47.1)
Coating	**0.88**	**100.00**	**(100)**	**879**	**(100)**

Measurement Based on Pounds of VOC per Gallon of Solids. For the MMPP rule described in this chapter EPA has adopted the units of lbs. of VOC per gallons of solids (g/L). In addition to subtracting the water and non-exempt solvents all other solvents must subtracted. This definition has the advantage of providing

a linear relationship between the VOC content and the VOC emitted. A significant problem with this method, however, is that the numbers are different from the numbers measured or computed in other rules. Another problem is that there is no established means of measuring the volume solids directly. Instead, the user must calculate the alternate VOC from the EPA Method 24 version. This calculation requires assumptions of densities for the solvents. Also the numbers for VOC in lbs./gal. [g/L] of solids are not familiar to the specifiers, users, applicators, and suppliers of these coatings. For coatings with relatively high VOCs based on the Method 24 definition, the VOCs using the alternate definition are exceedingly high because of the high ratio of solvent to non-volatile solids.

Air Quality For Lead

General

Lead has been known to be toxic to humans for thousands of years. One of the major routes of exposure to humans is through inhalation of lead dust particles. In the 1970s, EPA established the NAAQS level of 1.5 micrograms (mg) of lead/m^3, averaged over 90 days.[33] This regulation was intended for continuous operations that produce lead dust, such as battery or pigment manufacturing, or lead smelters. It was not intended for temporary operations such as abrasive blast cleaning of lead-containing coatings on bridges and other structures. The 90-day provision allows for some variations in the daily emission levels as long as the 90-day average meets the criterion.

This regulation indirectly affects the coatings industry because of the lead dust generated when lead-containing coatings are removed from bridges, water towers, and other industrial structures. There is no requirement in the EPA statute for monitoring lead particulate from a paint removal project. The industry, however, has used the NAAQS standard as a benchmark to determine the success of containment structures in preventing the lead dust from contaminating the environment.

Abrasive blast cleaning or power tool cleaning of lead paint can produce extremely high levels of lead dust in and adjacent to the workplace.[34] The EPA standard, however, is intended to protect the public health, not that of employees who are covered by the Occupational Safety and Health Administration. Thus, the air is typically monitored at the property limits (i.e., immediately outside the location of the structure or facility from which the coating is being removed).

Air Monitoring for Lead

Ambient air monitoring for lead is performed relatively infrequently on most industrial projects. One reason is that on many projects, the abrasive blasting or removal operation is of short duration, or occurs sporadically, rather than constantly. Also, as noted, the Federal regulation is not enforceable on lead removal projects.

A few local regulatory agencies, such as Allegheny County (Pennsylvania), have established specific limits for the level of lead dust based on a 24-hour average rather than the 90-day limits established by EPA.[35] Currently, under Title X of the 1992 Housing and Community Development Act, EPA is considering developing national guidelines on the need and procedures for monitoring ambient lead.[36]

Monitoring Procedures

As lead or other hazardous substances are removed, instruments can be used to measure and monitor airborne materials in accordance with EPA criteria. Monitors are placed at appropriate locations based on wind direction and proximity to homes, playgrounds, businesses, or bodies of water. The following descriptions of methods for measuring ambient lead are derived from SSPC TU 7 and SSPC Guide 6. [32, 37]

90-Day TSP Monitoring Using High Volume Samplers. High volume air samplers equipped for the collection of total suspended particulate (TSP) are used in accordance with the EPA criteria. The Code of Federal Regulations does not give specific procedures for the number or placement of air monitors because of the irregular configuration of water towers, bridges, and other structures. SSPC-TU 7 specifies the number and placement of monitors based on the size of the structure, prevailing wind, and proximity to schools, or other sensitive receptors.

Modification for Under 90 Days. Because paint removal operations are not normally conducted continuously over a 90-day period, it may be appropriate to establish a daily monitoring criterion. It is advisable to verify that the suggested modifications of the procedure are acceptable to state or local

environmental officials.

For example, if a project lasted only 30 days, the Daily Allowance would be 4.5 mg/m^3 instead of 1.5 mg/m^3. The emission of 4.5 mg/m^3 for 30 days would give an average emission equivalent to the 1.5 mg/m^3 for 90 days, assuming the emission was zero for the additional 60 days.

The procedure also provides an allowance criterion for a 24-hour period. In order to convert this value to an allowance corresponding to the hours worked, multiply the 24-hour allowance by three. Thus, if lead dust were produced for 8 hours, the adjusted daily allowance would be 13.5 mg/m^3 (4.5 mg/m^3 x 3).

Perimeter Monitoring for Lead. In this approach, air quality measurements for lead are determined in accordance with NIOSH Method 7082 using personal monitors outside of the containment areas.[37] Method 7082 is intended to determine whether workers in adjacent areas are exposed to elevated lead dust levels. The procedure is described in SSPC-TU 7. The criterion typically used is the Action Level of 30 µg/m^3 per OSHA's *General Industry Standard, 29 CFR 1910.1025* and *Construction Industry Standard 29 CFR 1926.62*. Both are discussed in the safety chapter of this book.

Air Quality For Particulates

General

Abrasive blasting and other paint removal or disturbing activities often generate large quantities of visible and non-visible dust and particulate matter. Regulatory agencies at federal, state, and local levels have sought to limit the effect of these particulates with various ordinances and restrictions.

The Federal NAAQS, as noted earlier, do not require agencies or contractors to monitor for these particulates. However, as is the case with lead dust, some specifiers, owners, and contractors in the painting industry have elected to use the federal compliance levels and monitoring procedures as a means to determine the effectiveness of containment structures designed to control the emission of dust particles.

The next section describes an SSPC position paper (included in SSPC-TU 7) that explains situations in which monitoring for PM-10 particulates is not as useful as monitoring for TSP-Lead.



Figure 1. Ambient air monitor for PM 10 particulates.

Definitions

Particulate matter is defined as any finely divided solid or liquid material. For airborne materials, this definition includes particles with a diameter of 100 micrometers or less.[39] (The criteria for particulates should not be confused with the more specific criteria for PM-10 particulates.) Other terms often used are air contaminant, fugitive emission, dust, and opacity.

Air contaminant means any substance (e.g., particulate, gas, fumes, smoke) other than water vapor that is released or emitted into the atmosphere. A fugitive emission is particulate matter that is not collected by a catcher system (e.g., stack) and is released into the atmosphere at the point of generation. Dust is defined as fine-grained particles light enough to be suspended in the air.

From the previous discussion, it is evident that there are numerous sources of air contaminants (fugitive emissions) arising from coating operations. These include dust and particulates from abrasive

blasting, solvent fumes from paint applications, paint or grease removal, or any activity that disturbs solid debris.

All of these would be classed as fugitive emissions because they are not discharged intentionally into the atmosphere by a stack, but rather escape from the area of operation. Fugitive emissions are generally considered undesirable and potentially harmful to humans and the environment.

PM-10 Emission Standards

Under 40 CFR 50.6, EPA has established the following criteria for PM-10 emissions:

• Level not to exceed 150 mg/m^3 averaged over a 24-hour period. This level is not to be exceeded more than once per year.

• Level not to exceed 50 mg/m^3 (annual arithmetic mean).

The procedures monitoring PM-10 emissions are described in SSPC-TU 7. As with the regulations for lead, these were not designed with coating application or removal projects in mind. The ambient air quality standards for particulates were based on controlling the overall air quality for relatively large air quality districts, not for small point source emissions.

There is relatively little information regarding the extent to which these criteria are exceeded in paint removal jobs. However, it is considered unlikely that the daily average (150 mg/m^3) will be exceeded outside of the work area except for extremely dusty operations.

Numerous states and localities have established their own regulations, criteria, and in some cases, permitting requirements for particulates and fugitive emissions.

Methods for Assessing Particulate Emissions

SSPC-TU 7 describes three methods for quantifying the amount of dust and debris escaping the work area. The first two are based on visual observations and provide immediate feedback on the emissions created, while the third method (ambient air monitoring using high-volume samplers) requires two to three days to receive results.

Users must contact the appropriate state and local authorities to ascertain which of the methods are accepted for monitoring emissions and to establish the appropriate acceptance criteria.

Visible Emission Based on Duration of Emission. This procedure is based on EPA Method 22 (40 CFR 60, Appendix A) and is described in SSPC-TU 7. It permits visible emissions at given frequencies or durations provided they do not extend beyond an established boundary line (e.g., property line). Possible frequencies include: no visible emissions, random emissions of a cumulative duration of no more than 1% of the workday (e.g., five minutes in an eight-hour workday), cumulative duration of no more than 5% or 10% of the workday, or unrestricted emissions.

Visible Emission Based on Opacity. This procedure is based on EPA Method 9 (40 CFR 60, Appendix A) and is described in SSPC-TU 7. Opacity is the degree of obscuring of light. It is often measured on a scale from 0% to 100%, based on the percent of light that fails to penetrate a plume of smoke. Zero percent represents zero obscuring and 100% represents complete obscuring of the light. Opacity measurements are made by trained, certified observers. Measurements are typically made at 15 second intervals for given periods of time (e.g., 5-10 minutes). The acceptance criteria must be established by the specifier. For example, a criterion might restrict the opacity to no more than 20% for any three-minute period in 60 minutes. Local regulations may provide guidance as to the level of opacity that should be required. Monitoring should be conducted prior to beginning the work, as appropriate, in order to establish background levels.

Ambient Air Monitoring for PM-10. This procedure is based on 40 CFR 50 (Appendix B, Item 7) and is described in SSPC-TU 7. High-volume air samplers equipped with PM-10 heads are used to assess the total amount of particulate matter ten micrometers (0.39 mils) or less in size that escape the contained work area. The number of monitors to be used is based on wind direction and proximity to homes, playgrounds, businesses, bodies of water, etc.

If acceptable to local and state air quality authorities, the EPA level of 150 mg/m^3 over a 24-hour period may be modified to 450 mg/m^3 over an eight hour period, provided no emissions occur from the work-site during the remaining 16 hours. Again, monitoring should be conducted for a few days prior to beginning the work (eight to 24 hours per day, as appropriate) in order to establish background levels.

Determining the Need for Air Monitoring on Paint Removal Projects

As noted earlier, existing ambient air quality standards are not being imposed routinely on paint removal projects. The thrust of such standards is for the continuous monitoring of large areas (e.g., entire cities) as compared with individual short-term projects. However, monitoring is being specified on some paint removal projects.

Monitoring might be initiated when there is a belief that emissions from a short term paint removal project (particularly lead) could have an effect on the overall air quality in a region. Monitoring may also be imposed when the lead paint removal site is in a residential area, or next to schools, hospitals, playgrounds, and other areas of public access to better assure public health and welfare. For work already underway, complaints over visible emissions or questions as to the seriousness of emissions could be investigated using monitors. Prior litigation over emissions may also trigger monitoring on future projects. For example, monitoring has been required in Allegheny County, Pennsylvania, since 1988 for most abrasive blast cleaning projects greater than 10,000 ft.^{2} (900m^2) in area as a result of earlier litigation over silica contamination.[35]

From the above, it is obvious that the decision regarding whether to monitor a given project is not clear-cut. However, if there is a potential for public exposure to the dust, such monitoring will provide a high degree of assurance that emissions are within acceptable limits. Without the monitoring, such judgments are strictly subjective. However, for work within the confines of a plant, where it can be established that dust and debris will not carry across the property line into a community, such monitoring will provide little benefit.

Duration of Testing and Placement of Monitors

The federal regulation *40 CFR 58.13 Operating Schedule* identifies the frequency of monitoring required (e.g., daily, every other day, etc.). This section is intended for long-term continuous (permanent) monitoring at sites across the nation in order to establish air quality data. As a result, it provides no guidance on the duration of monitoring for short-term projects such as lead paint removal. Approaches in the coatings industry include: continual monitoring throughout the entire project; monitoring during the initial week or two of the project; and monitoring only when complaints are received.

Regardless of the approach selected, background levels for the job-site must be established. The approach used for monitor placement in Allegheny County, Pennsylvania, has been reported by Sadar and Patel.[40] A great deal of judgment is required for selecting placement sites. Additional detail on air particulate monitoring is given in the *Industrial Lead Paint Removal Handbook.*[41]

SSPC Position Statement

This statement included in SSPC-TU 7 defines conditions for reducing or eliminating the use of PM-10 high volume monitors on lead removal projects.[41] It summarizes work undertaken by the New York State DOT comparing the number of exceedances from PM-10 and TSP-Lead on about a dozen bridge paint removal projects. The paper concluded that the use of PM-10 high-volume air monitoring is not required or recommended for the vast majority of lead paint removal projects because TSP-Lead provides more useful data on the extent of damaging emissions.

State and Local Regulation of Air Quality

A number of state and local air quality agencies have enacted regulations to control air contamination by paint removal activities. In addition to imposing NAAQS, control of emissions has been regulated by requiring permits (e.g., for abrasive blast cleaning), by general language restricting excessive or objectionable visible emissions, or by limiting the opacity of a dust plume.

Agencies that have required permits for blast cleaning include Allegheny County (Pittsburgh) Pennsylvania, the City of St. Louis, Missouri, and the City of Cleveland, Ohio. Among the agencies that have instituted some control of opacity are Allegheny County (Pittsburgh) Pennsylvania (20%), Washington County, Nevada (40%), Maricopa County (Phoenix) Arizona (20%), Wayne County (Detroit) Michigan (20%), State of Virginia (20% for short periods and 60% for any period), and the State of California (40%). The State of California, the U.S. Navy, several DOTs, and various private facility owners also restrict the type of abrasive. California requires that abrasives be certified in a biennial program in which they are evaluated for their dusting and breakdown characteristics.[43, 44] The U.S. Navy specification for for shipyard

abrasives includes limitations on heavy metal content and fine (dust-producing) particles.[45]

Some agencies have also regulated the airborne level of silica abrasive. These include several cities in Massachusetts, Wayne County, Michigan, and Allegheny County (Pittsburgh) Pennsylvania. Silica hazards to workers are discussed in the chapter about safety and health.

References

1. Clean Air Act. Public Law 91-04, 1970.
2. Comprehensive Environmental Response, Compensation, and Liability Act. Public Law 96-510, 1980.
3. Clean Air Act Amendments of 1990. Public Law 101-549, 1990 and Public Law 102-187, 1991.
4. Implementation Strategy for the Clean Air Act Amendments of 1990; 1992 update. Publication 400-A-92-004. U.S. EPA: Washington, DC, 1992.
5. U.S. EPA Office of Air and Radiation. *The Clean Air Act Amendments of 1990: A Guide for Small Business.* Publication 450-K-92-001. U.S. EPA: Washington, DC, 1992.
6. Santire, S. 1990 Federal Clean Air Act Amendments: An Overview. *Journal of Protective Coatings and Linings*, September 1993, pp 46-50.
7. National Paint and Coatings Association. *The Clean Air Act and The Paint and Coatings Industry: Issue Analysis;* NPCA: Washington DC, 1992.
8. *Federal Register,* July 18, 1997, pp 38652-38896.
9. EPA Issues Revised Standards for Ozone and Particulate Matter. *Journal of Protective Coatings and Linings,* October 1997, pp 37-40.
10. SSPC Home Page. http://www.sspc.org/site/regnews/EPAwpost.html *New Air Pollution Limits Blocked on Appeal; Judge's Ruling May Curb Agencies' Powers* (accessed April 2002).
11. U.S. EPA. *Control of Volatile Organic Emissions from Existing Stationary Sources, Volume VI: Surface Coating of Miscellaneous Metal Parts and Products*, EPA-450-/2-78-015 and NTIS PB-286-157*;* U.S. EPA: Washington, D.C., 1978.
12. Moore, Bruce. *MACT Approach for Miscellaneous Metal Parts, Revised Draft.* U.S. EPA: Washington, D.C, 2001.
13. Fact Sheet: Revision of Schedule for Regulation of VOC Emissions from Consumer and Commercial Products Under the Clean Air Act (Section 183[e]), 1999.
14. EPA Home Page. http://www.EPA.gov/ttn/oarpg/t1/fact_sheets/183_e_li.pdf *Report to Congress: Study of Volatile Organic Compound Emissions from Consumer and Commercial Products, 1999* (accessed April 2002).
15. Appleman, B.R. New Regulations Affecting Shop Painting. Presented at *National Steel Bridge Alliance Special Session on Bridge Painting,* October 2, 2001, Chicago, IL.
16. National Volatile Organic Compound Emission Standards for Architectural Coatings. *Code of Federal Regulations,* Section 59, Title 40, *Fed. Regist.* 1998, *63,* 48848-48887.
17. Regulation News: California South Coast Proposes VOC Regulation. *Journal of Protective Coatings and Linings,* May 1999; *see also:* http://www.arb.ca.gov/drdb/sc/cur.htm.
18. Appleman, B.R. CARB Completes Survey on 1996 Coatings and VOC Usage. *Journal of Protective Coatings and Linings,* July 1999, pp 66-72.
19. SSPC Home Page. http://www.sspc.org/site/regnews/VOCbyOTC.html *Alliance of Regulatory Officials Issues Proposal to Slash AIM Coatings VOC Limits* (accessed April 2002).
20. EPA Proposes Shipyard Coating Rule. *Journal of Protective Coatings and Linings,* March 1995, pp 31-36.
21. *EPA's Maximum Achievable Control Technology Rule for Shipyards: A Plain English Interpretation;* Technical Report Prepared for the National Shipbuilding Research Program. Austin Environmental, Inc., 1996.
22. U.S. EPA Office of Air Quality Planning and Standards. *Summary of BACM/MACT Options: Shipbuilding and Ship Repair;* NESHAP/CTG. U.S. EPA: Washington, D.C., 1993.
23. South Coast Air Quality Management District. Rule 1107: Coating of Metal Parts and Products as adopted June 1, 1979, and amended November 9, 2001; *see also:* http://www.aqmd.gov/rules/html/r1107.html
24. *SSPC Guide 10: Guide to Specifying and Testing Coatings Based on Volatile Organic Content;* SSPC: Pittsburgh, 1994.
25. Hare, C.H. Thinning Coatings in the Field. *Journal of Protective Coatings and Linings,* June 1999, pp 24-33.
26. *Federal Register;* 64 FR 52731 (t-butyl acetate).
27. Centers for Disease Control Home Page. http://www.atsdr.cdc.gov/tfacts70.html *Fact Sheet for 1,1,1-*

Trichloroethane/ToxFAQs, 1996 (accessed April 2002).
28. Determination of Volatile Matter Content, Water Content, Density, Volume Solids, and Waste Solids of Surface Coatings: Appendix A, Method 24. *Code of Federal Regulations,* Section 60, Title 40; *Fed. Regist.*
29. ASTM D 3690. *Standard Practice for Determining Volatile Organic Compound (VOC) Content of Paints and Related Coatings;* ASTM: West Conshohocken, PA.
30. ASTM D 2369. *Standard Test Method for Volatile Content of Coatings;* ASTM: West Conshohocken, PA.
31. EPA Revises VOC Test Method. *Journal of Protective Coatings and Linings,* September 1992, pp 78-79.
32. *SSPC Technology Update 7: Conducting Ambient Air, Soil and Water Sampling During Surface Preparation and Paint Disturbance Activities;* SSPC: Pittsburgh, 2000.
33. National Primary and Secondary Ambient Air Quality Standards for Lead. Code of Federal Regulations, Section 50.12, Title 40, *Fed. Regist.*
34. Trimber, K.A.; Manown, G.; Lambert, L. Air and Soil Monitoring During Blast Cleaning Operations. In *Lead Paint Removal from Industrial Structures;* SSPC: Pittsburgh, 1989, pp 20-25.
35. Allegheny County Bureau of Air Pollution Control. Sections 533: Abrasive Blast Cleaning. Pittsburgh, PA, 1988.
36. U.S. Congress. Title X: Residential Lead-Based Paint Hazard Reduction Act—Housing and Community Development Act of 1992.
37. *SSPC Guide 6: Guide for Containing Debris Generated During Paint Removal Operations;* SSPC: Pittsburgh, 1997.
38. NIOSH Method 7082: Lead.
39. National Primary and Secondary Ambient Air Quality Standards for Particulate Matter. *Code of Federal Regulations,* Section 50.6, Title 40, *Fed. Regist.*
40. Sadar A.J.; Patel, H.L. Air Monitoring Guidance for Abrasive Blasting Operations. *Journal of Protective Coatings and Linings*, December 1987, pp 31-32, 68, 70.
41. Trimber, K.A. *Industrial Lead Paint Removal Handbook, 2nd edition;* SSPC: Pittsburgh, 1993.
42. Zamurs, J.; Bass, J. Evaluation of Ambient Air Quality Monitoring Procedures Outside of Containment. *Journal of Protective Coatings and Linings,* October 1998, pp 65-77.
43. State of California Air Resources Board Executive Order G-00-066.
44. Title 17: California Code of Regulations, Section 92000. Certification of Abrasives for Permissible Outdoor Blasting, December 26, 2000.
45. MIL-A-2262A (SH). *Abrasive Blasting Media for Ship Hull Blast Cleaning;* Naval Sea Systems Command: Washington, D.C., 1987.

Acknowledgements

The author and SSPC gratefully acknowledge Gary Tinklenberg's peer review of this document.

About the Author

Bernard R. Appleman

Dr. Bernard R. Appleman has been active in the protective coatings industry since 1974. He served as executive director of SSPC from 1984-1999, prior to his current position as vice president and technical director of KTA-Tator, Inc. He has also worked at Federal Highway Administration on research and testing of bridge coatings, at Exxon Corporation on coatings and corrosion for the petrochemical industry, and for the U.S. Navy on corrosion and fouling-resistant ship coatings. He is an SSPC protective coatings specialist (PCS) and has published over 100 technical publications.

Chapter 9.2
Waste Handling and Disposal

Bernard R. Appleman

Sources of Waste in Painting Activities

Waste is generally defined as any material that is discarded and not intended for some other productive use. EPA defines solid waste as any garbage, refuse, sludge, or semisolid. The definition also includes liquid wastes, which are not otherwise regulated under the Federal Water Pollution Control Act.[1]

Surface preparation and coating operations typically generate a variety of wastes. Some of these waste streams may be large (e.g., spent abrasives). These materials are listed in **Table 1.**[2,3]

Waste materials must be handled properly to protect workers from health or safety hazards. Some wastes are considered hazardous because they can pose a substantial risk to human health or the environment. EPA and local regulatory agencies have established very stringent procedures for handling hazardous wastes and for discharging water containing potentially hazardous materials:

- Special protection of areas where hazardous waste is generated and stored
- Warning signs about the presence of hazardous waste
- Limits on the amount of hazardous waste and the duration that it can be stored on site
- Special containers and labels for the waste
- Methods for sampling and testing the waste
- Training for workers who will handle the waste
- Preparing and retaining records of the type, amount, and properties of the waste
- Restriction on treating or using the waste for other purposes

Table 1. Examples of Waste Streams from Painting Operations.

Operation	Description/Composition of Waste
Blast cleaning with disposable abrasives	Spent abrasive (fractured particles, fines, and dusts), rust, mill scale, old paint
Blast cleaning with recyclable abrasives	Reusable abrasive particles: spent abrasive (fractured particles, fines, and dusts), rust, mill scale, old paint
Power and hand tool cleaning	Rust, mill scale, old paint
Chemical/solvent stripping	Liquid stripper residue, rust, mill scale, old paint
Wet abrasive blasting	Sludge consisting of water, spent abrasive (fractured particles, fines, and dusts), rust, mill scale, old paint
Cleaning paint equipment	Spent solvent and thinner
Solvent cleaning	Spent solvent, containers of oil- and grease-contaminated solvents; rags and cloths contaminated with oil, grease, dirt and solvents
Solvent distillation	Still bottoms
Manual painting	Paint disposables (brushes, rollers)
Storing paint	Containers of partially used mixed/unmixed 2 pack paints or expired paint containers
Covering work area	Cloth, canvas and other materials used to contain coating operation
Containment	Tarps, panels and other materials used to contain surface preparation operation
Paint spraying in booths and dust collection	Filters contaminated with paint or dust particles
Dust Collection	Filters contaminated with paint or dust particles

Regulating Hazardous Waste

The Federal EPA has jurisdiction over handling and disposing of hazardous and solid waste. The major federal regulation dealing with this is the Resource Conservation and Recovery Act (RCRA).[4] Enacted by Congress in 1976, RCRA was amended in 1984 by the Hazardous and Solid Waste Amendments (HSWA).[5] RCRA and HSWA are designed to track and regulate hazardous waste from manufacture to final disposal ("cradle to grave").

Another federal regulation, Comprehensive Environmental Response Compensation and Liability Act (CERCLA), also known as "Superfund," was enacted in 1980.[6] CERCLA is intended to control cleanup and designate liability for abandoned,

uncontrolled, or inactive waste sites, and to deal with hazardous waste releases in an emergency. CERCLA is discussed in Chapter 9.3.

Congress' main goal under RCRA is to reduce or eliminate the generation of hazardous waste and to ensure that wastes are treated, stored, and disposed of so as to minimize present and future threats to human health and the environment.

RCRA regulations include subtitles A through J as published in the Code of Federal Regulations, Title 40, Parts 261-281. Sections most relevant to the protective coatings industry are:

- Part 261 Identification and Listing of Hazardous Waste
- Part 262 Standards Applicable to Generators of Hazardous Waste
- Part 268 Land Disposal Restrictions

Classifying Waste

There are two means by which a waste can be classified as hazardous: it may be specifically included on any one of four lists of hazardous wastes, or it may have one of the characteristics that define hazardous wastes.

Listed Wastes

EPA has identified over 400 substances that are considered hazardous, based on their known properties. These include spent paint solvents, such as xylene, acetone, ethyl acetate, and methyl isobutyl ketone (MIBK), spent halogenated solvents (e.g., methylene chloride, 1,1,1-trichloroethane, and carbon tetrachloride), cyanide and compounds, toxic organics, and sludges from various manufacturing and treatment processes. Each of these has been assigned a specific EPA hazardous waste number (e.g., F003 for xylene).

Characteristic Wastes

These substances are defined as hazardous based on one or more of the following four characteristics:

- ignitability
- corrosivity
- reactivity
- toxicity

Ignitability: An ignitable waste is a liquid having a flash point of less than 140°F (60°C). This includes waste from solvent-borne paint, degreasing compounds, and other solvents not considered listed wastes.

Corrosivity: This category includes materials that have a low or high pH (less than 2 or greater than 12.5) or are excessively corrosive to steel, including rust removers and acid or alkaline cleaning fluids (e.g., certain chemical strippers).

Reactivity: This characteristic applies to materials that are unstable or undergo rapid or violent chemical reactions with water or other materials. Examples are cyanide, plating waste, waste bleaches, and other oxidizers.

Toxicity: These are wastes that, when subjected to an extraction procedure using an acid, are found to contain high concentrations of heavy metals or pesticides that could be released into ground water. This is the characteristic by which lead or other toxic paint residues may be classified as hazardous waste. It is the RCRA provision with the greatest impact on the protective coatings industry. Other metals that may cause waste to be classified as toxic include arsenic, chromium, barium, cadmium, and mercury.

Using EPA Method 1311: Toxicity Characteristic Leaching Procedure (TCLP), the abrasive, paint, or other waste is broken up into small pieces (less than 3/8 inch sieve size) and agitated in an acid for 16-24 hours.[7] If the amount of lead or other metal that leaches (dissolves) into the acid is greater than or equal to the threshold value, the debris is considered hazardous.

A waste from which 5 mg/L of lead or more leaches is a "characteristic" hazardous waste.[8] **Table 2** lists the threshold limits for the eight metals, each of which is assigned a specific waste code. The "D" series is designated for characteristic toxic wastes (e.g., lead is D008). This test method is discussed further in the sections on sampling and testing and treatment and disposal of waste.

Other Considerations for Waste Classification

Acutely Hazardous Waste. EPA has established special requirements for small quantities of waste considered extremely hazardous, including certain pesticides and materials containing dioxin. These are not commonly generated in the protective coatings

industry, but do require special treatment and reporting.

Table 2: Characteristic Levels for Toxic Metals.

Code	Metal	Threshold Concentration (mg/L)
D004	Arsenic	5.0
D005	Barium	100.0
D006	Cadmium	1.0
D007	Chromium	5.0
D008	Lead	5.0
D009	Mercury	0.2
D010	Selenium	1.0
D011	Silver	5.0

Recycled or Reused Hazardous Waste. A waste that is classified as hazardous but is to be reused or recycled in some beneficial fashion is not subject to the requirements of Subtitle C. (See 40 CFR Part 260, Appendix 1, Figure 3 for special provisions for certain hazardous wastes intended to be legitimately and beneficially used, re-used, recycled, or reclaimed.) In a May 1998 rule, EPA confirmed that lead-contaminated steel grit intended to be recycled is not considered a waste.[9,10]

Residues of Hazardous Waste in an Empty Container. Under 40 CFR 261.7 definitions of an "empty" container are:

- All wastes have been removed using commonly employed procedures for emptying the container
- No more than 1 inch (25 mm) of residue remains on the bottom of the container
- No more than 3% by weight of the capacity of the container remains in containers with a capacity of 110 gal. (418 L) or less
- No more than 0.3% of the weight of the total capacity remains in containers with a capacity greater than 110 gal. (418 L)

An "empty" container as defined above would not be subject to RCRA rules. If the container held more than this amount of solvent-thinned paints or paint residue, there is a potential that the waste would require treatment as hazardous. Some disposal facilities may have more stringent criteria for a container to be considered empty.

Disposal of Scrap Metal. Scrap metal, even if coated with lead paint, is considered a recyclable material not subject to the requirements of Subtitle C. For this exemption to apply, a steel mill or ferrous foundry must reuse the scrap metal as raw materials in the process. If the scrap metal were simply to be discarded, then it would need to be treated as potentially hazardous and tested by the TCLP method. In any case, workers handling the scrap metal must be protected in accordance with OSHA's *Lead in Construction Standard.*

Responsibilities for Hazardous Waste

Major Parties

Under RCRA, EPA has assigned responsibilities to three key groups: the generator of the waste; the shipper (transporter) of the waste; and the treatment, storage, and disposal (TSDF) facility. The protective coatings industry is generally not directly involved in transporting, treating, or disposing of hazardous waste, although these activities may be an incidental part of the work done by a painting contractor or a facility owner. The major role of owners and contractors is that of generator.



Figure 1. Clean up of polluted waste site.

Waste generator. A "generator" is defined by EPA as any person whose act or process creates a hazardous waste or makes it subject to RCRA. A facility owner is the primary generator of the hazardous waste produced by removing coatings from structures. This is true even though a contractor may be the party that physically removes the paint (e.g., by abrasive blast cleaning). In the preamble to the EPA Rule on

Certification and Training for Residential Deleading (published August 29, 1996), EPA confirmed that the owner and the contractor may be regulated as co-generators of waste from lead-based paint activities (such as removal or abatement). [11] Under co-generator status "both parties remain legally responsible for proper disposal of the waste and for RCRA compliance."

This designation however, does not relieve the facility owner from full responsibility for ensuring that all operations (i.e., generation [by removal], transportation, and disposal) and the other activities described here are performed in accordance with RCRA rules.

The disposal of waste paints or thinners determined to be hazardous may sometimes be the responsibility of the contractor who purchased them. If the coatings have been used in shop application (e.g., rail car or steel fabricating shop), the shop facility is the waste generator.

Waste Transporter. A transporter is defined as the person engaged in the transportation of hazardous waste off the site of generation. Only licensed transporters may be involved in shipping hazardous waste off site. Transporting the waste within a site (i.e., relocating to a special storage area from the generation area) does not fall within 40 CFR Part 263, and may be performed by the generator without any additional permit.

Treatment Storage and Disposal Facilities (TSDF). Treatment, storage, and disposal of hazardous waste are most commonly performed by specially licensed facilities located off the premises of the waste generation site. Under some circumstances the waste generator may deliberately or inadvertently "treat" the hazardous waste. It is important to understand what types of treatments or processes are regulated and what the permitting or reporting requirements are.

Responsibility of Generators

Classification of Generators. Generators are classified based on the amounts of hazardous waste generated. These are:

• Large quantity generator—Generates greater than or equal to 2,200 lbs. (1,000 kg) per month, or accumulates more than 13,200 lbs. (6,000 kg) at the site at any one time.

• Small quantity generator—Generates between 220-2,200 lbs (100 kg and 1,000 kg) per month and accumulates less than 13,200 lbs. (6,000 kg).

• Conditionally exempt small quantity generator—Generates less than 220 lbs. (100 kg) per month.

A large quantity generator must comply with all the requirements listed in this section. There are some minor differences in the requirements for a small quantity generator.[35] A conditionally exempt small quantity generator does not need to follow the reporting requirements, but still must assure that the waste is properly tested and disposed. These activities are the responsibility of the generator:

Identification of Waste. Under 40 CFR 262.11, EPA requires that the generator determine if the waste is hazardous. This is accomplished by applying knowledge of the hazardous characteristics of the material in light of the process used, or through laboratory testing of waste samples. If a project is consistently producing material with a similar composition and consistency, the generator can utilize the documented process and test data as evidence of the material characteristics. For paint removal projects, the variability of the waste is such that using "applied knowledge" is not appropriate, and representative samples must be taken from different waste streams and tested in a laboratory.

Laboratory testing is intended to simulate the type of long-term leaching that could occur in sanitary landfills. In the case of lead paint debris, if the leaching meets or exceeds the allowable levels, the debris is considered to be hazardous due to the characteristic toxicity.

EPA Identification Number. Under 40 CFR 262.12, the generator must obtain a number to treat, store, transport, or dispose of the hazardous waste. This number is obtained from the state or local EPA office. Different types of EPA identification numbers are available. The owner should determine the type needed. The different types are:

• **Regular—**Permanent ID numbers are intended for facilities that will generate a hazardous waste on a long-term, constant basis. Owners may obtain a permit under one ID number for all of their facilities where

lead-containing debris will be generated.

• **Site Specific—**These ID numbers are intended for facilities that will generate a hazardous waste once. Owners may obtain a unique ID number for each water tower, bridge, or tank farm.

• **Provisional—**These ID numbers are intended for unforeseen circumstances where a large amount (greater than 2,200 lbs. [1,000 kg]) of hazardous waste is generated: for example, soil clean up after an accidental diesel fuel spill.

The owner may delegate obtaining site specific and provisional EPA ID numbers to the contractor.

Notification and Certification. The generator must provide notification and certification for each shipment of debris in accordance with 40 CFR 268.7 and 40 CFR 268.9. The specific wording is found in the regulations, and it varies according to whether the waste tests hazardous or non-hazardous, or has been treated to render it non-hazardous. Notification (from the generator to a licensed TSDF) indicates the desire to ship a hazardous waste to a facility. In practice, most disposal facilities confirm the required information back to the generator. These notifications include the TSDF permit number, their authorization to treat the specific waste being shipped, and their ability to handle the volume of waste being shipped. The contractor is generally responsible for providing this information (i.e., the "notification") to the owner prior to the generation of hazardous waste.

Certification (from the TSDF to the generator) after disposal of a waste, attests that the waste has been received, properly treated, and disposed. The certification that the waste has been disposed is returned to the generator.

Manifesting the Waste. 40 CFR Parts 262.20 through 262.23 require that the generator complete a hazardous waste manifest to accompany each shipment. The manifest includes a description of the waste, the amount, and the handling requirements. The generator signs the manifest as does each transporter and the TSDF. The completed manifest must be returned to the generator within a designated number of days (45 days for large-quantity generators and 60 days for small-quantity generators). It assures that the waste is properly handled from debris collection to final disposal. The manifest must be obtained from the state where the waste is being disposed, if that state requires its use. If the disposal state does not supply the manifest, the form from the state where the waste is generated should be used. If neither state requires a specific manifest, the federal form can be used.

Packaging and Labeling Requirements. The waste must be packaged in accordance with the requirements of 40 CFR 262.30 through 262.33, as well as U.S. Federal Department of Transportation regulations presented in 49 CFR 173, 178, and 179. Labeling should be in accordance with 49 CFR 172.[12] Essentially, these sections require that the packaging be leak-proof during normal transportation conditions as well as upset conditions (e.g., the container falls out of the truck). The rules also require the use of labels, marking, or placards to identify the characteristics or dangers associated with transporting the waste.

Container Enclosure Requirements. The requirements for the large- and small-quantity generators (40 CFR 265) vary, but both essentially order the use of leak-proof drums or bins with secure lids or covers for containing the material and locked storage site located on well-drained ground. The containers must be inspected weekly for corrosion and leaking.

Contingency Plan and Training. Sections 40 CFR 265 and 40 CFR 262.34 require that the personnel involved with handling hazardous waste, including paint removal crews, be trained to respond effectively to emergencies. Basic safety information must be available, including hazard labels on containers, the date that the accumulation of hazardous waste began, the name and telephone number of the site employee serving as emergency coordinator, telephone number of fire department, location of fire extinguishers, etc.

Waste Analysis Plans for On-Site Treatment. If the generator decides to treat the waste on-site to render it non-hazardous, a written waste analysis plan must be filed according to 40 CFR 268.7 with the EPA regional administrator a minimum of 30 days prior to the treatment activity.

Waste Accumulation Time. There are restrictions on

the length of time that the waste may accumulate on-site (40 CFR 262.34). A large-quantity generator may accumulate hazardous waste on-site for 90 days or less without a treatment permit from the EPA. An extension of up to 30 days may be granted due to unforseen, temporary, or uncontrollable circumstances. A small quantity generator may accumulate waste on-site for 180 days with a possible exemption for up to 270 days. If these time limits are exceeded, the generator may be considered an operator of a storage facility and subject to very extensive requirements.

Recordkeeping and Reporting. The signed manifests and associated documentation must be maintained for at least three years (40 CFR 262.40 through 262.44). For generators treating the waste on-site, the recordkeeping requirements can be more elaborate.

Responsibilities of Transporters and Treatment, Storage and Disposal Facilities (TSDF)

Transportation. The generator can transport waste containers to temporary holding areas on-site without special hauling permits. However, for off-site transportation, the requirements of *40 CFR 263, Standards Applicable to Transporters of Hazardous Waste,* apply.

Treatment, Storage and Disposal. Treatment, storage, and disposal are defined as follows under *40 CFR 260.10, Definitions.*

• **Treatment—**Any method, technique, or process, including neutralization, designed to change the physical, chemical, or biological character or composition of any hazardous waste so as to neutralize such waste, or so as to recover energy or material resources from the waste, or so as to render such waste nonhazardous, or less hazardous; safer to transport, store, or dispose of; or amenable for recovery, amenable for storage, or reduced in volume.

• **Storage—**The holding of hazardous waste for a temporary period, at the end of which the waste is treated, disposed of, or stored elsewhere.

• **Disposal—**The discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into or on any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment or be emitted into the air, or discharged into any waters, including ground waters.

Following treatment, the TDSF must also provide the generator with certification of disposal. The extensive requirements for these facilities are described in 40 CFR Parts 264 and 265.42. Details of generator, transporter, and TSDF responsibilities and specific application to hazardous lead paint are provided in the *Industrial Lead Paint Removal Handbook.*[13]

Sampling and Testing

As noted previously, it is the generator's responsibility to determine if waste is hazardous. For listed wastes, such as xylene and other solvents, there is no need for testing. The waste is hazardous by definition. For waste paints, the determining factor for ignitability is the flash point. This may be obtained from the manufacturer; alternatively, an outside testing laboratory or an in-house testing facility could easily determine it using EPA Method 1010.[14] For solvent-borne paints, it may be prudent to assume that the waste is hazardous and handle and treat it accordingly.

Determining the pH of acid or alkali cleaners or chemical strippers can be readily accomplished in the field using standard pH paper. The manufacturer's material safety data sheets (MSDS) will identify the characteristics of the material, including the pH and any toxic components at 1% or greater. Unless the material has been diluted, mixed, or otherwise altered, it is important to assume that the most hazardous properties of the material are also true of the waste.

Analysis of Solid Waste

For solid paint waste or abrasive residue suspected of containing lead or other heavy metals, the TCLP test is normally required to determine the leachate concentration of the metals. The collection and sampling of the waste to be tested must be performed according to EPA procedures. For example, the sampling must be taken from a homogeneous mix, using random sampling techniques.[15] Typically, a minimum of four samples are required to demonstrate that a sample is non-hazardous (e.g., less than 5 mg/L for lead). If the generator is willing to handle and

dispose of the material as a hazardous waste, it is not necessary to test for the presence of lead or other heavy metals. However, at least one sample is recommended for historical records, to guide the disposal facility in the appropriate treatment procedures, and to provide a summary of the expected waste characteristic. Samples required for the TCLP test normally must be about 1 lb. (300–400 g) and placed in labeled containers. Additional information on sampling procedures is contained in refs. 16–17.

Analysis of Liquid Waste

Liquid waste (water) is often generated when waterjetting and wet abrasive blasting are the paint removal methods. The procedures to analyze liquid waste differ from those used for solid waste.

Water generated during coating removal operations may need to be contained and captured along with the paint chips and other larger debris. These materials are filtered from the water using coarse screens. The filtered water is then often pumped to a holding tank for reuse or disposal. Once the project is completed, the solid debris is sampled and tested using the standard TCLP method. The testing procedure for the liquid depends upon the percentage of solid material in the liquid waste.[18]

Greater Than 0.5% Solids. Samples containing greater than 0.5% solids must be analyzed according to a multi-phase protocol. An example of such a waste would be that generated during wet abrasive blast cleaning operations.

First, the free liquids are removed from the original sample and retained. A minimum of 100 g of the remaining solid material is extracted according to standard TCLP. The extract that is derived from the solid portion is then combined proportionally with an aliquot of the liquid that was removed from the original sample. It is this combined sample that is analyzed for toxic metals.

The result of this analysis will dictate whether the liquid will require additional filtering or treatment prior to transportation to a publicly owned treatment facility for disposal. These facilities often have different requirements or thresholds for the level of toxic metals as well as the maximum amount of solids permitted in the liquid waste. Most landfills do not accept liquid waste.

Less Than 0.5% Solids. If a multi-phase sample contains less than 0.5% solids, the liquid sample itself is analyzed for its metal content (which is therefore "total" metals rather than "leachable" metals). An example of a multi-phase sample containing less than 0.5% solids is the waste generated during hygiene activities (e.g., water from the shower). As above, the results of this analysis will dictate whether or not the liquid will require additional filtering or treatment prior to transportation to a publicly owned treatment facility for disposal. If liquid waste is treated the final concentration of lead must be 0.69 mg/L or less, according to the *Universal Treatment Standard.* [19]

Treatment and Disposal of Hazardous Waste

Lead Treatment Standards

If lead waste is treated and has a leachable lead level of 0.75 mg/L it can be classified as non-hazardous.[19] Thus a treated waste initially tested at 3 mg/L can be classified non-hazardous. However, if a waste is initially tested at 20 mg/L and has a leachable lead level of 3 mg/L after treatment, it is still classified as hazardous. This regulation has the greatest impact on facilities that treat lead prior to disposing of it. The requirements are summarized in **Table 3.**

Table 3. Criteria for Treated and Untreated Lead-Containing Wastes.

Threshold Level	Untreated Wastes	Treated Wastes
Previous threshold level for lead (per TCLP)	5.0 mg/L	5.0 mg/L
New threshold level for lead (per TCLP)	5.0 mg/L	0.75 mg/L

If a waste that has been collected and tested is determined to be hazardous, the generator must arrange for treatment to render it non-hazardous. This requirement is based on the 1990 Land Disposal Restrictions, or "Land Ban," Rule (40 CFR 268).[20] "Land Ban" prohibits the land disposal of any hazardous waste. Treatment is not required if the material is to be recycled or reused for beneficial purposes.

Hazardous waste treatment can be performed on- or off-site. EPA permits on-site treatment under very special circumstances. Off-site treatment services are offered by a number of firms that specialize in this.

Off-Site Treatment of Hazardous Wastes

Treatment Methods. Common treatment methods for lead-containing wastes involve the use of lime or Portland cement.[21] Once treated and found to be below the regulatory limit, EPA regulations permit the material to be disposed of in a Subtitle C (hazardous) or Subtitle D (nonhazardous) landfill. However, states may have additional requirements for testing and manifesting the waste.

Waste thinners and paints are typically incinerated, because once the solvent is burned the explosion or fire hazard has been eliminated. Acids and bases can be readily treated by neutralizing with other bases or acids, respectively.

Disposal Procedure. State or regional EPA offices can provide assistance in identifying an appropriate TSDF. The generator must inform the TSDF of the quantity and the hazardous nature of the waste, so the facility can treat it prior to disposal. It is the generator's responsibility to assure that the TSDF is permitted and reputable.

It is also necessary to select a hazardous waste transporter. Hauling waste from the temporary storage site to the TSDF must be performed by a transporter with an EPA identification number. A list of licensed hazardous waste haulers can be obtained from the appropriate state agency.

On-Site Treatment of Hazardous Waste

Generators can treat waste on-site in 90-day holding containers or tanks, if approved by the state or regional EPA office. A waste analysis plan must be submitted prior to treatment.

Pretreatment of Blast Abrasives

There are several types of materials that, when added to abrasives prior to blasting lead-containing paint, will result in non-hazardous waste. Examples are steel grit and a proprietary cementitious-type material. These additives chemically react with the lead during the TCLP digestion procedure and reduce the solubility of the lead compound below the threshold limit of 5 mg/L.

Adding Iron Filings to Paint Waste. Adding steel shot, grit, or iron filings to lead paint waste can cause the waste to test as non-hazardous even at relatively high levels of total lead. This effect is caused by a chemical reaction in which the lead "plates out" and remains insoluble. However, numerous studies have shown that this reaction is often only temporary and after the iron oxidizes the lead can become resolubilized. Accordingly, in 1998 EPA banned the use of iron filings for this purpose.[8] Although EPA did not include steel abrasives in this ban, adding any steel to lead-containing paint waste with leachable lead of 5 mg/L or greater is considered an on-site treatment requiring special permits. When steel grit is used in abrasive blasting, it is typical to declare the waste hazardous, regardless of the results of any TCLP testing.

Adding Steel Grit to Expendable Abrasives. A Federal Highway Administration (FHWA) study has shown that adding 3–6% by weight of G-80 steel grit to conventional expendable abrasives has reduced the leachable level of lead from over 50 mg/L to less than 2 mg/L.[21] The same study and other field histories have indicated that the "stabilization" of lead may not be permanent, because over time the lead solubility could increase as the steel grit oxidizes. Thus, this treatment, while satisfying the letter of the RCRA law, could cause lead to leach into the environment, after the waste has been disposed. In the 1998 rule on iron filings, EPA cautioned against this practice, noting that the generator is not shielded from future liability, as the lead eventually leaches into the soil. A potential solution to this problem is to further treat the grit-stabilized lead waste with a cementitious material. In this case, however, the recordkeeping would be simplified because the waste is not hazardous and the requirements for holding containers and the waste analysis plan are not in effect.

Proprietary Additives. These are typically incorporated at 15-18% of the weight of the conventional abrasive (e.g., coal slag, copper slag, silica sand). One such additive has been found to effectively reduce the leachable lead content to approximately 0.1 mg/L—well below the threshold level.[21] This stabilization method, as identified by the manufacturer, involves pH control and encapsulation. Unlike waste containing steel grit additives, waste containing this proprietary material shows no increase in leachable content after running multiple leaching procedures. Because this material is blasted onto the surface along with the abrasive, it should be manufactured or treated to

reduce dusting and to avoid leaving a soluble deposit on the steel to be subsequently painted. Another proprietary material is first applied to the structure by spraying. When the surface is subsequently abrasive blast cleaned, the proprietary surface treatment results in non-hazardous waste.

Minimizing Paint, Solvent and Thinner Waste

Eliminating or Reducing the Use of Solvents. Coating application shops use solvents in a variety of cleaning and degreasing operations including parts and process equipment cleaning and surface preparation for coating applications. Some of the major solvents used are petroleum distillates and oxygenated (esters, ethers, ketones, and alcohols) and halogenated solvents.[2]

Eliminating solvent use eliminates the waste associated with it.[22,23] Non-solvent cleaning agents may be used instead or the need for cleaning eliminated altogether. Alternatives to solvent stripping agents include aqueous stripping agents, plastic media, or cryogenic or thermal stripping.

Solvent usage may be reduced by controlling air emissions at the source, using solvents and equipment efficiently, and maintaining solvent quality. Source control addresses ways in which solvent can be contained, reducing the chances for evaporation loss. Efficient use of solvent and equipment through better operating procedures can reduce the amount required for cleaning. Maintaining the quality of solvent will extend its life-cycle effectiveness.

Solvent Recycling. The final cost of solvent used for various cleanup operations is estimated at nearly twice the original purchase price primarily because of the expense associated with disposal, transportation, and manifesting. Increasing the recyclability of solvents can be achieved by maintaining the quality of the solvent, standardizing the solvents used, and consolidating the use of solvent within the facility. Maintaining solvent quality can be viewed as a measure that will reduce the amount of solvent used, as quality is much more critical when solvents are recycled.

There are several options available for recycling solvent waste. Solvents can be recovered on- or off-site, where usually depends upon the capital outlay and operating cost, volume of solvent waste generated, and personnel requirements. A variety of solvent recovery and recycling systems are commercially available.

Reducing Paint Waste. Paint waste may include left over sludge in paint containers, overspray, paint that is "out of spec" or beyond its shelf life, still bottoms from recycled cleaning solvents, and rags and other materials contaminated with paint. In many cases, the amount of paint waste generated can be reduced through the use of improved equipment with high transfer efficiencies, alternative coatings, and good operating practices, such as purchasing paint in either in bulk containers or the smallest quantities required.

State Regulation of Hazardous and Non-Hazardous Waste

Almost every state has enacted regulations regarding production, storage, transport, treatment, or disposal of hazardous substances or waste. RCRA encourages states to assume some of the federal responsibilities for operating their own waste programs. In general, state laws and standards are required to be equivalent to or more stringent than federal requirements. There are some variations from state to state, and certain states have enacted more stringent hazardous waste requirements than others.

For example, California has established a Soluble Threshold Limit Concentration (STLC) for leachable content of heavy metals and Total Threshold Limit Concentration (TTLC) for total heavy metal concentration.[24] Under Title 22, this state has also added several metals that are not on the EPA hazardous waste list, most notably zinc and zinc compounds. Thus, if zinc exceeds 250 mg/L in the STLC test or 5,000 mg/kg under TTLC, it is classified as a hazardous waste. Prior to 1997, Michigan also classified zinc as hazardous waste, but the state has subsequently removed it from the list.[25]

States are also responsible for disposing of nonhazardous waste, which is not included in RCRA. Non-hazardous wastes are often classified as municipal and special, industrial, or residual wastes. Municipal wastes can be disposed of in a municipal landfill, along with household garbage. Non-municipal wastes often require special handling and paperwork. For example, Illinois EPA requires that any waste from abrasive blasting or other lead removal projects be

tested and manifested, even if it is below the 5 mg/L threshold level for hazardous waste.[26] For this "industrial" waste, licensed haulers are required. Pennsylvania also has special regulations for "residual" wastes, which again require special handling and recordkeeping.[27]

In these instances, the cost of disposing of non-hazardous waste may approach that of hazardous waste because ultimately the same standards are being applied. In states where there are no special requirements for non-hazardous waste, costs for disposal are significantly lower (e.g., on the order of $100 rather than $400 per ton). Often, landfill operators are reluctant to accept waste that may still present a risk because it contains lead or other hazardous constituents, even though it is characterized as non-hazardous by TCLP.

References

1. Federal Water Pollution Control Act. Public Law 92-500, 1971; Clean Water Act. Public Law 95-217, 1977.
2. NSRP 0378. *Solvent Recycling for Shipyards;* 1993; NSRP 0418. *Hazardous Waste Minimization Guide for Shipyards;* 1994; National Shipbuilding Research Program and National Steel and Shipbuilding Co.
3. Appleman, B.R. Treatment and Disposal of Hazardous Waste. In *Procedure Handbook: Surface Preparation and Painting of Tanks and Closed Areas;* SSPC: Pittsburgh, 2000.
4. Resource Conservation Act. Public Law 94-580, 1976.
5. Hazardous and Solid Waste Amendments. Public Law 98-616, 1984.
6. Comprehensive Environmental Response, Compensation, and Liability Act. Public Law 96-510, 1980.
7. U.S. EPA. Toxicity Characteristic Leaching Procedure. In *Test Methods for Evaluating Solid Waste (Manual SW-846), 3rd Edition;* U.S. EPA: Washington, D.C., 1995.
8. Table 1: Maximum Concentrations of Contaminants for the Toxicity Characteristics. *Code of Federal Regulations,* Section 261.24, Title 40; *Fed. Regist.*
9. Metal Waste and Mineral Processing Wastes Treatment Standard. *Fed. Regist.* 1998, *63,* 28555.
10. EPA Changes Treatment Standard for Lead Wastes; Bans Iron Filings as Permanent Treatment Method. *Journal of Protective Coatings and Linings,* September 1998, pp 97-98.
11. Requirements for Lead-Based Paint Activities in Target Housing and Child-Occupied Facilities; Final Rule. *Code of Federal Regulations,* Section 745, Title 40; *Fed. Regist.* 1996, 45778-45830.
12. U.S. Department of Transportation Regulations on Transporting Waste. *Code of Federal Regulations,* Section 172-179, Title 40; *Fed. Regist.*
13. Trimber, K.A. *Industrial Lead Paint Removal Handbook 2nd Edition;* SSPC: Pittsburgh, 1993.
14. EPA Method 1010: Pensky-Martens Closed-Cup Method for Determining Ignitability. In *Test Methods for Evaluating Solid Waste (Manual SW-846), 3rd Edition;* U.S. EPA: Washington, D.C., 1995.
15. Tinklenberg G.; Smith, L.M. The Criticality of Sampling and Quality control for Hazardous Waste Testing. *Journal of Protective Coatings and Linings*, April 1990, pp 36-44.
16. *SSPC Guide 7—Guide for the Disposal of Lead-Contaminated Surface Preparation Debris;* SSPC: Pittsburgh, 1995.
17. Tinklenberg, G. Sampling for Lead Analysis. In *SSPC Lead Paint Bulletin;* Summer 1993.
18. Corbett, W.D. Determining the Toxicity of Liquid Wastes Generated During Coating Removal. In *SSPC Lead Paint Bulletin;* First Quarter 1997.
19. SSPC Home Page. http://www.sspc.org/site/regnews/EPAWASTERULE.html *EPA's Regulation on Lead Waste Treatment and Handling* (accessed April 2002).
20. Land Disposal Restrictions—Phase IV. *Code of Federal Regulations,* Sections 148, 268, and 271, Title 40; *Fed. Regist.* 1998, *63,* 28555-28604.
21. Smith, L.M.; Tinklenberg, G. L. *Lead Containing Paint Removal, Containment, and Disposal;* FHWA-RD-94-100; Federal Highway Administration: Washington, D.C., 1995.
22. Kaelin, A. Handling and Disposing of Paint and Solvent Waste. *Journal of Protective Coatings and Linings,* May 1999, pp 42-47.
23. *Solvent Waste Reduction Alternatives;* EPA/625/4-89/021; U.S. EPA: Washington, D.C., 1989.
24. California Administrative Code. Title 22, Section 66261.24.
25. SSPC Zinc-Rich Task Force. The Effect of Zinc-Rich Coatings on the Environment. *Journal Protective Coatings Linings*, July 1992, pp 45-53.
26. Illinois Issues Fact Sheet on Disposal of Lead-Based Waste. *Journal of Protective Coatings and Linings*, March 1992, p 45.

27. *Guidelines for Disposal of Residual and Household Waste;* Harrisburg: Pennsylvania Dept. of Environmental Resources, 1992.

Acknowledgements

The author and SSPC gratefully acknowledge Gary Tinklenberg's peer review of this document.

About the Author

Bernard R. Appleman

Dr. Bernard R. Appleman has been active in the protective coatings industry since 1974. He served as executive director of SSPC from 1984-1999, prior to his current position as vice president and technical director of KTA-Tator, Inc. He has also worked at Federal Highway Administration on research and testing of bridge coatings, at Exxon Corporation on coatings and corrosion for the petrochemical industry, and for the U.S. Navy on corrosion and fouling-resistant ship coatings. He is an SSPC protective coatings specialist (PCS) and has published over 100 technical publications.

Chapter 9.3
Other Regulations Affecting Protective Coatings

Bernard R. Appleman

Introduction

This chapter discusses the impact of regulations concerning:

- Water quality (surface water, ground water, and sediment)
- Potable water in storage tanks and pipes
- Hazardous materials
- Secondary containment of above-ground storage vessels
- Leak prevention for underground storage tanks
- Coatings for food and beverage facilities
- Soil quality
- Fouling resistant coatings
- Slip resistance of erected steel

Water Quality

Federal Clean Water Act

The 1972 Federal Water Pollution Control Act (FWPCA) and subsequent amendments in 1977 and 1987 established the current framework for water quality controls.[1] The goal of this legislation is to minimize pollutant discharge into navigable waters (lakes, streams, oceans) and to achieve water that is suitable for human recreation and aquatic organisms.

The two basic approaches utilized are:

- Controlling the concentrations of toxics in the water
- Controlling discharge of toxics into the water at the point of discharge

Both of these approaches are incorporated into the FWPCA, commonly referred to as the Clean Water Act.[2]

As with other environmental statutes, the Clean Water Act is a far-reaching, comprehensive, multi-faceted federal/state program. Several of the provisions of the Clean Water Act potentially impact protective coatings activities, including:

- Reportable quantities for hazardous substances (40 CFR 117)
- Permits issued under the National Pollutant Discharge Elimination System (40 CFR 122)
- Water Quality Standards (40 CFR 131)
- National Drinking Water Standards (40 CFR 141)

Reportable Quantities For Hazardous Substances

Approximately 300 chemicals have been designated by EPA as potential hazards when dissolved in water. Any discharge exceeding the reportable quantity is in violation of the Clean Water Act and must be reported. The list includes only a few materials commonly used in protective coating activities, such as toluene, xylene, and sodium nitrite (a wet blast inhibitor). Certain lead compounds are on the list, but not the type that have been used in painting industrial structures.

However, when the material being discharged is a waste product, the activity would be subject not only to FWCPA but also to the Comprehensive Environmental Response Compensation and Liability Act (CERCLA).[3] Reportable quantities for lead or lead compounds and other toxic metals such as chromate are covered by CERCLA.

Ambient Water Quality Standards

EPA has established National Ambient Water Quality Standards (NAWQS) for a variety of materials including lead, chromium, copper, and cadmium.[4] These standards place limits on the maximum concentration of material at a given site for a one-hour period (acute) or over a four-day period (chronic). Standards are set for human consumption (ground or drinking water) and for aquatic life.

Water Standards for Aquatic Life. The ambient water quality standards for toxic metals address fresh water and salt water conditions. In fresh water, for several metals the acute and chronic levels are based on hardness. Some examples are given in **Table 1.**

Drinking Water Standards. EPA has also established

standards for maximum concentrations of metals and other constituents in drinking water.[5,6] Some of the criteria are listed in **Table 2.**

Table 1. Water Standards for Aquatic Life.

	Freshwater Aquatic Life (µg/L)		Saltwater Aquatic Life (µg/L)	
	1 hr.*	4 day	1 hr.*	4 day
Cadmium	4.3**	2.2**	4.2	9.3
Chromium (VI)	16	11	1100	50
Copper	13**	9	4.8	3.1
Lead	65**	2.5**	210	8.1
Mercury	1.4	0.77	1.8	0.94
Aluminum (ph 6.5-9)	750	87	-	-
Zinc	120**	120**	90	87

* These levels may be exceeded only once every three years.
** This level is based on a water hardness of 100 g $CaCO_3$. Allowable level is increased as hardness increases.

Table 2. Drinking Water Standards.

Metal	Maximum Concentration Limit	Comment
Cadmium	5 µg/L	Primary Standard
Chromium (VI)	100 µg/L	Primary Standard
Copper	30 µg/L	Action Level for Primary Standard *
Lead	15 µg/L	Action Level for Primary Standard *
Zinc	5000 µg/L	Secondary Standard

* Lead and copper are regulated by a treatment technique that requires systems to control the corrosiveness of their water. If more than 10% of tap water samples exceed the action level, water systems must take additional steps.

There is a direct relationship between the level for drinking water and the level for certain heavy metals under the Toxicity Characteristic Leaching Procedure (TCLP).[7] EPA assumes that water leached from a landfill will be diluted by a factor of 100 before it can penetrate into drinking water sources. For example, chromium-containing waste cannot be land-disposed unless the leachable chromium content is less than 5,000 µg/L (5 mg/L), which is 100 times the drinking water standard of 5 µg/L (50 PPB). The drinking water standard for lead has recently been reduced from 50 µg/L to 15 µg/L. The TCLP level for lead, however, is still 5 mg/L, rather than 1.5 mg/L, which would represent "100-times" the drinking water standard.



Figure 1. Water contamination from blasting debris.

Impact of Paint Removal on Aquatic Life. Smith has reviewed a number of studies on the effect of lead paint removal and other painting activities on aquatic life.[8] These studies present no evidence that such activities have resulted in any long-term or immediate violation of the Clean Water Act.

A few researchers have conducted bioassays of fish to determine the sensitivity of various organisms to suspended or dissolved substances resulting from new paint materials and paint and abrasive debris. In two studies, there was evidence of toxic effect from some surface cleaning compounds used to pre-wash a bridge and from lead and other paint ingredients. The levels of concentration used in these studies exceeded the levels measured in field analyses.

A California Department of Transportation study investigated the effects of bridge painting operations on fathead minnows, rainbow trout, and other species.[9] The results indicate that lead-pigmented and zinc-rich paints may cause toxicity. Biocides from water-borne paints and cleaning detergents tested were highly toxic. A set of guidelines was developed to assist highway officials in determining and mitigating the impact of bridge painting projects on the aquatic environment. Blasting abrasives range in toxicity from somewhat toxic to innocuous.

The Department of Fisheries and Oceans of Vancouver, British Columbia, has also issued guidelines for the protection of fish and fish habitats during bridge maintenance.[10] These are based on a series of tests on the effects of abrasives, paints, and surface cleaning agents on rainbow trout and other species. The degree of toxicity depended on the specific paint formulation, with some chemicals found to have lethal

effects and cause long-term damage. The guidelines provide procedures and strategies, including regular meetings among the affected parties; scheduling to avoid spawning seasons; pre-testing of cleaning agents; greater control of degreasing; use of pressurized waterjetting without abrasives; and containment.

Even if federal water quality standards are not exceeded, it is prudent to avoid contaminating any bodies of water with paint or abrasive materials or waste. A number of states have more stringent regulations than EPA. For example, the North Carolina Division of Environmental Management has an action level of 50 µg/L for zinc in fresh water.[11]

In addition, visible evidence of inadequate containment of debris from a structure (e.g., paint chips and residues floating on the water's surface) can result in local complaints. At the very least, such actions will generate bad publicity for the facility owner and the contractor. Citations for violating local "nuisance" ordinances, fines, and delays or shutdowns are also likely to occur.

National Pollutant Discharge Elimination System[12]

Point Source Discharge and Permits. The National Pollutant Discharge Elimination System (NPDES) established under the Clean Water Act requires permits for all point sources of discharged effluent. A point source is normally an industrial or municipal discharge that is designed to emit effluent into a water body. Thus it covers operations at manufacturing plants, fabrication shops, mills, and shipyards. An example of a non-point source would be municipal or agricultural runoff. These are not covered under NPDES. Discharges from painting bridges or other structures over or near water are not point sources because there is normally not an intent to discharge into the body of water. Some states are utilizing best management practices (BMPs) to regulate any processed water discharges.

Controlling Storm Water Discharge. In 1990, EPA started requiring industrial facilities and municipalities to acquire permits for storm water discharge and municipal storm water systems.[13] An exception is that permits are not required for publicly owned treatment works (POTW). Industries affected include waste treatment facilities, metal scrap reclaimers, paper mills, chemical plants, primary metals industries, fabricators of structural metal, and construction activities on five or more acres.

Paint and surface debris from a painting or paint removal activity that is not properly contained and collected could be considered an unpermitted discharge. Such discharge may be limited by state or federal water quality standards or other state or local ordinances. Preventing storm water discharge normally entails a combination of controls. Drop cloths are often placed under points of likely emission to facilitate clean up in the event of a sudden storm. In addition, dikes, booms, or other materials may be placed around entries to storm or sanitary sewers to collect debris for subsequent clean up.[14]

State Ordinances and Best Management Practices (BMPs). EPA has given states much of the responsibility to enforce the Clean Water Act and eliminate discharge into water bodies. Some states issue ordinances regarding floating objects or debris, scum, and oil or other materials. BMPs are used by the states typically to control non-NPDES permitted sources (e.g., lead paint discharge). They establish a minimum acceptable level of practice, frequently invoking a combination of control techniques to minimize the risk to the environment. Where a BMP exists, there is typically no subsequent requirement to file for permits or conduct testing. The obligation is simply to comply with the BMP: for example using a three-stage system to filter gray water prior to discharge to a POTW. Similarly, a BMP on waterjetting operations may not allow any direct discharges.



Figure 2. Another case of water contamination.

Water and Sediment Monitoring

It may be necessary to sample water or

sediment in the vicinity of paint removal projects to determine if the level of lead or other hazardous metal exceeds the EPA CWA or state limits. A procedure for site sampling is given in *Project Design.*[14] It is noted that in fast moving or deep water, meaningful samples may not be available. SSPC-TU 7 describes a procedure for lead sampling analysis and reporting for water and sediment.[15] A "dip" or "grab" sample is used to collect about 8 oz. (240 mL) of water. For sediment sampling, a scoop is stipulated. Samples are typically collected at project start-up and completion at a minimum and analyzed for lead in accordance with EPA Method 3050.[16]

Potable Water In Storage Tanks

Regulation of Additives

The Safe Drinking Water Act (SDWA) of 1974 charged EPA with the responsibility for issuing guidance to states on additives to drinking water.[17] The EPA program, which included a list of approved coatings for potable water tank interiors, expired in April 1990. In its place, NSF International (formerly the National Sanitation Foundation) established voluntary standards in conjunction with the American Water Works Association, the Conference of State, Health, and Environmental Managers (COSHEM), and the Association of State Drinking Water Administrators (ASDWA).[18] The principal standard of interest is ANSI/NSF Standard 61, *Drinking Water System Components Health Effects,* which deals with indirect additives that may contaminate drinking water. It was approved by NSF and ANSI in 1989. *Section 5: Protective Barrier Materials* includes requirements for submittal and testing of coatings intended for use in potable water systems. The testing is designed to measure the quantity of heavy metals and organics leached from cured film and applied to a glass substrate. The maximum allowable levels (MALs) of these contaminants is set at 10% of the maximum contaminant level (MCL) from EPA's *Primary Drinking Water Standards,* or by an alternate procedure outlined in Standard 61. The standard also evaluates the ability of coatings to support microbial growth.

As part of the submittal, coating manufacturers must furnish composition data and product data sheets, including use and application instructions. An important variable, which affects the solubility of a leachate, is the ratio of the surface to volume of the vessel. This ratio increases as tank size decreases. Thus, the standard includes a normalization factor for MALs to account for this variation.

Table 3. ANSI/NSF 61 Qualified Coatings.

Coating Type	Approved in Cold Water (30°F,-1°C)	Approved in Hot Water (180°F, 82°C)
Asphalt	X	
Epoxy	X	X
Epoxy Phenolic	X	X
Cement	X	
Hot dip galvanized	X	
Lubricant	X	
Polyurethane	X	X
Styrene Butadiene rubber	X	
Polymer Modified Asphalt Membrane	X	
Vinyl ester	X	X

Certification of Coatings to ANSI/NSF 61

Coatings meeting the criteria of this health-based standard are certified by NSF International.[19] The NSF has also established a program to evaluate coatings against the standard. Other third party organizations may also serve as certifying bodies. The coatings submitted for testing are classified based on the temperature of the intended service and the size of the tank. Examples of coatings that have met the requirements of ANSI/NSF 61 are:[20]

- Water tanks greater than 500 gallons [1,900 L] (cold)—epoxy
- Water tanks greater than 1,000 gallons [3,800 L] (cold)—epoxy, vinyl, polyurethane
- Water tanks greater than 1,000 gallons [3,800 L] (tested at 180°F [82°C])—phenolic epoxy
- Water tanks greater than 50,000 gallons [190,000 L] (cold)—epoxy
- Four-inch (100 mm) pipe and greater (cold)—asphaltic coating
- Six-inch (150 mm) pipe and greater (cold)—polyurethane
- Repair materials—epoxy filter

Examples of qualified coatings are given in **Table 3.** Information on specific test requirements and

a list of approved systems can be obtained from NSF International.

ANSI/NSF 61 does not address performance aspects such as durability, resistance to undercutting, and application tolerance. These properties must be ascertained by the specifier or owner, as is done for other immersion-type linings. In addition, this standard does not evaluate taste or odor.

Hazardous Materials

Toxic Substances Control Act

The Toxic Substances Control Act (TSCA), passed in 1976, was intended to cover uses and exposures to toxic chemicals not covered specifically under other environmental or health and safety regulations.[21] Substances, such as pesticides, that are covered by other regulations are not are not addressed.

TSCA is often thought of as a set of regulations that primarily affect paint formulators, and several sections are important to this segment of the industry. However, other sections of the act can soon be expected to affect the kinds of paint end users can apply.

Provisions That Will Affect End-users. EPA intends to use TSCA to respond to broad concerns about exposure to lead, as it has in the past to regulate asbestos and polychlorinated biphenyls (PCBs). It is in the process of conducting a comprehensive review of lead under the act and is considering a variety of steps up to and including a ban or severe restrictions on the use of lead pigments in industrial paint.

At present, there is no restriction on the amount of lead paint permitted in industrial paints. The Consumer Product Safety Commission has established a maximum of 0.06% by weight (600 PPM) of lead in paint commonly used by the general public.[22]

Provisions Primarily Affecting Formulators. TSCA authorizes EPA to obtain and evaluate information on the health and environmental effects of chemicals. If EPA concludes that a particular substance poses an unreasonable risk, it also has the authority to restrict, or even ban the use and manufacturing of the material.

A manufacturer is required to notify the EPA before manufacturing, using, or importing a new chemical. A chemical may be considered new if it does not appear on the TSCA Inventory, a list of chemicals published by EPA. Formulators must file a Premanufacture Notice (PMN) for such a chemical unless they qualify for exemptions such as the one available for chemicals used only for research and development. Reviews may also be expedited for chemicals made or imported in quantities less than 2,200 pounds (1,000 kilograms) per year.

The PMN should list the chemical's identity, intended use, volume to be produced, by-products, number of people likely to be exposed through manufacturing, and intended means of disposal. EPA normally has 90 days to review the information and to evaluate the risks of the chemical, usually by examining existing chemical literature and comparing it to similar chemicals. A notice of the review must appear in the Federal Register.

In some cases, EPA may extend the review and request additional information. The agency has authority to temporarily or permanently ban materials under review, but generally prefers to develop consent agreements under which the manufacturer agrees to restrictions on the use of the chemical.

Restrictions may involve stipulating the amount of a material used and the way it is used, or requiring personal protective equipment for those exposed to it. By issuing a significant new use rule (SNUR), EPA can extend the restrictions in such an agreement to other companies interested in manufacturing, using, or importing the substance.

There are also several requirements for recordkeeping and reporting. For instance, chemical manufacturers, processors, and distributors are required to keep records of health or environmental effects, such as those reported by employees or consumers. They are also required to report to the EPA within 15 working days any study or event that suggests that a particular chemical poses a substantial risk. Rauscher provides a description of the manufacturing steps required in producing a new material.[23]

Lead Regulations Under TSCA

EPA Title X and TSCA Title IV. Under Title X, the Lead-Based Paint Reduction Act of 1992, Congress had tasked EPA to promulgate a rule to assure that the public, the environment, and employees are protected during lead paint activities. EPA's 1994 response added Title IV to TSCA.[24]

The four sections of TSCA Title IV are:
• Section 401: General
• Section 402: Training, Certification, and Work Practices Standard
• Section 403: Hazards Requiring Action in Buildings and Housing
• Section 404: Process for States to Administer the Program

Proposed Rule for Industrial Structures. The EPA proposed rule included requirements for training and certifying workers, supervisors, and firms for both residential and child-occupied public buildings and commercial and industrial structures.[25] The rule addressing residential structures was finalized in 1996. The portion of the rule for industrial structures was to be issued at a later date, as the most pressing concerns for lead paint was the potential health hazard for children under 6 years old exposed to lead paint dust or residue from old housing and schools.

For industrial workers and supervisors, the 1994 proposal stipulated 32 hours of training and defined the responsibilities of each. In addition, the certified supervisor would be required to submit a written deleading plan and to document work schedules, certifications, and deleading methods used. Any lead-containing waste generated during lead paint activities would require disposal in accordance with RCRA. EPA did not delineate specific standards for acceptable levels of lead in soil, dust, or paint.

In 1998, EPA conducted some public hearings to focus on the needs for protecting the public from deleading activities on commercial and industrial structures.[26] The agency decided to separate commercial buildings from industrial structures because of the wide difference in practices and exposures to the public. In 2000, EPA renewed activity to revise the 1994 proposal. A second proposed rule is expected in 2003.

Residential Structures Rule.[27] The scope of the rule, issued in 1996, is target housing and child–occupied public buildings. It has four basic elements:
• Training and certification to ensure the proficiency of individuals and firms who conduct lead-based paint inspection, risk assessment, and abatement
• Accreditation requirements for training programs
• Work practice standards to ensure that lead-based paint activities are conducted safely, reliably, and effectively
• Procedures for states to apply for authorization and administration of these programs

As a result of eliminating OSHA training, EPA reduced the total training hours for workers from 32 to 16. EPA also reduced the emphasis on instruction in basic construction techniques to focus on abatement methods and practices. EPA was to maintain a list of accredited training providers in order update them on technology advances. A certification exam was to be required for supervisors, project designers, and risk assessors.

Work practice standards have been established for conducting three lead-based paint activities: inspection, risk assessment and abatement. EPA does not prescribe detailed work practices to be followed in each unique situation. Instead EPA refers to existing documents from the Department of Housing and Urban Development (HUD) and to other EPA guidance documents. EPA does not specify that certain technologies be used for sampling, analysis, or abatement.

Some work practices are explicitly prohibited by the rule. EPA bans the use of open flame burning and torching when deleading target housing. Heat guns operated above 1,100°F (579°C) are prohibited. Machine sanding, grinding, and abrasive blasting require HEPA exhaust controls. Dry scraping and sanding are permitted only around electrical outlets or in treating very small areas. No restrictions have been established for cleaning with pressurized water.

EPA Definition of Lead Hazard. In a rule effective in 2001, EPA defined what constitutes a lead-based hazard in paint, and contaminated dust and soil in residental settings.[28]

A paint lead hazard is:
• Any lead-based paint on a surface subject to abrasion or friction where the lead dust levels on the nearest horizontal surface (e.g., a window sill or floor) equal or exceed the dust-lead hazard
• Any damaged or deteriorated lead-based paint on a surface (e.g., a door frame) that is subject to impact from another building component (e.g., a door)
• Any chewable lead-based painted surface on which there is evidence of teeth marks
• Any other deteriorated lead-based paint in or on the exterior of any residential building or

child-occupied facility

A dust-lead hazard is any surface that, based on wipe samples, contains:
- 40 µg/ft^2 or more of lead on floors
- 250 µg/ft^2 or more of lead on interior window sills

A soil-lead hazard is bare soil on a residential or child-occupied facility property that contains:
- 400 PPM or more of total lead in a play area
- An average of 1,200 PPM or more of lead in any other area

Generally, abatement work must reduce lead concentrations to below the hazard levels listed above. These levels have been set as the upper limits to the "clearance" levels mentioned in existing regulations. Furthermore, soil removed from a lead abatement project cannot be reused as top-soil at another residential or child-occupied property.

CERCLA and Superfund

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), issued in 1980, is intended to prevent and correct spills and releases of hazardous substances and wastes.[3] It is also known as "Superfund" because the act is to use a fund based on petroleum and chemical industry taxes, corporate environmental taxes, and general revenues to clean up hazardous waste sites. The act was extended in 1986 under the Emergency Planning and Community Right to Know Act (EPCRA), more commonly known as the Superfund Amendment and Reauthorization Act (SARA). This clarified provisions of CERCLA and increased the funds for clean-up.[29]

CERCLA authorizes EPA to force responsible parties to remove and remediate any release of hazardous substances into the environment. The definitions of these terms provide EPA with very broad power.

Hazardous Substances—Hazardous substances are defined by reference to substances listed or designated under other statutes , including waste under the Resource Conservation and Recovery Act[30] (40 CFR 261 hazardous substances [Section 311]); toxic pollutants [Section 307] under the Clean Water Act; hazardous air pollutants (Section 112) under the Clean Air Act; hazardous chemicals (Section 7) under TSCA; and substances listed under CERCLA (Section 102).

Release—A release is defined as a discharge or spill of any amount of the hazardous substances identified above. Thus there is no minimum quantity below which a facility owner is exempt. Under CERCLA, EPA also requires that any release at or above a designated quantity be reported to the National Response Center. For example, for lead compounds, the reportable quantity is 10 lbs. (4.5 kg) of hazardous lead released within a 24-hour period. Amounts less than the reportable quantity need not be reported but are still sufficient to establish liability.

Table 4. Selected Hazardous Substances and Reportable Quantities.

Hazardous Substance	Reportable Quantity **	Comments
Lead (as hazardous waste)	10 lbs (4.5 kg)	Report if > 5 mg/l per TCLP
Hydrochloric Acid	5,000 lbs (2,270 kg)	Used for etching concrete
Methyl Ethyl Ketone	5,000 lbs (2,270)	Paint solvent
Methylene Chloride	1,000 lbs (454 kg)	Paint Stripper
Sodium Hydroxide	1,000 (454 kg)	Paint Stripper, neutralizing agent
Sodium Nitrite	10 lbs (4.5 kg)	Wet blast inhibitor
Toluene	1,000 lbs (454 kg)	Paint solvent
1,1,1, -Trichloroethane	1,000 lbs (454 kg)	VOC-exempt paint solvent
Trichloroethylene	100 lbs (45 kg)	Degreasing solvent
Xylene	1,000 lbs (454 kg)	Paint solvent
Zinc Metal	1,000 lbs (454 kg)	Zinc-rich paints, galvanizing

* (40 CFR 302.4, Appendix A)
**The spill must be reported if this amount of waste is spilled in a 24-hour period.

Threat of Release—Even if a release does not occur, a party can be held liable for remedial costs based on a "substantial threat of release." Examples include lead lying on the ground, badly corroded chemical storage tanks, or abandoned drums.

Environment—The environment is defined broadly to include surface water, ground water, drinking water supplies, land surfaces, sub-surface strata, and ambient air.

Violations Triggering CERCLA Actions. Examples of

leaks and spills that have triggered CERCLA actions are:[31]

- Depositing hazardous lead waste onto ground adjacent to paint removal operations on bridges and tanks
- Leaks from tanks containing solvents and other chemicals (Note: Petroleum products are specifically exempt from CERCLA.)
- Leaching of metal (e.g., lead) from a hazardous waste landfill. (Note: If the material has passed the TCLP and been properly buried, there is no longer any liability under RCRA; CERCLA liability, however, extends indefinitely.)

CERCLA violations can be brought to EPA's attention through National Response Center reports, state and local investigations or inspections, or citizen complaints. **Table 4** presents a list of selected hazardous substances and reportable quantities.

Other Requirements of CERCLA Regulations. The regulations provide details on the following procedures:

- Setting priorities for cleanup
- Identifying remedial actions
- Identifying responsible parties
- Determining liability for cleanup costs
- Enforcement and inspection of cleanup
- Recordkeeping

Superfund. Overall, the Superfund program as administered by EPA has made little progress in achieving the intended hazardous waste cleanups. Over 50% of the several billion dollars that make up the fund has gone to administrative and legal fees.

Sara Title III ("Right-To-Know")

The use of industrial chemicals is also affected by reporting regulations developed under EPCRA (SARA Title III).[29] This legislation established requirements for federal, state, and local governments and industry regarding emergency planning and "community right-to-know" reporting on hazardous and toxic chemicals.

Planning and Response. Sections 301–303 of SARA Title III require state and local governments to develop or designate emergency planning and response commissions. Another provision requires companies to determine whether any chemical found on a list of over 300 extremely hazardous substances (40 CFR 355) is present at their facilities in an amount exceeding the Threshold Planning Quantity (TPQ), a quantity that triggers regulation. Companies that determine that they have had more than the TPQ on-site must notify authorities and appoint a facility coordinator who will participate in local emergency planning.[32]

Emergency Notification. To comply with Section 304 of SARA Title III, companies must determine whether they produce, use, or store a hazardous substance that is included on the list of extremely hazardous substances (40 CFR 355) or the list of substances subject to emergency notification requirements, found under CERCLA (40 CFR 302.4). A company that does produce, use, or store such a substance is covered by Section 304. It must notify the National Response Center and the state and local emergency planning committees if it spills or accidentally releases more than the reportable quantity of any such substance that may result in exposure outside the company site. This does not include releases such as permitted discharges to water or emissions to air. The notification should include:

- chemical name
- an indication of whether the substance is extremely hazardous
- an estimate of the quantity released into the environment
- the time and duration of the release
- known or anticipated acute or chronic health effects
- proper precautions
- name and phone number of a contact person

A written emergency notice should include response actions and any need for medical attention for those exposed.

Material Safety Data Sheet. Sections 311–312 of SARA Title III apply to any company that must prepare or maintain a material safety data sheet (MSDS) for any of the materials it uses, stores, or manufactures. An MSDS is required for any material that is a physical or health hazard, including materials that can catch fire; are suspected of causing cancer; can cause central nervous system effects; or can irritate skin, eyes, or the respiratory system. The regulations apply

to a very broad range of chemicals, including solvents, paints, and most other materials commonly used in the coatings industry. The MSDS must include information on any component present at concentrations of 1% or greater. Carcinogenic compounds that make up 0.1% of a mixture or greater must also be included.

Toxic Chemical Release Forms. Companies with more than 10 employees must ascertain if Section 313 applies to them. They must first determine whether they "manufacture, process, or otherwise use" any material on the list of chemicals found in that section. Many materials common used in coating operations are on the list, including the solvents methanol, n-butyl alcohol, methyl ethyl ketone, 2-nitropropane, toluene and xylene, and such pigments as zinc dust, zinc chromate, titanium dioxide, and nickel titanate. Some paint additives and resin components are also found on the list, including melamine, dibutyl phthalate, diethanolamine, ethyl acrylate, formaldehyde, vinyl chloride, methyl methacrylate, and toluene-2,3-diisocyanate.

Companies must next note if their use of these materials exceeds the TPQ. The TPQ for materials that a company "manufactures or processes" is 25,000 pounds (11,360 g). The TPQ for a material that is "otherwise used" is 10,000 pounds (4,540 g). To meet the requirements of Section 313, companies that exceed the TPQ must annually report routine emissions of each such chemical, including releases into water, air, or soil during the preceding year.

A company finding that the provisions of Section 313 apply to one or more of its materials should draw a process flow diagram to determine each point at which the material leaves the system. For many coating operations, the primary release is the evaporation of solvents and other materials in a coating as it is applied.

After identifying all sources of chemical releases, the quantity released must be identified for each chemical that exceeds the TPQ. A number of approaches and formulas can be used to do this, including direct measurement, mass balance formulas, and engineering calculations. Overspray releases are often the most important factor in estimating releases from coating operations, and published estimates are available for some types of spraying methods and surfaces. However, site-specific calculations may be required.

Current SARA 313 thresholds require only larger coating operations to report. These businesses often have greater resources and specialized personnel, and are better able to comply with 313 requirements. Proposals to lower TPQs would result in smaller operations, perhaps those using as little as 500 gallons (1,900 L) of paint, also being required to report under 313.

Secondary Containment for Above-Ground Storage Tanks and Vessels

Effect on Coating Suppliers and Contractors

Federal regulations require that some above-ground storage (AST) tanks be supplied with secondary containment, i.e., a structure capable of preventing material stored in a tank from migrating to soil, groundwater, or surface water. Another incentive for companies to invest in such systems is avoidance of CERCLA liability and civil liability associated with a spill. The need for secondary containment systems provides a business opportunity for coatings suppliers, specifiers, and contractors. Concrete is the material most often used for secondary containment structures. Coatings are an integral part of such designs because they increase the impermeability and chemical resistance of concrete and prevent cracking.

Regulatory Requirements

Applicable Regulations. Tanks that are used to store and treat hazardous wastes are subject to 40 CFR Part 264, Subpart J of the *Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities* (part of RCRA).[33]

The title of this section is somewhat misleading as the requirements apply to treatment, storage, and disposal facilities and to large quantity generators (defined as those generating more than 2,200 lbs. [1,000 kg] of hazardous waste a month or storing the material for more than 90 days on site). Tanks containing hazardous waste must be equipped with secondary containment structures. An exemption is provided for hazardous waste that contains no free liquids and is stored inside a building with an impermeable floor.

In order to prevent migration, a secondary containment system must be capable of containing spills and leaks, and must be equipped with a leak detection system to alert owners and operators to such

an event. A containment system must also be made of or lined with materials compatible with the waste stored in the system. The system must include an appropriate foundation or base and be sloped or designed in such a way as to permit draining and removing liquids.[34]

The Oil Pollution Act of 1990 required EPA to study the need for similar regulations applicable to above ground tanks used to store petroleum products.[35] The American Petroleum Institute (API) has reported that there are more than 700,000 above ground petroleum tanks in North America.[36]

Acceptable Containment Structures. An external liner, a vault, a double-walled tank, or an equivalent device may provide containment. External liners and vaults must be capable of containing 100% of the capacity of the largest tank within their boundaries. They must also prevent rain from entering the secondary containment system unless the system has the capacity to hold the extra liquid.

External liner systems must surround the tank completely and cover any surrounding soil likely to come in contact with leaked or spilled waste. Vault systems must include water stops that are capable of resisting the waste in all joints, and must be coated with a waste-compatible lining that will prevent the waste from permeating the concrete. They must also be able to prevent the formation of and ignition of vapors within the vault. Double-walled tanks must be designed so that the outer tank completely surrounds the inner tank, preventing any releases and protecting the exterior of the inner tank from corrosion.

Materials that could cause the tank or ancillary equipment or the containment system to rupture, leak, or fail may not be placed in the tank. Owners and operators must use appropriate measures to prevent spills and overflows and must visually inspect visible portions of the tank and review data from monitoring and leak detection equipment at least once each operating day.

Coating Choices for Secondary Containment Systems

A secondary containment system must be able to survive contact with the substance in the tank until a leak or spill can be removed. Since leaks and spills should be infrequent and a detection system is often required, secondary containment components are usually only exposed to the material for a short period of time. When a tank is used to store an extremely toxic or dangerous material, the secondary containment system should be more durable than it would be for a less hazardous material. Choice is complicated by the fact that a coating may need to be capable of resisting several different materials. Installation performance and other properties of coatings for secondary containment are described in SSPC TU-2.[37] Types of coatings commonly used to protect secondary containment systems include:

Thin Films. Thin films (up to 10 mils [0.25 mm]) of unreinforced spray-applied coatings are adequate for containment of less hazardous materials, and are less expensive than other approaches. However, some may not withstand long periods of chemical exposure. Epoxies and polyurethanes are commonly used in this way.

Flake and Fiber-filled Coatings. Flake and fiber-filled coatings typically result in films of 40 to 80 mils (1 to 2 mm). They cost more than thin film coatings. Some may provide a longer period of containment.

Reinforced Thick-film Systems. Reinforced thick film systems can be used to create films of more than 80 mils (2 mm). Glass cloth or synthetic fibers are chosen on the basis of their resistance to a particular chemical. These systems can be effective in preventing some cracks, and should be designed to withstand exposure to the most aggressive chemicals for up to 72 hours. A resinous topcoat improves their chemical resistance.

Composite Lining System with Leak Detection. A coatings manufacturer has developed a composite system consisting of an epoxy-impregnated three dimensional (3-D) glass fabric that is bonded to the tank floor.[38] The system allows for detecting leaks through the epoxy laminate, thereby serving as the primary containment with the tank serving as a secondary containment. The 3-D glass fabric provides interstitial air spaces that the manufacturer claims can be monitored for leaks by hydrostatic pressure, vacuum, or liquid or gas sensor. The state of Florida, which will require double-walled tanks as of 2009, is considering this system as an alternative.[39]

Underground Storage Tanks

Background

Potential for Spills. Certain underground storage tanks (USTs) are regulated because they may leak and pose a threat to the environment and human health. Coatings and lining systems are among the accepted means of preventing leaks in underground storage tanks (USTs) and complying with federal and state regulations.

There are several million underground storage tanks in the United States containing petroleum or hazardous chemicals. The tank system consists of the tank itself and associated piping. A tank system is considered underground if at least 10% of the volume is below grade level. The vast majority of underground storage tanks (in particular those installed before 1980) were constructed of bare carbon steel. As a result of differential aeration of soils, aggressive soil conditions, pH variation, and the presence of water and other corrosive materials inside the tank, there is the possibility of severe corrosion of both the interior and exterior of tanks and piping.

As a result of corrosion as well as piping and mechanical failures and installation mistakes, many thousands of USTs are leaking. Leaks may also result from spills and overfills during filling, emptying, or operating the tanking system. Leaking underground storage tanks can contaminate groundwater, which is a major source of drinking water for U.S. populations. EPA estimates that as many as a quarter of all the tank systems in the U.S. are leaking.[40]

1984 Federal Regulations. In 1984, Congress included requirements for technical standards and corrective action for owners and operators of underground storage tanks. These are part of the RCRA regulations discussed in the chapter on waste handling and disposal. The underground storage tank regulations (40 CFR 280) are intended to:

- Prevent leaks and spills
- Identify and correct problems
- Ensure that owners and operators are able to pay for spill prevention and correction

The regulations apply only to USTs storing petroleum or hazardous chemicals. Some tanks are specifically excluded from the regulations, including certain residential motor fuel and heating oil tanks and pits. Responsibility for complying with the regulations falls on the owners and operators of the tanks. The specific requirements depend on the date of tank installation.

Types of Underground Structures Regulated

New Petroleum USTs. USTs installed after December 1988 must meet these requirements:

- **Qualified Installation.** The tanks must be properly installed by qualified installers following industrial codes. Examples are those established by Steel Tank Institute, American Petroleum Institute, National Leak Prevention Association, Petroleum Equipment Institute, and NACE International.
- **Spill Prevention.** The tanks must be equipped to prevent spills and overflow through proper filling procedures, catchment basins, and alarms.
- **Leak Detection.** Approved methods for leak detection must be part of the design.
- **Corrosion Protection.** Among the methods to ensure proper corrosion protection for new tanks are the use of a corrosion-resistant coating together with cathodic protection; construction with non-corrosive material (e.g., fiberglass-reinforced plastic, or FRP); installation of a bonded, secure system liner. (Note: The liner is not acceptable for piping.)
- **Other Requirements.** Special instructions are provided for tanks of a certain size and age and for pressure or suction piping. These instructions cover monitoring soil vapors and liquid in groundwater, automatic tank gauging, and automatic shutoff and tightness tests.

Existing Petroleum USTs. For tanks built before December 1988, EPA has set deadlines for establishing corrosion protection, incorporating filling devices to prevent spills and overfill as well as leak detection systems.

These options are available to upgrade tanks for corrosion protection:

- Install an interior lining. The lining must be inspected within 10 years after installation and every 5 years thereafter. (40 CFR 280.3 gives requirements for the inspection.)
- Install cathodic protection systems. Using the various methods described in 40 CFR 280.21, the tank must

be internally inspected to ensure that it is free of corrosion holes. NACE RP0285-95 may be used to verify proper inspection and operation of a cathodic protection system.[41]

• Use both an internal lining and cathodic protection.
• Use a thick liner bonded to the exterior of the tank. This requires excavations around the tank and is not often feasible for existing tanks.



Figure 3. Installing an underground storage tank.

Metal piping must be upgraded using a cathodic protection system. December 1998 was the deadline for upgrading corrosion protection systems for all tanks and piping. All new and existing tanks were also required to have leak detection installed by December 1993.

The regulations also provide instructions on how to correct problems caused by leaking, how to permanently or temporarily close (take out of service) a tank system, and how to meet the extensive record-keeping and reporting requirements.

Underground Hazardous Chemical Tanks. Underground storage tanks containing hazardous chemicals are also regulated under 40 CFR 280. Hazardous chemicals are those that are listed in CERCLA (40 CFR 302.4, Table 1). Hazardous wastes are excluded from this section of the regulation because they are covered under other provisions of RCRA. These tanks are subject to many of the same regulations as petroleum tanks. All chemical USTs installed prior to December 1988 were required to be upgraded by December 1998. As with petroleum tanks, corrosion protection can consist of installing a liner, a cathodic protection system, or a combination. The tank must also be provided with devices that prevent spills and overfills while detecting leaks. Tanks installed after December 1988 must meet the same requirements as the new petroleum USTs (i.e., properly installed, spill and overfill protection, protection from corrosion, and leak detection).

In addition, new tanks containing hazardous materials must be provided with secondary containment. The primary containment is the tank or pipe wall itself. The requirements for secondary containment of underground chemical storage tanks are essentially the same as the requirements for secondary containment of storage tanks containing hazardous waste.

There are three types of secondary containment used for underground tanks and piping:

• Double-walled systems in which one tank is placed inside another, or one pipe inside another
• Concrete vaults that surround tank and piping systems, isolating them from the ground
• Chemical resistant liners placed around the tank to isolate it from the ground

In addition, chemical USTs must have a leak detection system that can detect a leak in the "interstitial" space between primary and secondary containment. The epoxy laminate system with interstitial spaces for leak detection, described for ASTs, may also be suitable for USTs.[38]

Corrosion Protection of Underground Storage Tanks

The approaches for preventing corrosion and leaking (primary containment) are:

• An external coating system applied to the exterior of the tank
• A lining system applied to interior of tank
• Cathodic protection applied to the exterior of the tank

- External coating plus sacrificial anodes
- FRP construction

External coating system. A coating system is designed to isolate the steel of the tank from corrosive soil conditions, thereby preventing the corrosion cell from being completed. A significant amount of testing, research, and evaluation has been conducted on underground coatings. Among the most important properties are adhesion, impact resistance, and impermeability. Among the most widely used coating systems are asphalt cutbacks, coal tar epoxy, polyurethane, and FRP. Several of these systems have been approved by the Steel Tank Institute under their STI-P3 system.[42]

Application of a coating to a new steel tank can be accomplished at the factory shop, which allows much greater control of the quality of the surface preparation, application, and environmental conditions. Applying an external coating to upgrade an existing tank requires excavating around the tank and back filling after application of the coating.

Internal Lining System. To upgrade an existing tank, the lining can also be applied to the interior. The American Petroleum Insitute (API) has issued recommended practice RP1631, *Interior Lining of Underground Storage Tanks,* which describes the various steps in preparing the tank and applying the lining, including qualifications of applicators and testing of linings.[43] A number of coating systems have been used for lining petroleum tanks, including epoxy polyamide, epoxy phenolic, epoxy amine, coal-tar epoxy, glass-flake-filled polyester, and fiber-reinforced polyester.

Cathodic Protection. This method consists of applying an external electric current to force the steel to behave as a cathode. Loss of metal occurs only at the anode, where the metal gives up electrons. Two types of cathodic protection have been developed: sacrificial anodes and impressed current. Sacrificial anodes are metals, such as zinc or magnesium, which are consumed (sacrificed) while the steel remains intact. Impressed current cathodic protection sends a continuous stream of DC electrical current through the steel. The current ensures that the steel cannot discharge current (i.e., in the form of ferrous ions) into the environment. Cathodic protection is also an integral part of the STI-P3 system.

External Coating Plus Sacrificial Anodes. For new tanks, a combination of a dielectric coating and sacrificial anodes has proven to be extremely effective over the last 30 years. The Steel Tank Institute (STI) has developed an industry standard known as STI-P3, which combines dielectric coating, sacrificial anodes, and electrical isolation.[44] The dielectric coating (e.g., typically coal-tar epoxy, polyurethane, or FRP lining) serves as the first line of defense, with a complete covering of the external surface of the tank. The galvanic anodes provide protection from nicks and scratches in the coating, which are often produced during transportation and installation or settling. The third component of the system is to prevent stray currents from entering the tank via the piping system or at other potential areas of metal-to-metal contact. STI also has established a quality assurance system for the testing of coatings, tank fabrication, and installation.

Fiberglass Reinforced Plastic (FRP) Construction. FRP is a composite consisting of a chemically reacted resin impregnated with glass fibers. The resin system, when reacted and cured, forms a strong, relatively impermeable barrier to moisture, while the fibers impart tensile strength. This results in a high strength-to-weight ratio for these light materials, and provides an optimum combination of corrosion resistance and strength. FRP, like other construction and corrosion protection materials, must be carefully selected, tested, designed, and installed to ensure proper performance and compliance with design criteria.

More detailed discussions of corrosion protection alternatives and materials are given in various publications available from STI, NACE, and SSPC.

State Regulation of Underground Storage Tanks

The underground storage tank program, like many federal laws, is delegated to the states. Numerous states have adopted existing federal regulations for upgrading USTs or installing new ones. Several states have adopted their own regulations, which may be more stringent than the federal. For example, some states, such as Connecticut, limit the number of times that a tank lining can be used to extend the life expectancy of a tank. Other states (e.g., Massachusetts and

Maine) require double walls in all new tanks. Certain states require that all new tanks (including petroleum and chemical storage tanks) be provided with secondary containment. Still others also require that installers be certified (e.g. Florida, Arkansas, and California).

Two standards, the Uniform Fire Code (UFC) 79 and National Fire Protection Association (NFPA) 30, are frequently cited in state UST regulations.[45] These standards outline safety parameters for tank lining procedures. UFC 79 does not permit repairs to USTs; NFPA 30 allows USTs to be repaired and lined.

Regulating Coatings for Food and Beverage Facilities

General

The U.S. federal government regulates coatings intended for surfaces at food and beverage plants to assure that sanitary conditions are maintained. The food and beverage industry consists of production, processing, and distribution facilities for fruits and vegetables, grain, meat and poultry, soft drinks, beer and other alcoholic beverages, and pharmaceuticals (because the end products are consumed). Federal agencies having jurisdiction are the Food and Drug Administration (FDA) and the U.S. Department of Agriculture (USDA).

Food and Drug Administration

The FDA regulates coatings that come into direct contact with food and beverages under 21 CFR 175, Parts 300-390.[46] These include coatings applied to floors, walls, and counters, as well as containers and vessels. The FDA limits ingredients to those that are listed in the CFR or that are generally recognized as safe for food. In addition, the cured film must meet limits for the maximum amount of extractable material. According to Boyer, there are no limitations on solvents, and a wide range of organic binders is permitted.[47] There are, however, limitations on the color of pigment allowed. The standard provides a description of the conditions under which resinous and polymeric coatings may be safely used as food contact surfaces. The standard also lists dozens of specific components that have been approved.

The extraction tests are based on the food types (e.g., acid, non-acid, dairy, beverages, bakery, and dry solids) and the temperature and sterilization conditions required. The FDA does not approve coatings, but sets the guidelines. It is the manufacturer's responsibility to ensure that the raw materials and test results comply with the federal regulations. An appropriate statement by a manufacturer would be that the coating will meet the requirements of 40 CFR 175.300 (FDA) for use in contact with specific foodstuffs. The phrase "approved by FDA" is not valid for protective coatings.

United States Department of Agriculture

Prior to November 1995, the USDA required coating manufacturers to provide a list of all the ingredients in the formulations or to certify that the coating would withstand daily cleaning, cyclic temperature, and wet conditions. However, under Food Safety and Inspection Service Directives, this requirement was eliminated.[48] The directive is in effect at "official establishments," which are federally inspected meat or poultry packing facilities.

Soil Quality Regulations

Sources of Lead in Soil

Because of extensive use of leaded gasoline and lead-containing traffic marking and bridge coatings, much of the soil in the U.S. contains measurable amounts of lead. The geometric mean in the U.S. is 16 mg/kg (ppm), but in urban or industrial areas or along roadways, concentrations often exceed 100 mg/kg.[49]

Soil can also become contaminated with dust, paint, and abrasive debris. One of the primary concerns is lead contamination of soils, because of the potential health effect on children in nearby communities.

Lead in Soil Regulations for Residential Area

In 1989, EPA adopted an interim guideline for cleanup of soil at Superfund sites of 500-1,000 mg/kg, with the lower end of the range being considered more appropriate for residential areas and the upper end for use in industrial settings.[50]

In 1995 under TSCA Title IV, EPA established guidelines for assessing hazards from lead in soils near housing.[51] For lead concentrations under 400 PPM, no action is required. For levels between 400 and 5,000 PPM, it is necessary to change the use patterns of the area (e.g., by restricting access or by planting ground cover). At levels above 5,000 PPM, it is necessary to abate the soil, including removal and

replacement or to create permanent barriers along with public notice.

In 1998's *Phase IV Land Disposal Restriction Rule,* EPA established a federal standard for treating lead contaminated soil.[52] The final concentration is required to be a 90% reduction or 7.5 mg/L by TCLP (whichever is less stringent).[53] Previously, EPA had required use of the TCLP level of 5.0 mg/L. (See discussion in the chapter on waste regulations.)

A review of guidelines of levels of lead in soil requiring cleanup in several states indicates a range from approximately 100–1,000 mg/kg, with most values in the range between 250 and 500 mg/kg.[49]

Regulating Lead in Soil for Industrial Areas

As of the first quarter of 2002, EPA had not issued a regulation on lead in soil in industrial areas. It is anticipated, however, that as part of the their mandate under Title X of the 1992 Housing and Community Development Act, they will issue guidelines or regulations on acceptable levels of lead in soil in industrial as well as residential areas.[24] These regulations may also require remediation or other treatment for soil exceeding a defined level of lead.

Monitoring For Lead in Soil

Facility owners and painting contractors often elect to measure the level of lead in soil prior to and following lead paint removal to determine if the removal process resulted in an increase. The number and locations of the samples collected are critical because of the large variability of lead levels on or slightly below the surface. SSPC-TU 7 describes a procedure for sample collection, analysis, and reporting. Each sample requires collecting 5 plugs of soil from the corners and center of a 12 inch (300 mm) template. The 5 plugs are mixed to form one sample with a duplicate taken approximately 3 inches (75 mm) from the first. The samples are analyzed for total lead in accordance with EPA Method 3050 by a laboratory participating in the Environmental Lead Laboratory Accreditation Program.[53] ASTM has also issued ASTM E 1727-95, *Standard Practice for Field Collection of Soil Samples for Lead Determination by Atomic Spectrometry Techniques.* This practice covers the collection of soil samples using coring and scooping methods for subsequent determination of lead concentration. Soil collection is limited to approximately the top half inch (1.5 cm) of the surface. ASTM's practices for analyzing lead samples by atomic absorption spectroscopy are covered under E 1726-95 while other analytical techniques are covered by E 1613-94.

Regulation Of Anti-Fouling Coatings

Use

Anti-fouling coatings are used to discourage colonies of mobile marine organisms, such as barnacles, mollusks, sponges, and algae from building up on the bottoms of ships or other substrates. Fouling increases the weight of ships, reducing speed and increasing fuel consumption. It also interferes with the operation of moving parts. Anti-fouling coatings are also being used to prevent zebra mussels from fouling fresh water intakes on power stations.[55] Power stations have reported condenser tube blockage in unheated intakes. Protective coatings have been evaluated as alternatives to chlorination, water filtration, and other chemical and physical treatments.

Regulations

Organotin Anti-fouling Paint Control Act. Until 1988, copper and organotins (such as tributyl tin oxide) were the compounds most commonly used to prevent fouling of underwater hulls of ocean-going ships. Both types kill target organisms by releasing small quantities of materials toxic to them. Concern about effects of organotin compounds on non-target organisms such as oysters and crabs led to passage of the Organotin Anti-fouling Paint Control Act in 1988.[56] The act limited releases of tin from such coatings to 4 μg/cm^2/day. The legislation also required each state to set up a plan to certify applicators of these coatings. Organotin coatings are now seldom used except on aluminum boats, where copper (for which there is no regulation for maximum release rate) cannot be used. Some states, for instance Virginia and New York, also regulate such materials under their water quality regulations. The U.S. Navy has voluntarily agreed to discontinue use of organotin paints on its oceangoing vessels.[57]

IMO Restrictions on Tributyl Tin Compounds. The International Maritime Organization (IMO) has recommended a ban on application of organotin based anti-fouling coatings after January 1, 2003.[58] Furthermore, by January 1, 2008, all ships are required to have

organotin compounds removed from the hulls or other external parts or be encapsulated to prevent leaching of the organotin. The ban would become effective 12 months after ratification by at least 25 nations representing at least 25% of the world's merchant shipping tonnage. The IMO indicated it would prepare a list of the anti-fouling systems covered by the ban. The provision applies to all ships, fixed and floating platforms, and other floating facilities.

Federal Insecticid, Fungicide, or Rodenticide Act (FIFRA).[59] Biocides like copper and organotin compounds are considered pesticides and must also be registered under the Federal Insecticide, Fungicide, or Rodenticide Act. According to some paint manufacturers, meeting all the requirements of registering a new biocide is so prohibitively expensive ($2-$5 million) as to effectively preclude introduction of new materials. Notwithstanding this concern, over the last few years, several manufacturers have introduced new biocides to enhance the fouling resistance of copper-based anti-fouling coatings. These are often designated "co-biocides."

Fouling-Release Coatings

Some ship and power plant operators have begun to use silicone, siloxanes, and fluorinated resins because these materials do not need to be registered under FIFRA. They are not considered pesticides because they do not kill marine organisms, but make it difficult for them to attach to the painted surface.

Slip Resistance Of Coatings For Steel Erection

Background and Rule Development

In July 2001, OSHA issued a regulation establishing standards for steel erection under 29 CFR 1926.754.[60] Part 3 of this standard addresses a concern for the possibility of workers falling off the structures during the erection process because of slippery paints.[61] In drafting this rule, OSHA has worked with a government industry task force known as SENRAC (Steel Erection Negotiated Rulemaking Advisory Committee).

Part 3 establishes a minimum coating slip resistance of 0.50 when measured in accordance with a device such as a variable incidence tribometer (VIT) using specified ASTM standards. The coatings industry had expressed several concerns about the rule, including the need for time to reformulate coatings, the inappropriateness of OSHA's proposed reference of bare steel, and the lack of a validated test procedure. The final rule addresses the first two concerns by allowing a five-year phase-in time and by establishing a numerical reference of 0.50 slip units. The coatings industry has established a task force (headed by SSPC and the American Institute of Steel Construction) to address the inadequacies of the test method This effort is expected to provide an improved procedure in time for the regulation's implementation date.

Preliminary Slip Rating of Coatings

The conclusions of the preliminary testing are:[62]

- Zinc rich coatings (both inorganic and organic) give high slip index
- Other organic coatings (e.g., epoxies, polyurethanes, and acrylics) give a range of slip indexes depending on the particular formulation
- Adding polyolefin beads to the formulation and applying the coating over blast cleaned steel significantly improves the slip properties

A major source of uncertainty is the test foot used to strike the surface during measurement.

Implementation of Rule

OSHA has commented that any projects that are bid after the fall of 2006 will be included in this regulation. According to the regulation, the testing could be done by the coating manufacturer or by an outside testing laboratory. In many cases, these coatings must also be pre-qualified by state departments of transportation under programs such as AASHTO's National Transportation Product Evaluation Program (NTPEP), or individual state qualification programs.[63] Qualification of a coating by these entities often takes one to two years or longer.

The expected responsibilities under this regulation are:

- Industry associations (SSPC, AISC, ASTM): develop suitable test methods and keep all parties informed
- Coating manufacturers: formulate and evaluate coatings meeting the OSHA requirements and also the well-established, long-term performance requirements
- Departments of transportation: incorporate the OSHA

standard into specifications and allow these new formulations to be tested under standard state protocols for laboratory and field performance

• Fabricators: be aware of the requirements for testing, including compliance dates, and maintain appropriate records

• Erectors: ensure that only qualified coatings are used (The erector has primary responsibility to conform to the regulation.)

Regulatory Language

The final language of this section is:

§1926.754 Structural steel assembly (Final rule)[51]

(3) Slip resistance of skeletal structural steel. Workers shall not be permitted to walk the top surface of any structural steel member installed after [INSERT DATE: 5 years after effective date of final rule] that has been coated with paint or similar material unless documentation or certification that the coating has achieved a minimum average slip resistance of 0.50 when measured with an English XL tribometer or equivalent tester on a wetted surface at a testing laboratory is provided. Such documentation or certification shall be based on the appropriate ASTM standard test method conducted by a laboratory capable of performing the test. The results shall be available at the site and to the steel erector. (Appendix B to this subpart references appropriate ASTM standard test methods that may be used to comply with this paragraph (c)(3)).

References

1. Federal Water Pollution Control Act. Public Law 92-500, 1971, and Clean Water Act. Public Law 95-217, 1977.
2. Clean Water Act. Public Law 100-202, 1987.
3. Comprehensive Environmental Response, Compensation, and Liability Act. Public Law 96-510, 1980.
4. National Recommended Water Quality Criteria. *Fed. Regist.* 1998, *63,* 68353-68364.
5. U.S. EPA Office of Drinking Water Criteria and Standards Division, Washington D.C.
6. Safe Drinking Water Act. Public Law 93-523, 1974.
7. U.S. EPA Method 1311, Toxicity Characteristic Leaching Procedure (TCLP).
8. Smith, L.M. *Water Quality Progress Report;* FHWA Contract DTFH61-89-C-00102, 1989.
9. Hunt, H.; Gidley, J. *The Toxicities of Selected Bridge Painting Materials and Guidelines for Bridge Painting Projects;* California Dept. of Transportation Report FHWA/CA/TL/90/08, 1990.
10. Canadian Fisheries Dept. Issues Guidelines on Protecting Aquatic Life During Bridge Painting. *Journal of Protective Coatings and Linings*, January 1992, pp 32-34.
11. Thorpe, G. Water Quality Impact: Environmental Viewpoint. In *Lead Paint Removal from Steel Structures*, SSPC: Pittsburgh, 1988 pp 50-54.
12. U. S. EPA Home Page. http://cfpub.epa.gov/npdes/ *National Pollutant Discharge Elimination System* (accessed April 2002).
13. U. S. EPA. *Update Paper: Overview of the Stormwater Permit Program;* Car Department Officers' Association Protective Coatings Committee: Washington, D.C., 1992.
14. Trimber, K.A.; Adley, D.P. *Project Design: Industrial Lead Paint Removal Handbook; Volume 2;* SSPC: Pittsburgh, 1994.
15. *SSPC Technology Update 7: Conducting Ambient Air, Soil and Water Sampling During Surface Preparation and Paint Disturbance Activities;* SSPC: Pittsburgh, 2000.
16. EPA Method 3050B Acid Digestion of Sediments, Sludges, and Soils. In *SW-846: Test Methods for Evaluating Solid Waste, 3rd Edition;* U.S. EPA: Washington, D.C., 1995.
17. U. S. EPA Office of Drinking Water Criteria and Standards Division, Washington D.C.
18. Bauer, M. Changing Regulations on Coatings for Contract with Potable Water. *Journal of Protective Coatings and Linings*, December 1988, pp 27-33, 89-90.
19. ANSI/NSF 61-2000a. *Standard for Drinking Water System Components–Health Effects.*
20. National Sanitation Foundation Home Page. http://www.nsf.org/Certified/PwsComponents (accessed April 2002).
21. Toxic Substances Control Act. Public Law 94-469, 1976.
22. Consumer Product Safety Commission Home Page. http://www.cpsc.gov/CPSCPUB/PUBS/SUCCESS/lead.html (accessed April 2002).
23. Rauscher, G. Compliance with TSCA for Product Development. *Journal of Protective Coatings and Linings*, May 1990, pp. 68-72.
24. U.S. Congress. Title X: Residential Lead-Based Paint Hazard Reduction Act—Housing and Community Development Act of 1992.

25. Kapsanis, K. EPA Proposes Title X Lead Rule. *Journal of Protective Coatings and Linings,* November 1994, pp 23-33.
26. U.S. EPA. Proposed EPA Rulemaking for OPPT's Bridges and Structures—Lead-Based Paint Activities Rule: Frequently Asked Questions. U.S. EPA: Washington, D.C., 1999.
27. Requirements for Lead-Based Paint Activities in Target Housing and Child-Occupied Facilities: Final Rule. *Code of Federal Regulations,* Section 744, Title 40, 1996; *Fed. Regist.* 2001, *66,* 45778-45812, 45813-45830.
28. Identification of Dangerous Levels of Lead: Final Rule. Code of Federal Regulations, Section 745, Title 40, 1996; *Fed. Regist.* 2001, *66*.
29. Superfund Amendments and Reauthorization Act of 1986. Public Law 99-499, 1986.
30. Resource Conservation Act. Public Law 94-580, 1976.
31. *Environmental Law Handbook*, *12th Edition;* Government Institutes Press: Rockville, MD, 1993.
32. U.S. EPA. *Title III Fact Sheet: Emergency Planning and Community Right-to-Know;* U.S. EPA: Washington, D.C., 1988.
33. Standards for Owners and Operators of Hazardous Waste Treatment, Storage, And Disposal Facilities. *Code of Federal Regulations,* Section 264, Title 40, *Fed. Regist.*
34. Nau, P.R.; Fultz, B. S. Coatings and Linings for Secondary Chemical Containment in Power Plants. *Journal of Protective Coatings and Linings*, October 1990, pp 42-49.
35. Oil Pollution Act. Public Law 101-380, 1990.
36. Myers, P. E. *Aboveground Storage Tanks;* McGraw Hill: New York, 1997; p 2.
37. SSPC TU-2/NACE 6G197. *Design Installation and Maintenance of Coating Systems for Concrete used in Secondary Containment;* SSPC: Pittsburgh and NACE: Houston, 1997.
38. O'Donoghue, M., et. al. Reinforced Glass Fabric Epoxy Linings with Leak Detection for Storage Tanks. *Journal of Protective Coatings and Linings,* March 1999, pp 24-37.
39. Kapsanis, K.; Markle, P. The Debate Over Tank Linings: Protecting Aboveground Storage Tanks and the Environment. *Journal of Protective Coatings and Linings,* May 1997, pp 53-56.
40. U.S. EPA Office of Underground Storage Tanks. *Musts for USTs;* U.S. EPA: Washington, D.C., 1990.
41. *Corrosion Control of Underground Storage Tank Systems by Cathodic Protection;* NACE RP0285-95; NACE: Houston, 1995.
42. Cronau, R.C. Protecting Underground Storage Tanks. *Journal of Protective Coatings and Linings*, August 1988, pp 48-49.
43. American Petroleum Institute. *Interior Lining of Underground Storage Tanks;* API RP 1631, 2nd Edition; API: Washington D.C., 1987.
44. Sti-P3. *Specification and Manual for External Corrosion Protection of Underground Steel Storage Tanks;* Steel Tank Institute, 1996 (http://www.steeltank.com/spec/stip3.htm).
45. *Uniform Fire Code 79;* International Fire Code Institute, 1997 and *NFPA 30;* National Fire Protection Association's Flammable and Combustible Liquids Code.
46. Indirect Food Additives: Adhesives and Components of Coatings. *Code of Federal Regulations*, Section 175, Title 21, *Fed. Regist.* (http://www.access.gpo.gov/nara/cfr/waisidx_99/21cfr175_99.html)
47. Boyer, C. Protective Coatings for Food and Beverage Plants: Regulatory and Formulating Issues. *Journal of Protective Coatings and Linings*, July 1990, pp 36-39.
48. Food Safety and Inspection Service Directives 11,000.4, Revision 1, 1995, and 11,000.4, 1994.
49. LaGoy, P. K.; Wilder, W. Evaluation of the Potential for Environmental Exposure to Lead Released from Paint Containing Zinc Dust. *Journal of Protective Coatings and Linings*, March 1993, pp 24-36.
50. U. S. EPA Office of Solid Waste and Environmental Response. *Interim Guidance on Establishing Soil Lead Cleanup Levels at Superfund Sites;* Directorate 9355.4-02; U.S. EPA: Washington, D.C., 1989.
51. U.S. EPA. *EPA Guidance on Identification of Lead-Based Paint Hazards (Section 403 of Title IV of the Toxic Substances Control Act);* U.S. EPA: Washington, D.C., 1995
52. Land Disposal Restrictions—Phase IV. Code of Federal Regulations, Sections 148, 268, and 271, Title 40, *Fed. Regist.* 1998, *63,* 28555-28604.
53. SSPC Home Page. http://www.sspc.org/site/regnews/EPAWASTERULE.html
EPA's Regulation on Lead Waste Treatment and Handling (accessed April 2002).
54. American Industrial Hygiene Association Home Page. http://www.aiha.org/LaboratoryServices/html/

lead.htm *Environmental Lead Laboratory Accreditation Program* (accessed April 2002).
55. Leitch, E.G.; Puzzuoli, F.Z. Evaluation of Coatings to Control Zebra Mussel Colonization: Preliminary Results, 1990-1991. *Journal of Protective Coatings and Linings*, July 1992, pp 28-38.
56. Organotin Anti-Fouling Paint Control Act. Public Law 100-333, 1988.
57. Swain, G. Redefining Antifouling Coatings. *Journal of Protective Coatings and Linings,* September 1999, pp 26-35.
58. IMO Adopts Controls on Harmful Antifouling Systems. *Journal of Protective Coatings and Linings,* December, 2001, pp 10-11.
59. Federal Insecticide, Fungicide, and Rodenticide Act. Public Law 92-516, 1982.
60. Structural Steel Assembly: Final Rule. *Code of Federal Regulations,* Section 1926.754, Title 29, *Fed. Regist.* 2001, *66,* 5317-5325.
61. Proposed OSHA Safety Standard for Steel Erection Could Affect Use of Coatings. *Journal of Protective Coatings and Linings,* January 1999, pp 65-67.
62. Appleman, B. R. Slip Testing to Meet Construction Safety Regulations for Coated Steel. *Journal of Protective Coatings and Linings,* October 2000, pp 73-82.
63. National Transportation Product Evaluation Program. *Project Work Plan for Laboratory Testing and Field Evaluation of Structural Steel Coatings;* American Association of State Highway and Transportation Officials: Washington, D.C., 2001.

Acknowledgements

The author and SSPC gratefully acknowledge Gary Tinklenberg's peer review of this document.

About the Author

Bernard R. Appleman
Dr. Bernard R. Appleman has been active in the protective coatings industry since 1974. He served as executive director of SSPC from 1984–1999, prior to his current position as vice president and technical director of KTA-Tator, Inc. He has also worked at Federal Highway Administration on research and testing of bridge coatings, at Exxon Corporation on coatings and corrosion for the petrochemical industry, and for the U.S. Navy on corrosion and fouling-resistant ship coatings. He is an SSPC protective coatings specialist (PCS) and has published over 100 technical publications.

Appendix
Selected Environmental Regulations From Title 40 Of The Code Of Federal Regulations: Protection Of The Environment*

40 CFR 50-99 Air Pollution Control Regulations
50 National Primary and Secondary Ambient Air Quality Standards
51 Requirements for Preparation, Adoption, and Submission of Implementation Plans
52 Ambient Air Monitoring Reference and Equivalent Methods
60 Standards of Performance for New Stationary Sources
61 National Emission Standards for Hazardous Air Pollutants
66 Assessment and Collection of Noncompliance Penalties by EPA
81 Designation of Areas for Air Quality Planning

40 CFR 100-149 Clean Water Act/Safe Drinking Water Act Regulations
112 Oil Pollution Prevention
116 Hazardous Substances Under Federal Water Pollution Control Act
117 Determination of Reportable Quantities for Hazardous Substances
125-125 National Pollution Discharge Elimination System Permits
136 Test Procedures for the Analysis of Pollutants
149-149 Drinking Water

40 CFR 150-189 Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) Regulations
152 Pesticide Registration and Classification Procedures
155 Registration Standards
156 Labeling Requirements for Pesticides and Devices

40 CFR 240-299 Solid and Hazardous Waste Programs
260 General Guidelines for Hazardous Waste Management
261 Identifying Hazardous Waste
262 Hazardous Waste Generators
263 Hazardous Waste Transporters
265 Owners and Operators of Hazardous Waste Facilities
266 Standards for Management of Specific
267 Interim Standards for Owners and Operators of New Hazardous Waste Land Disposal Facilities
268 Land Disposal Restrictions
280 Underground Storage Tank (UST) Regulations

40 CFR 300-399 Superfund, Emergency Planning, and Community Right-to-Know Programs
300 National Oil and Hazardous Substances Pollution Contingency Plan
302 Designation, Reportable Quantities, and Notification
355 Emergency Planning and Notification
370 Hazardous Chemical Reporting
372 Toxic Chemical Releases Inventory Reporting, Community Right-to-Know

40 CFR 400-699 Clean Water Act (CWA) Regulations
40 CFR 700-799 Toxic Substances Control Act (TSCA) Regulations
710 Inventory Reporting Requirements
720 Premanufacture Notice
721 Significant New Use of Chemical Substances
722 Premanufacture Notice Exemptions

*Citations include some sections reserved for future regulations.

Chapter 10.1
Total Protective Coatings Programs

Richard W. Drisko and James F. Jenkins

Introduction

This chapter describes how to prepare and manage a total protective coatings program for an industrial or government activity. The program can be implemented using in-house or contract services. The choice of in-house or contract personnel will depend on the particular type of organizational management. The goals of such a program include:

- Most economically maintaining assets of activity in operating condition
- Minimizing operational down time and subsequent loss of productivity for repair or replacement of deteriorated components
- Meeting all health, safety, and economical requirements
- Providing a working environment for good productivity

Four basic steps must be taken to initiate and implement a total protective coatings program:

- Obtaining continuing management financial support
- Designing facilities and protective systems for minimizing long-term costs
- Periodic monitoring of conditions of facilities and protective systems
- Maintaining protective systems in a systematically programmed manner based upon the condition data

A total protective coatings program must also include other appropriate methods of deterioration control that can effectively supplement the protective coatings program. Thus, such considerations as design, including material selection, cathodic protection, and altering the environment can often be used to work in conjunction with protective coatings to provide a longer-lasting, more economical total protective program.

Background

A total protective coatings program can be defined as a systematic process of establishing:

- How effectively are structures and equipment currently being protected?
- What actions and costs are currently required to upgrade and/or maintain the desired levels of protection?
- What maintenance actions and costs can be expected in the next few years?
- Precisely what materials and methods should be used for these maintenance actions?
- How can these actions be combined or scheduled to reduce costs?
- Who should be responsible for each action?
- What coordination is needed with other scheduled actions by the organization?

By utilizing a well planned and executed protective coatings program, plant facilities can be protected in the most economical manner. Health and safety needs and worker morale will also be addressed. The total protective program can best be utilized by a computer program that incorporates a database containing:

- Initial designs of structures and equipment and their subsequent modifications
- An initial detailed survey of conditions of structures, equipment, and their coatings and scheduled (e.g., annually) reinspection to note (1) changes that have occurred in the original construction and (2) present conditions.
- Corrective actions to be taken for different types and levels of deterioration
- Specific materials and methods to be used for these actions
- Prioritizing these actions
- Scheduling these actions
- Requesting funding prior to actual need

The economics of corrosion control is discussed in Reference 1. Specifying and managing protective coating projects are described in Reference 2.

Selling the Program to Management

All programs for long-term, economical protection of plant facilities require continuing management support. The presentation must convince management that systematic use of new engineered materials and methods will result in much financial reward, as compared to the present approach. It will include the following important items:

- A review of the presently used coating and other protective systems
- A review of past costs for protection of facilities by coatings
- Proposed new technologies for reducing costs, extending life of protection, meeting governmental regulations, and protecting workers and property
- Aesthetics and associated effects on worker morale and productivity
- A request for continuing management support and budgeting to meet annual needs as determined from periodic condition surveys

Management is more responsive to budgeting for specific out-year requests for funding as determined from condition surveys and past experience than merely allocating funds for use, as required. Economic considerations must be stressed.

Design Facilities for Protection and Maintenance

Ideally, programmed painting is initiated with a new plant so that design of its structures and equipment can be considered for both initial and maintenance painting. Then, as modifications are made to structures and equipment, they are designed to fit into the program.

More often, a protective coatings program is set up for existing facilities with different protective designs and various degrees of deterioration. In such cases, it is necessary to:

- Conduct a thorough survey of all structural and equipment components to determine (1) their conditions and the conditions of their coatings and (2) what actions must be taken to bring them up to acceptable conditions.
- Review the existing designs of structures and equipment in the program to determine how they can be modified to reduce deterioration and/or simplify maintenance before initiation of the program.

The following structural designs should be avoided:

- Incompatible materials/systems
- Contact of dissimilar metals
- Water traps
- Crevices
- Difficult-to coat components (bolted seams, sharp edges, etc.)
- Inadequate access for maintenance

In new construction or modification of existing construction, newer, alternative materials may be available that will provide more effective protection than more traditional materials. Some of the building materials that may be used more effectively, with or without coatings, than more traditional materials in very corrosive or other unique environments include:

- Corrosion-resistant metals and platings
- Plastics
- Composites
- Ceramics

Also, new high-performance materials coating systems are available to provide longer, more-economical periods of protection. While they meet all present and anticipated governmental requirements, care must be exercised to ensure that they are compatible with existing coating systems when overcoating is required.[3]

Identification of Existing Coating and Other Corrosion Control Systems

Before initiating the protective coatings program, all structures and equipment in the program, as well as their components and corrosion protection systems must be completely identified. Corrosion protection systems may include coatings, corrosion-resistant materials, cathodic protection, environmental control, or other types of systems. In all cases, all appropriate drawings, operating manuals, and specifications should be included in the total program package.

It is essential to identify the generic type of the finish coat of the existing coating system in order to select a compatible maintenance coating to be applied over it. If this information is not available from records, identification by field sampling must be done.

The most precise method of identification of the generic type of an organic finish coat is to submit a small sample of the cleaned (washed and dried) finish

coat to a laboratory for infrared analysis of the binder. The cleaned surface coating can be removed by light sanding and analyzed in a potassium bromide disc.[4]

An even simpler sampling procedure was reported at SSPC '96.[5] The finish coat is lightly sanded with a piece of silicon carbide sandpaper glued to a wooden disc cut from a doweling. The disc is cut to fit directly in a Fourier Transform infrared (FTIR) spectrophotometer so that a diffuse reflectance spectrum can be made. Because silicon carbide is transparent in infrared light, it did not interfere with the coating spectrum. Since organic coatings slowly oxidize in sunlight, their spectra have an increased amount of oxidation (e.g., carbonyl groups) as compared to the same unexposed coatings.[4]

There are simple methods of chemical identification of organic coating resins as described in Reference 6. Identification of exterior epoxy coatings can be verified by their heavy chalking.

Thermoplastic coatings can be distinguished from thermosetting coatings by a simple methyl ethyl ketone (MEK) rub test.[5] Thermoplastic coatings are soluble but thermosetting coatings are not. Alkyds and other coatings that cure by chemical reaction of drying oils with oxygen in the air are initially relatively soluble in MEK but become more insoluble as they increase in molecular weight by continuous cross-linking.

Besides establishing the identity of the finish coat, testing must also establish whether the total coating system contains lead or other toxic constituents.[7] If these are present in significant quantity, special containment, collection, and disposal procedures may be required for generated toxic debris.

Selection of Coating Systems

Initial Coating System

Care must be taken to select the best available coating system for each facility in an industrial plant. It is wise to coat as many of the facilities as appropriate with the same coating system to permit more economical future maintenance. The following factors should be taken into account in selection of the initial coating system:

Long-Term Performance in Specific Environment and Service. Each environment in which coating protection is desired is unique unto itself. Thus, coating systems that have performed well in this environment before should be considered for use again.

Long-Term Economics. Long-term economics is always an important factor in coating selection.

Conformance to All Existing and Anticipated Governmental Regulations. All coatings selected must meet present government regulations for the intended use. Also, all should meet scheduled or anticipated future regulations such as those related to VOC content.

Present and Future Availability. The selected coating system should not only be available at the present time but also in the future, so that repairs can be made to the system as it deteriorates. Availability may not only be affected by governmental regulations but also by availability of raw materials.

Ease of Application/Need for Skilled Applicator. It is desirable to select a coating system that is relatively easy to apply. With some newer coating (e.g., high solids) and application (e.g., plural component) systems, applicators with specialized training are necessary.

Ease of Repair. Ease of repair is desired because maintenance actions will be required as the system deteriorates. Repairs are usually made with the same coating system or a system of the same generic type because they will be compatible with the initial system.

Field Assistance from Coating Manufacturer. It is wise to select a coating system that is recommended for the particular service with all coats from the same manufacturer. It is also wise to select a manufacturer who provides field assistance in the application of a coating system.

Later Overcoating

As stated previously, deteriorated coatings are usually repaired with the initial or a similar compatible system. One exception is the repair of systems with inorganic zinc-rich primers. Organic zinc-rich primers are normally used for repairs involving overcoating of inorganic zinc-rich primer because inorganic zinc-rich primers do not usually bond well to themselves or to organic coatings.

Overcoats do not normally bond well to aged thermosetting coatings because they are not softened

or penetrated by topcoat solvent. In such cases, the recommendations of the coating manufacture should be followed. Common recommendations include sweep blasting the existing system and use of tie coats.

It may be desirable to upgrade the performance or resistance of an existing coating system with a system that is normally incompatible. Universal primers or tie coats can often be used for this purpose.

Periodic Inspection of Facilities

Structures

Each structure and piece of equipment in the program should be inspected periodically (e.g, annually, as done by the military and some highway agencies) by qualified personnel. Special items should be inspected on a more frequent basis. Large structures such as buildings should be broken down into smaller areas (e.g., sides of buildings) for inspections. Some buildings may require maintenance action only on the side exposed to the most severe environment.

The periodic inspections should be performed according to established procedures and recorded on standard forms, so that the condition of each inspected structure can be followed over the life of the facility and can be compared to the condition of other structures in the facility. This will enable the corrective actions to be prioritized and/or grouped regularly to record current conditions. During periodic inspections, all information pertinent to the facility owner/operator should be recorded. In addition, an estimate should be made as to when corrective actions should be taken. All leaks and other deficiencies detected that require immediate attention should be addressed first. Others will be addressed according to priorities.

Protective Coatings and Substrates

During periodic inspections, the type and extent of coating and substrate deterioration should be determined. The extent of coating deterioration should also be determined. This includes both the severity of the deterioration and its distribution. It is often necessary to define the amount of loose peeling paint in order for specification writers to estimate the amount of repair areas to be addressed. Loose peeling paint is defined as any paint that is easily removed with a dull putty knife.

If the distribution of coating deterioration is localized, spot repairs may be adequate. If distribution is extensive, then total removal and recoating may be necessary. Standard block diagrams for estimating coating deterioration on ships are described in Reference 8. They are usually adaptable to most fixed structures.

During periodic inspections, the type and extent of substrate deterioration (e.g., rusting) should also be determined. Substrate deterioration is often best defined through written commentary. However, comparison with a visual standard such as SSPC-VIS 2[9]/ASTM D 610 can be helpful in quantifying the extent of rusting of coated surfaces.[10]

Cathodic Protection Systems

All impressed-current cathodic protection rectifiers should be checked monthly. All of these voltage and current outputs should be recorded. Structure-to-electrolyte potentials of both impressed-current and galvanic cathodic protection systems should be recorded at least annually, and all exposed connections should be checked for tightness. Potentials should be above –0.85 volts (with respect to a copper/copper sulfate reference half-cell), but not above –1.0 volt to prevent accelerated coating deterioration. If this is not the case, corrective actions must be taken.

Corrosion-Resistant Materials

The condition of special corrosion-resistant materials should be recorded separately. Any coating or other necessary remedial actions must be taken separately from those for conventional steel.

Maintenance of Facilities

During each periodic inspection (which may be annually or more frequently, if necessary) immediate and future maintenance requirements should be noted. These data will be used by the program manager to arrange for procurement of necessary materials and scheduling of necessary maintenance actions. The program manager should group the similar maintenance actions to be taken on different structures and equipment and coordinate them to result in minimum expense and down time. In the event of limited funding, prioritizing the work will ensure that the critical repairs are made first.

As stated earlier, the program database will contain recommended maintenance schedules and

standard procedures to correct deficiencies. These schedules and procedures should be reviewed by the corrosion engineer. Depending on the maintenance requirements, SSPC Paint Application Guide No. 5 may be used as a guide for maintenance painting procedures.[11] However, in all cases, the procedures should be reviewed by corrosion engineers or coating specialists to determine what modifications may be necessary to meet special requirements.

Protective Coatings

Maintenance painting is described in a separate chapter.

Deteriorated Structural Components

Deteriorated components should be replaced or rehabilitated before they become significant structural, operational, or safety problems. Delays in replacement may result in more costly damage.

Management and Execution of Program

Whether maintenance work is accomplished by in-house or contract personnel, or by a combination of the two, the specification for the maintenance work should be written or reviewed by a specialist available in each of the different corrosion control method being affected. Even small jobs require thorough planning, thorough and accurate cost estimates, and development of work progress schedules to complete the work satisfactorily, on time, and within budget. Scheduling and estimating can be simplified by the use of standard forms and charts. Scheduling must take into account the work being done simultaneously by other trades.

Summary

A total protective coatings program for industrial facilities involves design, monitoring, and maintenance of the facilities and protective systems. A systematic process must be used to determine when preventive actions are required, what actions are required, and how those actions are to be performed and coordinated. Cost comparisons are a vital part of programmed corrosion control. Programmed corrosion control has the following advantages:

- Life-cycle cost savings
- Long-term protection of valuable assets
- Reduction of operational down time
- Easier procurement of necessary funding

A total protective coatings program requires that all structures and pieces of equipment and all protective systems in the program to be inspected periodically for condition. This includes protective coatings and substrates, cathodic protection systems, and corrosion-resistant materials. Programmed corrosion control also calls for a maintenance plan. For protective coatings, there are various levels of maintenance. Maintenance procedures for cathodic protection systems and deteriorated components should also be included.

When preparing a corrosion control program for an existing facility, surveys of existing structures and equipment are necessary to determine maintenance requirements and any requirements for modification of the design. Existing coatings and other corrosion protection systems must also be identified.

References

1. Economics of Corrosion Control. In *Corrosion and Coatings;* Drisko, Richard W. and Jenkins, James F. SSPC: Pittsburgh, 1998.
2. *C-2: Specifying and Managing Corrosion Projects;* SSPC: Pittsburgh, 2001.
3. SSPC-TU 3. *Overcoating;* SSPC: Pittsburgh, 1997.
4. Drisko, Richard W.; Crilly, Joseph B. Identification of Weathered Paints by Infrared Spectroscopy. *Materials Performance*, NACE: Houston, December 1972, pp 49-51.
5. Drisko, Richard W. Total Protective Coatings Program. In *Proceedings of SSPC '96.*
6. Vind, Harold P.; Drisko, Richard W. Field Identification of Weathered Paints. *Materials Performance*, NACE: Houston, October 1973, pp 18-21.
7. Trimber, Kenneth A. Hazardous Waste: Testing, Handling, Disposal, and Releases. In *Industrial Lead Removal Handbook;* SSPC: Pittsburgh, 1991.
8. ASTM F 1130. *Practice for Inspecting the Coating System of a Ship;* ASTM: West Conshohocken, PA.
9. SSPC-VIS 2. *Standard Method of Evaluating Degree of Rusting on Painted Steel Surfaces;* SSPC: Pittsburgh.
10. ASTM D 610. *Standard Test Method for Evaluating Degree of Rusting on Painted Steel Surfaces;* ASTM: West Conshohocken, PA.
11. SSPC Paint Application Guide No. 5. *Guide to Maintenance Painting Programs; Steel Structures Painting Manual: Volume 2; Systems and Specifications, 7th Edition;* SSPC: Pittsburgh, 2000.

About the Authors

Dr. Richard W. Drisko

Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society for Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy's center of expertise on coatings for shore structures. He is a professional engineer in the state of California, an SSPC certified protective coatings specialist (PCS), and a NACE International certificated corrosion specialist. Dr. Drisko received his BS, MS, and PhD degrees from Stanford.

James F. Jenkins

James F. Jenkins retired in 1995 after 30 years of service to the U.S. Navy in corrosion control for shore and ocean-based facilities. Now a consultant, he is a registered corrosion engineer in the state of California. Mr. Jenkins received his BS degree in metallurgical engineering from the University of Arizona.

Chapter 10.2
Comparative Painting Costs

L. Brian Castler, Jayson L. Helsel, Michael F. MeLampy, and Eric Kline

Introduction

Protective coatings and linings are used primarily to preserve the life of facilities and structures constructed of steel, concrete, or other substrates. Increasing the life of these structures is one of the primary economic reasons for applying protective coatings and linings. Other reasons include but are not limited to aesthetics, washability, improved visibility, surface leveling, and creating electrical barriers. Painting costs should be considered in terms of both a first cost and life cycle cost, with attention to design life of the substrate structure. Life cycle costs are heavily dependant on estimating technique and longevity or durability of the coating material to provide corrosion prevention and protection. The amount of coating breakdown and corrosion allowed prior to maintenance painting can be highly subjective and dependant on short- and long-term budgeting and cash flow issues with the owner.

This chapter is divided into three distinct but related topics: general estimating issues, comparative life cycle costing, and contract mechanisms. The purpose of this chapter is to provide the coatings specifier with an overview of these three important topics as each can significantly lead to the success or failure of a long-term economic protective coatings and lining program.

General estimating issues are briefly discussed as an introduction to the issues that can drive costs. The contractor or coatings applicator needs to have an estimating system for determining potential costs for a specific project so proper bid prices and budgets can be prepared effectively. It should be noted that this chapter makes no attempt at meeting specific estimating needs for use on an actual project. Finally, a brief look at painting costs over time will provide the reader with a view of basic cost trends in recent years.

Life cycle costing focuses on comparisons of one generic coating system versus another. Comparing these “apples and oranges” is always a difficult process and often a primary concern of a specifier. A portion of this chapter will provide information on how a specifier can compare coating systems from a life-cycle cost approach. The estimated usable life of numerous generic coating systems is provided along with simple relative cost estimating tools. The basic information provides a guide for the specifier to use and embellish with historical and proprietary information regarding specific coating systems. It should be noted that because all generic coatings are not equivalent, all ambient environments are not alike, and all work forces are not equal, these tools should not be used to develop actual job estimates.

Contract mechanisms are an integral component of overall cost controls for a project and the predominate types are reviewed. Implied and specific guarantee and warranty requirements can also have a dramatic effect on costs.

Elements Of Field Painting Costs

When selecting paint or a protective coating system, a study of comparative costs is usually made. Typical choices involve generic types of coating, number of coats, shop or field application, and surface preparation methods.

The cost of coating projects is dependent on the condition of the substrate, geographic location, accessibility, size of the project, site conditions, specification requirements, and other factors. In almost every case each coating project is unique and should be treated as such. Adding to the difficulty is the constantly changing cost of labor, equipment, and materials. A coating system considered too expensive today might become economically attractive in the future if a technological improvement reduces the required labor.

One method for evaluating a coating system is to secure a detailed analysis and cost estimate from an experienced coatings estimator such as a painting contractor. In this manner, specifics of the particular job can be dealt with, and the estimate will reflect practical real world aspects that might otherwise be missed.

The cost of each comparative potential project

should be considered on a total project basis rather than a per square foot basis for several reasons. First, the magnitude of the work can be recognized and reflected in the "total project" cost estimate. Second, while certain aspects of the work are better evaluated on a square foot basis, others are better evaluated on a whole project basis. Different surfaces will often have different costs per square foot (structural steel, tanks, piping, valves, etc.). Certain elements of the estimate such as productive labor operations (abrasive blasting, coating application, etc.) lend themselves to a square footage basis for production rates. However, support operations and equipment are generally expressed in terms of productive labor requirements (e.g., one pot tender for every two "productive" workers during the abrasive blasting and priming operation). And finally, some operations are most appropriately expressed in terms of the total project, such as mobilization, demobilization, worker health and safety, rigging, and similar operations.

This chapter and the information provided is not applicable for actual job estimating or costing, but is provided as a basis for discussion. Seek the help of a professional estimator for actual project estimating or seek more thorough estimating tools available from various industry groups.

Elements Of Costs

Labor. Labor should be estimated on a person-hour or person-day basis for the project based upon the operations performed. Typically, these include cleaning, abrasive blasting, application of each coat of paint, pot tending (for abrasive blasting), rigging, general labor such as removing spent abrasive, and supervision. Productive operations are calculated on the basis of labor production rates applied to each type of surface involved. Surface types might include large structural shapes, small structural shapes, miscellaneous steel (handrails, ladders, etc.), piping, valves, equipment, vessels, and so forth. The following is a description of typical labor categories:

• **Pot Tender—**Assists abrasive blasting operators to adjust abrasive blasting pots, regulate pots, and may assist priming operations.

• **Abrasive Handlers—**Handle spent abrasive when required. Most frequently, abrasive handlers are used to remove the abrasive from inside a vessel or from the immediate work area.

• **Helpers—**Number varies with the requirements of the project. Helpers may be used to mix paints, move and clean equipment, and assist in rigging.

• **Riggers—**Riggers deploy, place, and remove equipment, enabling workers to gain access to surfaces to be cleaned and coated. This normally includes hanging suspension scaffolding, erecting scaffolding, etc.

• **Supervisors—**Field supervision. This is normally estimated based on the number of crew days and corresponding number of supervisors required.

• **Competent Person—**Staff that is competent in hazardous paint removal operations, scaffolding, and other areas involving safety. May perform other work that does not interfere with Competent Person duties.

• **Quality Control Inspector—**Staff that ensures that specifications are met and that the quality goals of the contractor are achieved. May perform other duties unrelated to production (e.g., serve as Competent Person).

• **Blaster and Painter—**Staff that is performing actual production work.

Once the person-hours for each labor operation are determined, the labor cost can be found by multiplying the person-hours by the hourly rate for each classification of worker. These rates include direct variable cost, labor cost, and labor-related overhead plus a fixed overhead charge. Labor cost is the sum of wages, fringe benefits, travel pay, and subsistence.

Companies differ in how they handle fees on labor and the other components of the total system cost. One method is to apply only payroll taxes, insurance, small tools, and expendables to the labor cost. Labor cost is then accumulated with equipment and material cost, and profit and overhead is applied to all of it as a group. Other firms consider payroll taxes and insurance as part of labor cost instead of fees, but the difference in methods is not significant for the purpose of comparison. Regardless of the

approach used, there may be a difference in wages paid to skilled and unskilled labor, and prevailing wage provisions must be followed.

Equipment. Equipment required for individual jobs varies with type of job, size and configuration of the structures, type of surface preparation, type of coating materials, etc. Following is a description of typical operations and the equipment required.

• **Abrasive Blasting Equipment and Air Supply—** Compressed air for abrasive blasting is determined by the nozzle size and other factors, figuring 350-450 ft.^{3}/min (CFM) per nozzle for a typical job. Blast pots, hose, nozzles, and helmets (with appropriate air line and filters) also need to be included.

• **Conventional Spraying—**Spray pots are estimated as required; the larger pots can handle two spray guns. If compressed air is not otherwise available, a small compressor may be needed.

• **Airless Spraying—**Production sized units can normally handle two guns unless the material is highly viscous or other circumstances warrant. A power source (electrical or compressed air) is required.

• **General—**Consider pickup or larger trucks to haul workers, equipment, and material Additionally, the project may require rigging, lifts, scaffolds, or similar items. Office trailers, change rooms, storage rooms, and sanitary facilities may also be required.

• **Containment and Ventilation—**Equipment necessary to protect workers and the environment from hazardous materials and nuisance dust, including containment materials and dust collection equipment. Ambient air monitors and other environmental compliance sampling and testing equipment may also be necessary.

• **Access Equipment—**All necessary equipment to access the work area, such as lifts, boats, and barges.

• **Safety Equipment—**All necessary equipment to protect workers and public, such as confined space equipment, respirators, traffic control devices, and fall protection equipment.

The cost of equipment is based on the number of days each piece of equipment is used, estimated using reasonable rental rates. Even if the firm owns the equipment, it should recognize that there were costs associated with its purchase and allow for recovering the investment in that equipment.

Supplies associated with rental equipment are either allowed for in the rental rates or are themselves rental items. Local rental firms or published sources can be used to determine rental rates. Rental rates are normally based upon continuous charge during the possession of the equipment on 5-day, 40-hour weeks. The renter normally furnishes fuel and the operator.

Materials.

• **Abrasives—**The cost is figured by applying consumption rate to the estimated number of abrasive blasting person-hours or person-days. For abrasives such as sand, slag, and many minerals, one-quarter to one-half ton is used per hour. Higher consumption rates would be expected on large jobs with continuous operating bulk equipment. The cost of abrasives can vary greatly and delivery costs may also become a major cost factor. The abrasive supplier should be contacted for a delivered price to the project site to avoid serious errors in the total abrasive cost.

• **Coating Materials—**The quantity of each paint or coating is determined by dividing the surface area to be covered by the practical coverage rate for each coat. The practical coverage is the theoretical coverage less a loss factor, typically 20-30%. The quantity of solvents required for thinning and clean up should also be estimated. Typically this is about 20-30% of the quantity estimated for paint. Freight costs should also be considered

Cost Summary. The costs calculated for labor, equipment, and materials are added together and a fee for overhead and profit applied to determine a total system cost. When considering alternatives, the fee for overhead and profit is not important for determining relative costs. On the other hand, if an owner is considering alternatives involving work by different vendors, differences in fees might become significant.

Painting Costs Over Time

Differences in painting costs between projects can be difficult to ascertain given that each project is

Table 1.

Connecticut Department of Transportation Cleaning & Painting Costs (Data from Bid Tabulation Sheets US Dollars Per Square Foot)

	1970	1985	1987	1988	1990*	1992**	1993	1994	1995	1996	1997	1998	1999	2000	2001
Containment					0.98	6.44	4.36	5.94	3.97	5.02	3.64	5.50	3.84	5.80	7.13
Blast Clean & Paint	0.12	0.80	1.65	1.65	3.84	5.28	5.75	3.28	5.38	4.44	3.06	3.76	3.94	4.84	5.62
Disposal					1.20	0.35	0.14	0.05	0.15	0.33	0.27	0.01	0.07	0.18	0.16
Sub Total	0.12	0.80	1.65	1.65	6.02	12.07	10.25	9.27	9.50	9.79	6.97	9.27	7.85	10.82	12.91
Lead Health & Safety							2.14	2.92	1.96	0.82	0.93	0.92	0.92	1.01	0.96
Total	0.12	0.80	1.65	1.65	6.02	12.07	12.39	12.19	11.46	10.61	7.90	10.19	8.77	11.83	13.87
% CPI Inflation	100%	277%	293%	305%	337%	362%	372%	382%	393%	404%	414%	420%	429%	444%	456%

* 75% Containment
** 100% Containment

unique in scope. A tank or bridge coating project performed one year can be different from a similar project performed the following year. Variations can include differing site conditions, differing labor costs and availability, differing project specifications and coating systems, differing quality expectations and warranty requirements, differing time of year, and differing numbers of projects available for contractors to bid on. As such, a study of cost trends is a difficult and ambitious endeavor.

Regulatory changes can have a major effect on costs and can drastically alter trends by increasing them significantly. One such recent event involved the lead-related worker safety regulations that went into effect in the United States during the 1992 and 1993 construction seasons. Costs easily doubled overnight as contractors suddenly had additional and significant capital equipment expenses and worker training requirements. The effect was so great that many ongoing projects and infrastructure preservation programs came to a halt. It took several years for some programs to get back on track as related costs of these regulations had to be absorbed. Many owners took a “wait-and-see” approach, hoping that costs would once again become reasonable.

On the positive side, many of the new high-performance coating systems that were developed to replace lead based coatings are providing longer structure preservation and improved aesthetics. High-performance coating systems and related application techniques will outlast the working careers of specifiers and applicators, and should be tracked to provide for future cost benefit analysis.

Connecticut State Department of Transportation (CDOT) is one such owner that has monitored contract blast cleaning and painting costs for several years. Records exist back to 1970 when blast cleaning and painting projects were contracted for twelve cents (U.S. $0.12) per square foot. The next available cost records indicate that contract project costs increased to U.S. $0.80 per square foot during 1985. Inflation, as determined using the Consumer Price Index (CPI) increased 277% during this period. Given this information, U.S. $0.12 in 1970 would only equal U.S. $0.275 in 1985, showing that real costs, in fact, increased nearly three times. Blast cleaning, coating application, material, and safety costs continued to increase throughout these years.

Significant regulatory changes occurred in the early 1990s, which altered costs appreciably. CDOT has tracked costs over the years by monitoring bid tally sheets for blast cleaning and painting projects and the blast cleaning and painting portions of rehabilitation projects. Data is presented in **Table 1.** This data does not take into account the size of the job, location, coating system specification, or other pertinent information. However, CDOT has used similar coating specifications with only minor revisions and updates, and has had many ongoing projects throughout the years, both large and small. All have been contracted within a relatively small state with generally the same climatic seasons, and CDOT has always provided for a consistent effort in ensuring specification compliance. Projects bid during 1992 were significantly higher than those bid in 1991 and earlier. Costs in 1991 averaged U.S. $6.02 while costs in 1992 were U.S. $12.07.

The remainder of this section will discuss CDOT costs during 1992 through 2001, where a

consistent approach toward cleaning and painting was achieved. Information on two data trends will be analyzed, blasting and painting costs and those of the total project, not including such costs as traffic control and other important costs unrelated to surface preparation and coating application efforts.

Figure 1 provides yearly average total project costs in dollars per square foot. Total project costs include containment, blasting and painting, disposimg of waste, and worker and environmental lead health and safety. Additionally, these same project costs are corrected for inflation (second bar). Yearly inflation for the purposes of this chapter are per the Consumer Price Index, (CPI) as provided by the U.S. Department of Labor Bureau of Labor Statistics for all urban consumers, U.S. city average, dated 2/20/2002. Note that in terms of actual dollars and, more dramatically, in terms of actual costs corrected for inflation, there is a downward trend in costs. The "corrected for inflation" data equates all costs to 1992 equivalent costs. The linear trend lines as provided on the charts do not make good predictors of future values but are interesting. Other series analysis and prediction tools might be employed to predict future costs, but this is outside the scope of this chapter. The downward trend of these lines seems to indicate that contractors generally have determined how to meet the requirements of the regulations and provide surface preparation and coating application in accordance with the specification. Possibly, contractors in general are not feeling the need for extensive contingency planning and funds as may have been required during the early 1990s. Other possible explanations include more competition and other macro-economic and micro-economic issues.

Figure 2 provides the same basic information as Figure 1, except it includes only the costs bid for blast cleaning and painting. These data points exclude regulation driven containment, disposal, and worker lead health and safety issues. That being stated, the divisions of costs on bid tally sheets may not be scientific and costs may be allocated to the wrong bid category. The general increase in these costs from 1988 through 1992 (only started tracking in 1990 as a separate item, see Table 1) may be attributable to newer increased efforts in surface preparation requirements and newer high-performance coatings. Note that the same downward trend in costs appears for the data collected from 1992 through 2001. Additionally, there seems to be a greater variability in the data provided (note the data for 1994 and 1997).

Drawing any correlations from the provided data is not of value since the data is limited in nature and there are many possible sources or unevaluated causes that may alter these costs. Even given the general downward trend of costs in both Figures 1 and 2 over the last nine years, there seems to be a short-term trend where costs are increasing during the last three or so years. However, real costs are still lower given the correction for inflation. As cleaning and painting operations progress into the future, other considerations may affect costs such as, but not limited to, contracting mechanisms, warranty requirements, regulations such as pollution and volatile organic compound limits, and additional safety measures for the workers and the public.

Cost Factors in Coating Selection

Identifying and justifying acceptable paint and protective coating systems for a given environment is difficult, and often neglected. If the project is a new plant, specifications often call for hand (SSPC-SP 2) or power-tool (SSPC-SP 3) cleaning, a shop primer, and one or two topcoats of alkyd applied at the job site. Sometimes an old specification from a previous job is simply pulled from the file, renamed, and used on the current job without consideration of whether or not it is acceptable in the new environment.

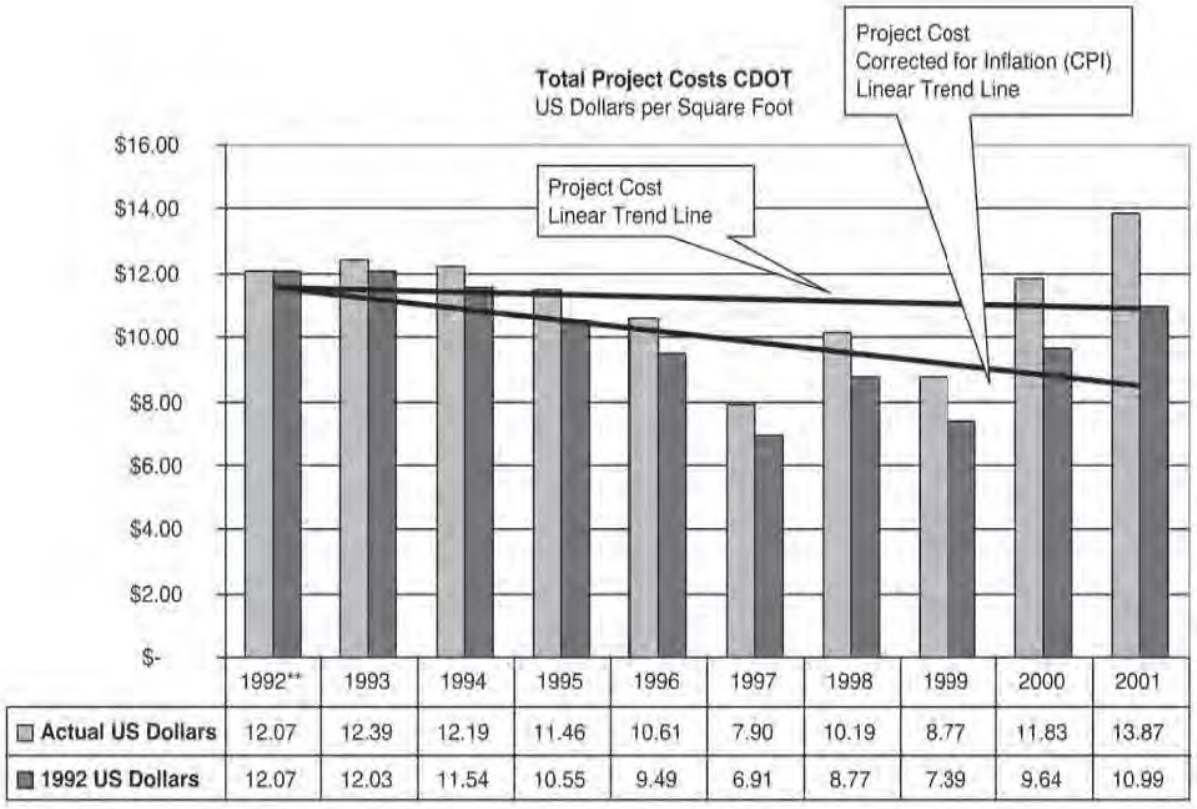
Frequently, the coatings engineer is nonexclusive and has other areas of responsibility. Paint and coating selection cost estimates and justification for new construction or maintenance can be a confusing and difficult task for the nonexclusive coatings engineer.

The purpose of this comparative cost guide is to help coating engineers understand basic cost elements, demonstrate how to calculate approximate applied costs, and outline procedures for arriving at a reasoned coating selection based on fact with supportable detail.

It must be emphasized that this cost guide is just that—a guide. It is not intended as an infallible or absolute cost source. It is not meant for use in calculating actual job costs, nor as a tool for negotiating with contractors and fabricators.

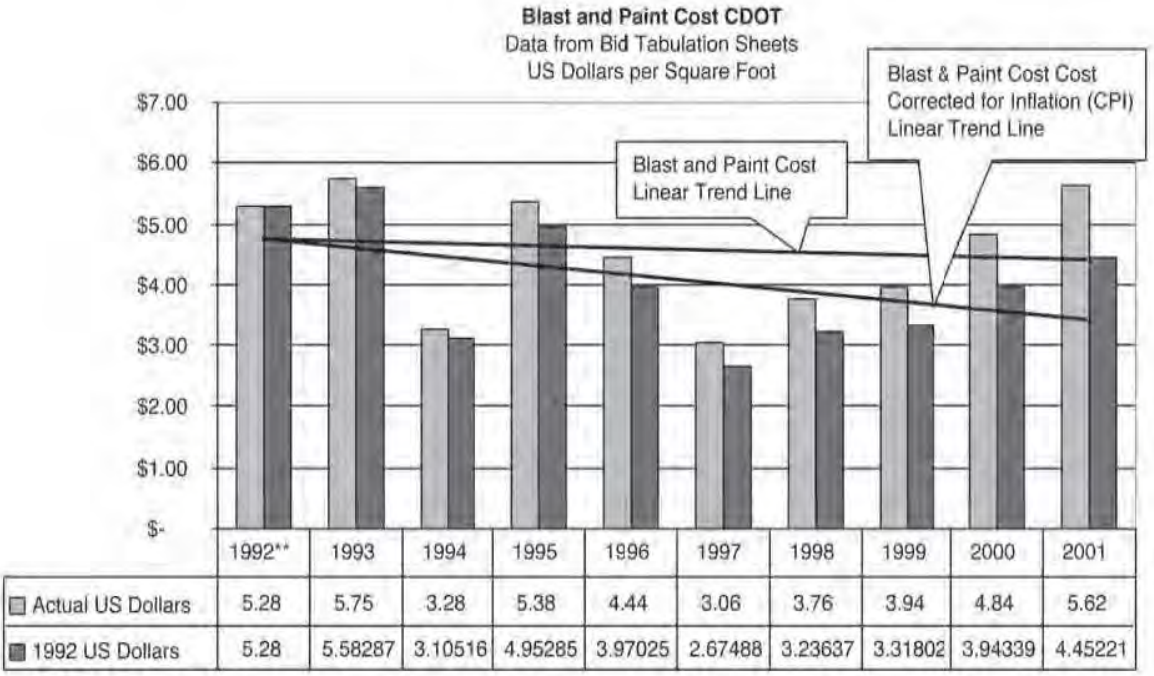
The cost guide provides the specifier with a simplified means of calculating total applied costs based on current materials, cleaning, and application costs. The cost information has been developed and

Figure 1.



	1992**	1993	1994	1995	1996	1997	1998	1999	2000	2001
Actual US Dollars	12.07	12.39	12.19	11.46	10.61	7.90	10.19	8.77	11.83	13.87
1992 US Dollars	12.07	12.03	11.54	10.55	9.49	6.91	8.77	7.39	9.64	10.99

Figure 2.



	1992**	1993	1994	1995	1996	1997	1998	1999	2000	2001
Actual US Dollars	5.28	5.75	3.28	5.38	4.44	3.06	3.76	3.94	4.84	5.62
1992 US Dollars	5.28	5.58287	3.10516	4.95285	3.97025	2.67488	3.23637	3.31802	3.94339	4.45221

supplied by representative contractor applicators and coating material suppliers. The base cost produced by the guide is for structural steel on the ground at the job site, with costs for jobsite touch-up if shop priming is considered. Percentage factors also are included to account for complex or elevated structures.

The cost guide provides specifying engineers with a method to help identify candidate systems for a given environment. It establishes a procedure for calculating approximate applied costs and for estimating expected service life and cost per year for each proposed system. The use of the guide facilitates comparison, selection, and justification of a suitable system.

Preliminary Cost Issues

Some common questions, factors, and influences that the specifying engineer will encounter are discussed here.

Why Attempt Cost Calculations?

• We live in a world of costs, numbers, and "justification." Decisions on most matters and materials are made on the basis of cost savings and economics. To make good selections, and have them accepted by management, the specifying engineer needs to include an economic analysis.

Why Paint at All?

• Unfortunately, without a protective coating, steel rusts and corrodes at varying rates depending on the service environment and/or climate. An alternative to painting is to specify heavier steel members to compensate for corrosion loss. Specific calculations need to be made to determine the economic advantage of paint versus thicker substrate material. Specifically the specifier would need to evaluate the effects of uniform and non-uniform (pitting) corrosion given the various long and short term, and expected and unexpected, ambient environments that may be in contact with the structure.

• Aesthetics are an important reason to paint. Structures simply look better when painted. While some people discount painting for appearance, it is in fact, an important consideration in many cases.

Importance of Initial Painting

• Once a structure is in operation, it is sometimes impractical, if not impossible, to do an adequate maintenance painting job. In most cases, the original painting is the only time in the life of the structure when the job can be done effectively and economically. Therefore, the initial coating selection is of critical importance.

Design For Total Structure Life

• Whether for new construction or maintenance, the coatings engineer should consider the total cost and number of maintenance paintings required for the design or total life of the structure. If the design life is three years, a coating system should be selected that will last only that long. However, if the design life is 20 years, a long-life system requiring a minimum number of maintenance paintings makes sense. To be cost-effective the immediate painting must be evaluated from both a short-term, immediate economic viewpoint as well as the long-term, total-structure-life viewpoint.

Why Blast Clean?

• Blast cleaning is a practical and effective means of cleaning the surface. It removes mill scale and creates an anchor pattern or profile, which can be essential for good paint adhesion.

Field vs. Shop Blast Cleaning and Prime Coating

• On new construction, shop blast cleaning appears to be lower in cost than field blast cleaning and even less than the cost of hand and/or power-tool cleaning in the field. This assumes that the fabricator uses centrifugal wheel-blast cleaning equipment.

• Another important factor is that blast cleaning and prime coating in the shop allows the application of a suitable protective coating system where application generally occurs on the ground and is easier, spray loss is reduced, and personal safety enhanced. Job-site conflicts, scheduling difficulties, and associated activities are reduced or eliminated.

• Selection of abrasion-resistant primers, such as inorganic zinc, plus use of wood dunnage for shipping, should be included to reduce in-transit damage and job-site touch up.

More Than One Coat In the Shop?

• Painting can be better controlled in the fabricator's

shop than at the job site. The entire coating system can be applied in the shop. When it is impractical to apply coatings in the field, such as an expansion of an operating facility in a highly corrosive environment, total shop application is desirable. On a practical basis though, it must be recognized that touching up the final coat after structure erection is needed, and the touch up will likely not blend into the shop-applied finish so as to be imperceptible.

Galvanizing vs. Zinc Rich Coatings

• Zinc coatings, which provide galvanic protection to steel by preferentially corroding, offer an alternative to conventional protective coatings. Galvanizing, usually a hot dip process, is limited to shop installation with restrictions on the size of members to be galvanized. Zinc-rich coatings can be shop or field applied and usually serve as the primer in a multi-coat system. Service life data suggests that zinc-rich coatings may have a shorter service life compared to the equivalent thickness of zinc galvanizing.

Cost Per Square Foot vs. Per Ton or Total Job Basis

• For system comparison and selection, cost per square foot can be estimated through use of this cost guide.

• To convert to typical painting costs per ton for a typical mix of steel, multiply cost per square foot by 250. For large structural members, use 100 sq.ft.^{2}/ton; for medium 200 sq.ft.^{2}/ton; for light structural, 400 sq.ft.^{2}/ton; and light trusses 500 sq.ft.^{2}/ton.

Delay Topcoating?

• Many new construction projects run over budget, and it is not uncommon for construction managers to search for items that can be delayed until after start-up when maintenance dollars are used instead of capital dollars. U.S. tax classifies maintenance painting as a deductible expense; thus, a delay in topcoating could represent reduced cost. To the uninformed construction manager, delaying topcoat application might appear to be a good idea, but this approach can lead to long-term protection problems.

• If top coating is selected for delay after the specification has been written and priming has been accomplished, problems may ensue. The selected primer may not have been designed for protecting steel for an extended period of time or in the specific environment without a topcoat. The specifying engineer must be aware of this possibility, and if it is likely to occur, a coating system must be selected with a primer that can resist the weather and environment for an extended period. The engineer must also include immediate and adequate touch-up of scars and bolts and thorough cleaning of the primer prior to application of final coats so rusting, undercutting, and poor adhesion between coats will not occur.

Do Prejudices Exist?

• Often the specifying engineer is confronted with

Extending Service Life by Upgrading the Coating System[1]

"Upgrading" refers to the application of an additional barrier coat to increase the protective life of an existing coating system. Choosing to "upgrade" the system may permit an owner to profit by "beneficial procrastination"—postponing total coating removal without the possible consequences of corrosion damage affecting the integrity of the structure. This alternative to a full coating system replacement would likely decrease the life cycle cost of the system. The strategy may also be a way of delaying the costly removal of lead-based paint.

An existing coating system can typically be upgraded at a relatively low cost with one of several generic coating types requiring little surface preparation. The delay might also permit new technology to develop, which in turn should lower the costs associated with paint removal projects in the future. If lead paint removal is at issue, the decreased cost for improved technology may make upgrading and deferred coating system removal particularly attractive.

To determine whether the coating system is a candidate for upgrading, the coatings engineer must evaluate the areas with at most 10% rust in terms of number of coating layers, coating thickness, adhesion characteristics, and the generic type(s) of coatings present. If the coating system exhibits less than 10% deterioration/corrosion, has total thicknessess in the 5 to 20 mil range, and has satisfactory adhesion, the system may be a candidate for applying an upgrade.

1. Kline, E. S.; Corbett, W. D. Beneficial Procrastination: Delaying Lead Paint Removal Projects by Upgrading the Coating System. *Journal of Protective Coatings and Linings*, March 1992.

preferences/prejudices by project/plant personnel or client representatives concerning types of coatings or suppliers (e.g., "can only afford alkyds," or "cannot afford or tolerate blast cleaning," etc.). These prejudices may or may not represent acceptable systems or conditions. They must be included in the analysis, making certain that the recommended system is sound and its selection is based on facts with supporting detail.

Maintenance Procedures

• The typical maintenance painting practice is based on the "practical" life of a coating, defined as the time until 5-10% coating breakdown occurs, active rusting of the substrate occurs, and Rust Grade 4 (SSPC-VIS 2) is present. Normal maintenance repainting cycles include: original painting ("practical" life); spot touch-up at the end of practical life; spot prime and full coat after an additional 25% of practical life; and a full system repaint after an additional 40% of practical system life.

• **Table 2** illustrates the "practical" maintenance painting sequence and estimates the cost of each painting operation depending on whether the initial painting occurred in the shop or field. An example of the "practical" approach for selected coating systems is shown in **Table 3.**

Economic Analysis and Justification

• This subject is sometimes misunderstood for paint and coating systems. Capital items require intricate analysis to identify full financial impact. Paint and coating systems are basically expense items without salvage value or depreciation considerations. Relatively few calculations are required to compare one system with another and to measure each system's true cost in comparable dollars reflecting the time value of money. An example of an economic analysis is provided in **Table 4.**

• For each system used or considered, list the timing, number, and cost of painting operations required to protect the structure for its projected life. This should include such items as original painting, touch-ups, maintenance repaintings, and full repaintings. The cost of each painting operation should be calculated in three categories:

1) At current cost levels.

2) At net future value levels (NFV)—current cost with inflation included. How much will it cost, in inflated dollars in the year scheduled?

3) At net present value levels (NPV)—the present worth of the inflated cost (the NFV) in monies today invested at current interest rates.

For example, a current cost of $10 today inflates to $12.76 in five years, assuming 5% inflation; $12.76 is the NFV. The formula for calculating this is:

$$NFV = \text{Current Cost} \times (1 + i)^n$$

(i = inflation, n = years)

To calculate the NPV, or "What the $12.76 is worth today invested at current interest rates (e.g., 10%) for five years?" use the following formula:

$$NPV = NFV \times 1/(1 + i)^n \text{ or } \$7.92$$

$7.92 invested today at 10% for five years = $12.76.

While interest and inflation rates are constantly changing, the decision on coating selection is usually based on current rates. By making these calculations for each system, the true cost and number of painting operations can be compared.

Steps for Calculating an Economic Analysis of a Coating System (See Table 4)

• For each candidate system (use a separate sheet for each), draw a time line for the projected life of the structure.

• For each system, mark on the time line when all painting operations will take place: original painting, touch-up, maintenance repainting, and full repainting. Insert their current costs.

• Using the current inflation rate, calculate and record the NFV for all painting operations.

• Using the current interest rate, calculate and record the NPV (of the NFV) for all painting operations.

• For each system, total the sum of the three categories (current cost, NFV, and NPV).

• Compare these values, particularly NPV, for a direct comparison of each systems' true costs in monies today.

A system may be less expensive to install initially, but if it has a shorter life and requires more frequent repaintings, its financial cost can be measured, and the impact of the repaintings on plant disruptions must be recognized.

Table 2.

Operation	Painting Occurs in Year	Cost if Original in Field	Cost if Original in Shop
Initial Painting	0	Original	Original
Touch-Up	Practical Life or "P"	Original x 40%	Original x 60%
Maintenance Repaint	"P" Life + 33% (i.e. "P" x 1.33)	Original x 70%	Original x 105%
Full Repaint	Year of Maint. Repaint + 50% of "P" Life (i.e. Maint. Repaint Year + ["P" x 0.50])	Original x 135%	Original x 205%

Examples Using Practical Maintenance Sequence
System With 12 Year Practical Life and Original Shop Installed Cost of $1.05 per Square Foot
System With 12 Year Practical Life and Original Field Installed Cost of $1.60 per Square Foot

Operation	Painting Occurs in Year	Cost if Original in Field	Cost if Original in Shop
Initial Painting	0	$1.60	$1.05
Touch-Up	12	$0.64	$0.63
Maintenance Repaint	16	$1.12	$1.10
Full Repaint	22	$2.16	$2.15

Table 3.

Typical System Costs, Life, Cost Per Year, Long-Term Costs, and Number of Paintings over a 35 Year Structure Life, Field Application

System	Surf. Prep.	Practical Maintenance Approach				
		Total Installed Cost			Long-Term Cost	
		Initial Installed Cost	Years Life (Moderate/C3)	Cost/ Year/ft²	No. Ptgs.	Total Cost @ Current Cost Levels
2-coat surf. tolerant epoxy	SP 6	$1.71	12	$0.14	6	$6.07
2-coat surf. tolerant epoxy	SP 3	$1.67	9	$0.19	7	$6.71
1-coat surf. tol. epoxy/polyurethane	SP 6	$1.74	9	$0.19	7	$8.53
1-coat surf. tolerant epoxy	SP 3	$1.22	5	$0.24	14	$11.96

Table 4.

Economic Analysis Worksheet
Total Painting Cost Per Sq. Ft. for 40-Year Plant Life, Field Application
Three-Coat Inorganic Zinc/Epoxy/Polyurethane, SP 6/NACE 3, 15 Year System Life (Severe/C5-I)

Painting Operation	Original Painting	Touch-Up Year 15	Maintenance Repaint Year 20	Full Repaint Year 23	Touch-Up Year 38	Totals
Cost in Current $'s	$2.23	$0.89	$1.56	$3.01	$0.89	$8.59
NFV costs Future value @ 3% inflation	$2.23	$1.39	$2.82	$5.94	$2.74	$15.12
NPV costs Present value @ 7% interest	$2.23	$0.50	$0.73	$1.25	$0.21	$4.93

On new capital projects, coating costs are often capitalized, which will require considerations for depreciation, taxes, etc. These are not necessary for maintenance work. When required, however, the same present value analysis should be conducted to make the coating selection, and the analyses turned over to project management for further financial treatment.

How To Use The Cost Guide

Before proceeding, it is suggested that the reader review the tables and worksheets presented in this section.

Estimated Service Life (Tables 5 and 6)

• How long will the coating system last? The answer depends on the particular user's approach to, and philosophy of, maintenance painting. Is protection alone important, or is appearance a consideration? Is painting viewed as a necessary evil, or is cost-effective protection the approach?

• The guide supplies system life estimates for a "practical" maintenance approach for coating systems in atmospheric exposure **(Table 5)** and immersion service **(Table 6).** The practical life is the time until 5-10% breakdown occurs, active rusting of the substrate occurs, and SSPC VIS 2 Rust Grade 4 is present. These tables have been substantially simplified from the previous version of this chapter; there are fewer service environments and data related to an "ideal" maintenance painting approach has been eliminated due to little actual use of that approach. Table 3 illustrates the typical system costs for a "practical" maintenance approach.

Paint and Coating Materials Costs (See Table 7)

• Material costs for most commonly used generic types of coatings are included in this table. Typical dry film thickness (DFT) per SSPC-PA 2 for each type are shown, as well as theoretical and practical costs.

Shop Painting Costs (See Table 8)

• For steel fabricators with automatic wheel-blasting equipment, **Table 8** gives regional U.S. 1997 costs for cleaning and painting in the shop. Note that costs for hot-dip galvanizing are listed in addition to those for shop paint application. Multipliers are given to adjust for size of job, size of members for galvanizing, and conversion of tons of steel to square feet.

Field Painting Costs (See Table 9)

• Regional U.S. 1997 costs for cleaning and paint application at the site are included in **Table 9.** Note the multipliers given to adjust for the type of structure, size of job, and existing coating conditions.

Worksheet A

• Use this worksheet for all systems to be applied in the shop. Note conversion factors at the bottom to convert costs from square feet to a per-ton basis.

Worksheet B

• Use this worksheet for all systems to be applied at the job site.

How to Make a Coatings Cost Analysis

• **Step 1:** What system(s) will work in the environment involved? Identify the specific environment and contaminants and begin with Table 5 or 6 for estimated service life. Review the system(s) that will work in the environment and examine their longevity. Select the ones that have the longest life, but include, for comparison and analysis, other systems that are popular

Table 5.

Type	Coating Systems for Atmospheric Exposure (primer/midcoat/topcoat)	Surface Preparation	Number of Coats	DFT Minimum (mils)	Service Life: Mild (rural)/ C2	Service Life: Moderate (industrial)/C3	Service Life: Severe (heavy industrial)/ C5-I	Service Life: Seacoast (Heavy Industrial)/ C5-M
Acrylic	Acrylic Waterborne/Acrylic WB/Acrylic WB	Hand/Power	3	6	12	8	5	5
	Acrylic Waterborne/Acrylic WB/Acrylic WB	Blast	3	6	17	12	9	9
Alkyd	Alkyd/Alkyd	Hand/Power	2	4	6	3	2	2
	Alkyd/Alkyd/Alkyd	Blast	3	6	14	9	5	5
	Alkyd/Alkyd/Silicone alkyd	Blast	3	4	11	6	3	3
Epoxy	Surface Tolerant Epoxy (STE)	Hand/Power	1	5	12	8	5	5
	Surface Tolerant Epoxy/STE	Hand/Power	2	10	17	12	9	9
	Surface Tolerant Epoxy/STE	Blast	2	10	21	15	12	12
	Surface Tolerant Epoxy/Polyurethane	Hand/Power	2	7	17	11	6	6
	Surface Tolerant Epoxy/Polyurethane	Blast	2	7	20	14	9	9
	Surf-Tolerant Epoxy/STE/Polyurethane	Hand/Power	3	12	23	17	12	12
	Surf-Tolerant Epoxy/STE/Polyurethane	Blast	3	12	26	20	15	15
	Epoxy 100% Sol Pent Sealer/Epoxy	Hand/Power	2	6	13	8	5	5
	Epoxy 100% Sol Pent Sealer/Polyurethane	Hand/Power	2	6	13	8	5	5
	Epoxy/Epoxy	Blast	2	6	18	12	9	9
	Epoxy/Epoxy	Blast	2	8	20	14	11	11
	Epoxy/Epoxy/Epoxy	Blast	3	10	23	17	14	14
	Epoxy/Polyurethane	Blast	2	6	17	11	8	8
	Epoxy/Epoxy/Polyurethane	Blast	3	8	20	14	11	11
	Epoxy Waterborne	Blast	3	9	18	12	9	9
	Coal Tar Epoxy	Blast	2	16	21	17	14	14
Epoxy Zinc	Epoxy Zinc/Epoxy	Blast	2	7	26	18	12	12
	Epoxy Zinc/Epoxy/Epoxy	Blast	3	11	30	21	15	15
	Epoxy Zinc/Polyurethane	Blast	2	7	24	17	12	12
	Epoxy Zinc/Polyurethane/Polyurethane	Blast	3	11	32	23	15	15
	Epoxy Zinc/Epoxy/Polyurethane	Blast	3	9	29	20	14	14
Inorganic Zinc	Inorganic Zinc (IOZ)	Blast	1	3	27	17	12	12
	IOZ/Epoxy	Blast	2	7	26	18	14	14
	IOZ/Epoxy/Epoxy	Blast	3	11	32	23	17	17
	IOZ/Polyurethane/Polyurethane	Blast	3	11	32	23	17	17
	IOZ/Epoxy/Polyurethane	Blast	3	9	30	21	15	15
	IOZ/IOZ/Waterborne Acrylic	Blast	3	6	24	17	12	12
Metallizing	Zinc Metallizing (minimum 90% zinc)	Blast	1	5	33	22	16	16
	Zinc Metallizing/Sealer	Blast	2	9	34	24	17	18
	Zinc Metallizing/Sealer/Polyurethane	Blast	3	13	39	27	22	22
Moisture Curing Polyurethane	MCU Pent Sealer/MCU/MCU	Hand/Power	3	7	15	14	7	9
	Zinc Rich MCU/Polyurethane/Polyurethane	Blast	3	9	30	21	15	15
	Zinc Rich MCU/MCU/MCU	Blast	3	9	29	21	14	15
Misc.	Universal primer/Epoxy	Hand/Power	2	6	12	8	5	5
	Universal primer/Epoxy/Polyurethane	Hand/Power	3	8	14	9	6	6

NOTES:

1. Service Life for Hot Dip Galvanizing as reported by American Galvanizers Association:
   Mild (rural) = 68 Years; Moderate (industrial) = 33 Years; Severe (heavy industrial) = 21 Years
2. Surface preparation definitions:
   Hand/Power - Requires SSPC-SP 3 "Power Tool Cleaning" or SP 2 "Hand Tool Cleaning"
   Blast - Requires SSPC-SP 6 "Commercial Blast" or SP 10 "Near White Blast"
3. Service Life Environments per ISO 12944-2, "Classification of Environments"
   C2: Low - Atmospheres with low levels of pollution; mostly rural areas; corresponds to "Mild (rural)"
   C3: Medium - Urban and industrial atmospheres, moderate sulfur dioxide pollution; coastal areas with low salinity; corresponds to "Moderate (industrial)"
   C5-I: Very High, Industry - Industrial areas with high humidity and aggressive atmosphere; corresponds to "Severe (heavy industrial)"
   C5-M: Very High, Marine - Coastal and offshore areas with high salinity; corresponds to "Seacoast Heavy Industrial"
4. Service Life Estimates:
   All estimates (in years) are for the "Practical" life of the system which is defined as the time until the first maintenance painting/touch-up occurs after 5-10% breakdown occurs, active rusting of the substrate occurs and Rust Grade 4 (SSPC-VIS 2) is present.

Table 6.

Estimated Service Life for Practical Maintenance Coating Systems for Immersion Service (in years before first maintenance painting)

Type	Coating Systems for Immersion Service (primer/midcoat/topcoat)	Surface Preparation	Number of Coats	DFT Minimum (mils)	Service Life: Potable Water	Service Life: Fresh Water Immersion	Service Life: Salt Water Immersion
Epoxy	Coal Tar Epoxy	Blast	2	16	--	17	14
	Epoxy/Epoxy	Blast	2	8	12	9	8
	Epoxy/Epoxy	Blast	2	6	10	8	6
Metallizing	Epoxy/Epoxy/Epoxy	Blast	3	10	15	12	11
	Zinc Metallizing/Epoxy	Blast	2	9	20	17	15
	Zinc Metallizing/Epoxy/Epoxy	Blast	3	13	24	20	18

NOTES:
1. Surface preparation definitions:
   Blast - Requires SP-10 "Near White Blast" for immersion service
2. Service Life Environment definitions:
   Potable Water - Immersion at an ambient pressure, coating generally requires NSF approval
   Fresh Water - Immersion at an ambient pressure
   Salt Water - Immersion at an ambient pressure
3. Service Life Estimates:
   All estimates (in years) are for the "Practical" life of the system which is defined as the time until the first maintenance painting/touch-up occurs after 5-10% breakdown occurs, active rusting of the substrate occurs and Rust Grade 4 is present.

or thought to be economical. Be sure the analysis includes the effect of surface preparation on expected life. Include, if possible, a comparison of the same generic system with different cleaning grades. If project/plant or client personnel confront you with prejudices/preferences, include their systems for economic comparison and analysis.

• **Step 2:** On new construction compare field painting vs. shop priming. As outlined before, if a minimum of 250 tons of steel is involved, shop blasting and priming is about half the cost of the same work at the site. The job may done more efficiently and many of the normal job site conflicts and compromises can be eliminated. Shop application usually gives better results but the requirements for, and appearance of, field touch-up must be considered. For the candidate system(s) selected in Step 1, include in the analysis a comparison of each system under both shop and field painting alternatives.

• **Step 3:** Prepare worksheets (A, B, or both) on all candidate systems.

• **Step 4:** Calculate the long-term cost and number of painting operations over the structure's life by preparing a present value analysis for each candidate system as outlined in this section.

Types Of Contracts, Bids, And Proposals

Listed here are the predominant types of proposals, bids, and contracts currently being used with an explanation of each. This list is not all-inclusive.

Types Of Bids And Proposals

Request for Proposal (RFP)

• These are solicitations of written offers on negotiated requirements. This usually encompasses a written or verbal request to various firms to submit a written proposal for the job at hand.

Invitation for Bid (IFB)

• These involve soliciting bids on formally advertised requirements. The resulting contract will usually be a fixed-price contract.

Types Of Contracts

Contracts generally fit into one of the following categories:

Firm Fixed-Price Contract

• Provides for a price not subject to any adjustment when work is within the requirements of the specifications. The scope of work/specification is set and is not expected to change.

Table 7.

Typical Material Costs of Paints and Protective Coatings (Approximate Cost Per Square Foot @ Typical DFT)

Coating	DFT	Theoretical	Practical Spray	Practical Brush/Roll
Acrylic, Waterborne Primer	3.0	0.145	0.207	0.161
Acrylic, Waterborne Topcoat	3.0	0.134	0.191	0.149
*Alkyd Primer	2.0	0.064	0.091	0.071
*Alkyd Gloss Topcoat	2.0	0.059	0.084	0.066
Alkyd Silicone	2.0	0.115	0.164	0.128
*Coal Tar Epoxy Standard	8.0	0.119	0.170	0.132
*Coat Tar Epoxy C200	8.0	0.152	0.217	0.169
Epoxy Thin Film 100% Solids Solvent Free	5.0	0.068	0.109	0.076**
Epoxy Clear Sealer 100% Solids Solvent Free	2.0	0.039	0.056	0.043**
*Epoxy Primer	2.0	0.050	0.071	0.056
*Epoxy HB Primer	4.0	0.100	0.143	0.111
*Epoxy HB Intermediate/Topcoat	4.0	0.110	0.157	0.122
*Epoxy Topcoat	2.0	0.069	0.099	0.077
Epoxy, Waterborne	3.0	0.192	0.274	0.213
Epoxy, Phenolic Primer	5.0	0.173	0.247	0.192**
Epoxy, Phenolic Finish	5.0	0.190	0.271	0.211**
Epoxy, HB Surface Tolerant	5.0	0.120	0.171	0.133
Epoxy, Ester, Primer	1.5	0.035	0.050	0.039
Epoxy, Ester, Topcoat	2.0	0.072	0.103	0.080
Latex Emulsion, Primer	2.0	0.055	0.079	0.061
Latex Emulsion, Topcoat	2.0	0.054	0.077	0.060
Universal Primer, 1-pack	2.0	0.072	0.103	0.080
Urethane, Elastomeric Solvented	20.0	0.910	1.300	1.011**
Urethane, Aromatic HB Primer	5.0	0.164	0.234	0.182
*Urethane, Aliphatic Acrylic	2.0	0.116	0.166	0.129
*Urethane, Aliphatic HB Acrylic Inter/Top	4.0	0.204	0.291	0.227
*Urethane, Aliphatic Polyester	2.0	0.150	0.214	0.167
Urethane, Moisture-Cured Aluminum	2.5	0.095	0.136	0.106
Urethane, Moisture-Cured Clear Sealer	2.0	0.076	0.109	0.084**
Vinyl Ester	20.0	0.740	1.057	0.822**
*Zinc Rich, Inorganic	3.0	0.134	0.191	0.149**
Zinc Rich, Organic	3.0	0.149	0.213	0.166**
Zinc Rich, Moisture-Cured Urethane	3.0	0.131	0.187	0.146**
Hot Dip Galvanizing	4.0	0.082	NA	NA

NOTES:
* = Available in high-solids versions. Applicable costs and cost per mil square foot are approximately the same as for lower-solids versions
** = Although these materials can be brush/roller applied, it is not recommended by some manufacturers
NA = Not applicable
Costs are approximate based on 1997 data secured from representative US paint and coating suppliers
DFT = Dry Film Thickness in mils (1mil = 25.4 microns)
Spray Practical = 30% loss, except 100% solids solvent free epoxy = 15% loss
Roll/Brush Practical = 10% loss

Table 8.

Shop Painting Costs per Sq. Ft. Including Labor, Equipment, and Related Costs (No Material Costs Included)

		East	Central	Gulf	West
Cleaning Grade	SP 2	$0.40	$0.40	$0.29	$0.28
	SP 3	$0.27	$0.27	$0.20	$0.19
	SP 6/NACE 3 Automated	$0.32	$0.32	$0.24	$0.23
	SP 10/NACE 2 Automated	$0.32	$0.32	$0.24	$0.23
	SP 5/NACE 1 Automated	$0.39	$0.39	$0.29	$0.28
	SP 6/NACE 3 Conventional with Recyclable Abrasives	$0.68	$0.68	$0.50	$0.48
	SP 10/NACE 2 Conventional with Recyclable Abrasives	$1.12	$1.12	$0.82	$0.79
	SP 5/NACE 1 Conventional with Recyclable Abrasives	$1.22	$1.22	$0.90	$0.86
	SP 6/NACE 3 Conventional with Expendable Abrasives	$0.75	$0.75	$0.57	$0.55
	SP 10/NACE 2 Conventional with Expendable Abrasives	$1.22	$1.22	$0.92	$0.89
	SP 5/NACE 1 Conventional with Expendable Abrasives	$1.33	$1.33	$1.01	$0.97
Shop Paint Application	One-Pack Products	$0.28	$0.28	$0.20	$0.20
	Two-Pack Epoxies	$0.40	$0.40	$0.29	$0.28
	Two-Pack Urethanes	$0.43	$0.43	$0.32	$0.30
	Zinc Rich Primers	$0.37	$0.37	$0.27	$0.26
Hot Dip Galvanizing	Labor, Equipment, Surface Preparation and Related Costs	$1.13	$1.13	$1.13	$1.13

Size of Job Multipliers (per foot^2)

10,000 – 25,000	120%
25,000 – 75,000	110%
75,000 – 125,000	100%
125,000 – 300,000	95%
300,000 – 1,000,000	90%
1,000,000+	80%

Conversion of Tons of Steel to Feet^2

Member Type	Ft^2/Ton
Typical mix size/shapes	250
Large Structural	100
Medium Structural	200
Light Structural	400
Light Trusses	500

Member Size Multipliers For Hot Dip Galvanizing
Member Weight Per Foot (Lbs/Ft)

0 – 20	80%
21 – 50	100%
50 – 125	115%
126 – 200	125%
200+	180%

NOTES:
Multiplier for using recyclable grit for: SP 6/NACE 3, SP 10/NACE 2, SP 5/NACE 1 above is 1.5 – 1.9.
Costs shown are approximate, based on 1997 data secured from representative US steel fabricators.
Steel plate cleaning costs are about 20% less than prices listed above for structural steel.
Costs labeled automated are for steel fabricators having centrifugal wheel blasting equipment.
There are member size limitations for hot dip galvanizing. The maximum depth is approximately 3 feet and maximum length is approximately 80 feet when double dipped in standard galvanizing kettles.

Table 9.

Field Painting Costs per Sq. Ft. Including Labor, Equipment, and Related Costs (No Material Costs Included)

		East	Central	Gulf	West
Cleaning Grade	SP 2 Hand Tool Cleaning	$0.47	$0.37	$0.34	$0.40
	SP 3 Power Tool Cleaning	$0.77	$0.61	$0.54	$0.69
	SP 11 Power Tool-Bare Steel	$3.05	$2.60	$1.98	$2.58
	SP 7/NACE 4 Brush-Off Blast	$0.59	$0.46	$0.43	$0.64
	SP 6/NACE 3 Commercial Blast	$0.81	$0.75	$0.64	$0.80
	SP 10/NACE 2 Near White Blast	$1.16	$0.98	$0.90	$1.06
	SP 5/NACE 1 White Metal Blast	$1.27	$1.09	$1.02	$1.27
	Water Wash Prior to Surface Prep.	$0.15	$0.13	$0.11	$0.20
	Hi Pres. Water/Steam Clean prior to Surface Prep.	$0.23	$0.20	$0.18	$0.21
	Water Slurry Blast	$1.17	$0.99	$0.90	$1.30
	Low Pressure wo/abrasive SP 1	$0.34	$0.30	$0.25	$0.25
	Low Pressure w/abrasive SP 10/NACE 3	$1.48	$1.18	$1.06	$1.25
	High Pressure w/abrasive SP 10/NACE 3	$3.15	$2.70	$2.28	$2.70
	Sponge Media Blast	$3.93	$3.32	$2.88	$3.44
	Bicarbonate	$1.68	$1.37	$1.27	$1.50
Field Application	One-Pack by Brush/Roller	$0.37	$0.30	$0.27	$0.33
	One-Pack by Spray	$0.26	$0.23	$0.20	$0.24
	Two-Pack Epoxies, by Spray	$0.28	$0.25	$0.23	$0.27
	Two-Pack Urethanes, by Spray	$0.31	$0.30	$0.25	$0.28
	Zinc Rich Primers, by Spray	$0.32	$0.31	$0.26	$0.28

Structure Multiplier		Field labor x's
Simple Structures < 50' high		120%
Simple Structures 50'-100' high		130%
Simple Structures > 100' high		145%
Complex Structures < 50' high		135%
Complex Structures 50'-100' high		145%
Complex Structures > 100' high		150%
Elevated tanks, intricate structures, structures greater than 50' high		150%
Ground Tanks		80%
Piping:	1-2"	140%
	4-6"	100%
	12" and 24"	95%
	48"	90%

Existing Coating Conditions	Total $/ft^2 x's
Light rusting, pitting/paint breakdown (SNAME T&R 21, Fig 5)(2) (Europe Std. Re 5-6)(3) (SSPC Vis. 1-C)(4)	100%
Heavy paint breakdown, severe rusting and pitting (SNAME T&R 21, Fig 3, 6)(2) (Europe Std. Re 8)(3) (SSPC Vis. 1-D)(4)	130%
Extremely heavy paint films >20 mils with extreme breakdown and substantial pitting and rusting (SNAME T&R 21, Fig 7)(2)	160%
Adherent Mill Scale (SSPC Vis. 1-A)(4)	125%

Size of Job Multiplier	Total $/ft^2 x's
10,000 – 25,000	115%
25,000 – 75,000	105%
75,000 – 125,000	100%
125,000 – 300,000	95%
300,000 – 1,000,000	90%
1,000,000+	80%

NOTES:
Multiplier for using recyclable grit for: SP 6/NACE 3, SP 10/NACE 2, SP 5/NACE 1 above is 1.5 – 1.9.
Costs shown are approximate, based on 1997 data secured from representative US painting contractors.
Costs shown are for calculating the base price of new steel cleaned and painted on the ground at the job site.
The Structure Multiplier is applied to the field labor costs per square foot.
The Size of Job and Existing Coating Condition Multipliers are applied to the total costs per square foot.

Worksheet A.

WORKSHEET A – SHOP COATING APPLICATION

Project Name: Structural Steel for Bridge Overpass
Project Location: Pittsburgh, PA

(A) Project Size (Ft.^{2} or Tons): 60,000 Ft.^{2}

Coating System: IOZ/epoxy/polyurethane
Intended Environment: Severe Industrial
Service Life: 15

I. Surface Preparation: SP 10 automated — Cost ($): 0.32 Per Ft.^{2}
(Includes labor, equipment and related costs, no materials) (Note: Automated or Conventional Method)
I. Sub-Total ($ Per Ft.^{2}) = 0.32

II. Application:
a) Paint Material
Spray — 1st Coat — Cost ($): 0.37 Per Ft.^{2}
Spray — 2nd Coat — Cost ($): 0.40 Per Ft.^{2}
Spray — 3rd Coat — Cost ($): 0.43 Per Ft.^{2}
II. Sub-Total ($ Per Ft.^{2}) = 1.20 (a)

OR

b) Hot Dip Galvanizing
(Includes labor, surface preparation and related costs)
II. Sub-Total ($ Per Ft.^{2}) = _____ (b)

Labor Sub-Total ($ Per Ft.^{2}) = 1.52
I + II (a or b)

III. Job Multiplier:
a) Job Size: 60,000 Ft.^{2} %: 110

b) Member Size: _____ %: _____

III. Adjusted Labor Cost ($ Per Ft.^{2}) = 1.672
(Labor x III.a x III.b.)

IV. Material Costs
Inorganic zinc — 1st Coat — Cost ($): 0.191 Per Ft.^{2}
Epoxy — 2nd Coat — Cost ($): 0.143 Per Ft.^{2}
Polyurethane — 3rd Coat — Cost ($): 0.166 Per Ft.^{2}
Total DFT = _____
IV. Sub-Total ($ Per Ft.^{2}) = 0.50

(B) Preliminary Project Cost ($ Per Ft.^{2}) = 2.17
(III + IV)

(C) TOTAL PROJECT COST ($) = 130,200
(A x B)

Conversion of Tons of Steel into Ft.^{2}:

Tons	Mult. by	= Per Ft.^{2}
Typical mix	250	
Large Structural	100	
Medium Structural	200	
Light Structural	400	
Light Trusses	500	

Worksheet B.

WORKSHEET B – FIELD COATING APPLICATION

Project Name: Elevated Water Storage Tank
Project Location: St. Louis, MO

(A) Project Size (Ft.^{2}): 30,000

Coating System: 2-coat acrylic waterborne
Intended Environment: Moderate industrial
Service Life: 10

I. Surface Preparation: (Includes labor, equipment and related costs, no materials) — Power tool, SP 3 — Cost ($): 0.61 — Per Ft.^{2}

Additional Cleaning:
Cost ($): _____ Per Ft.^{2}
Cost ($): _____ Per Ft.^{2}
Cost ($): _____ Per Ft.^{2}
I. Sub-Total ($ Per Sq. Ft.) = 0.61

II. Application:

Method:		Cost ($):	Per Ft.^{2}
Spray	1st Coat	0.23	
Spray	2nd Coat	0.23	
	3rd Coat		

II. Sub-Total ($ Per Ft.^{2}) = 0.46

Labor Sub-Total ($ Per Ft.^{2}) = 1.07 (I + II)

III. Structure Multiplier:
General Configuration: Elevated (Simple/Complex) — Height: 100 — %: 150
OR
_____ (Unique) — (Size): _____ (If pipe) — %: _____
III. Adjusted Labor Cost ($ Per Ft.^{2}) = 1.605 (I + II) x (%)

IV. Material Costs

		Cost ($):	Per Ft.^{2}
Acrylic WB prime	1st Coat	0.207	
Acrylic WB top	2nd Coat	0.191	
	3rd Coat		

Total DFT = 6
IV. Sub-Total ($ Per Ft.^{2}) = .398
(B) Preliminary Project Cost ($ Per Ft.^{2}) = 2.675 (III + IV)

V. Project Multipliers
(C) Existing Conditions %: 130
(D) Project Size %: 105

(E) Adjusted Project Cost ($ Per Ft.^{2}) = 3.65 (B x C x D)

(C) TOTAL PROJECT COST ($) = 109,500 (A x E)

Fixed-Price Contract Escalation

• Provides for the upward or downward revision of stated contract price upon occurrence of certain contingencies specifically defined in the contract.

Fixed-Price With Redetermination

• Calls for the subsequent negotiated adjustment, in whole or in part, of the originally negotiated (base) price. Consistent with the particular form of price redetermination clause selected, contract price should be adjusted upward or downward, retroactively or prospectively, or both.

• Retroactive After Completion: Fixed price cannot be negotiated initially; amount so small or time so short any other contract type is impractical.

Fixed-Price Incentive Contract

• A fixed-price contract providing for adjustment of total target profit and establishment of contract price by a formula based on the relationship which the final negotiated total cost bears to the total target cost.

• Where cost uncertainties exist and there is the possibility of cost reduction by giving the contractor a degree of cost and responsibility, and a positive profit incentive.

Cost Plus Fixed-Fee Contract (CPFF)

• A cost-reimbursement contract providing for payment of a fixed fee to the contractor. The fixed fee, once negotiated, does not vary with actual cost but may be adjusted as a result of any subsequent changes in the work or services to be performed under the contract.

Cost Plus Fixed Fee and Award Contract (CPFFA)

• A cost reimbursement contract providing for payment of a fixed fee to the contractor plus an award fee. The fixed fee, once negotiated, does not vary with actual cost but may be adjusted as a result of any subsequent changes in the work or services to be performed under the contract. The award fee is determined monthly based on defined criteria established in the negotiating process. Typical criteria would be: costs, schedule, and quality.

Cost Plus Incentive Fee Contract (CPIF)

• A cost-reimbursement contract with provisions for a fee that is adjusted by formula in accordance with the relationship which total allowable costs bear to target costs.

Time and Material (T & M) and Labor Hour (L-H) Contracts

• Provides for purchase of property and services on the basis of direct labor hours at specified hourly rates (including direct and indirect labor, overhead, and profit) and material (T & M); direct labor hours at specified hourly rates (including direct and indirect labor, overhead, and profit) and no material (L-H)

Letter Contract

• A written preliminary contractual instrument authorizing immediate commencement of work, or the performance of services including but not limited to pre-production planning and procurement of necessary materials.

Two-Step Formal Advertising

• The owner will request, in step one, technical proposals based on design and performance requirements, operational suitability and ease of maintenance, and the need for special skills and facilities.

• The contractor responds and technical proposal is evaluated.

• Acceptable proposers are asked to price their proposal only.

• Award is made to the low bidder.

Effect of Contracting Mechanisms on Cost

The two major types of contracts typically being used are the lump sum and the time-and-materials contracts. Both have advantages and disadvantages. Additionally, extensive warranty requirements are typically being added to lump-sum contracts.

Advantages of the lump-sum contract are that contractors are required generally to provide the most cost-competitive contract. Often the list of contract bidders has met some sort of pre-qualification requirement. Additionally, lump-sum contracts provide the owner with a fixed, budgeted contract price, with little need to renegotiate during or after the contract work is completed.

Disadvantages include the fact that all work and contingencies need to be completely determined prior to requesting bid prices, otherwise change orders and potential claims can change overall cost. Other disadvantages include the potential for the successful bidder to provide reduced effort in assuring contract quality and specification compliance. As such, many owners provide construction inspection services to ensure contract compliance.

Advantages to the time-and-materials contract include allowances for incomplete work, scope development, and constant altering of work to be performed. In some facilities, determining when and how long a particular piece of equipment can be taken out of service is difficult to guess, and as such the total scope of work may be increased or decreased as allowed by the equipment downtime. Economic advantage can be found in using time-and-materials contracts where potential bidders do not have to budget for contingencies or unknowns in the project.

Disadvantages include not having a firm budget for project work and the potential that the contractor is not driven by economic pressures to complete the work. As such, cost may increase over similar work performed under a lump-sum contract.

Warranty requirements, implied or written, are showing up in more contract documents. Disadvantages of multi-year warranties include increased costs associated with warranty financing. Some recent warranties of 2, 5, and 10 years have been procured. Conceptually, the design life a coating system as specified will be much greater than that of the warranty period. Why pay for a 5-year warranty when the design life of the properly applied coating is 15-20 years or longer? Provisions of a year or two for catastrophic failures related to surface preparation and coating system application are prudent, but the specifier should be careful not to increase project costs for no apparent gain. Additionally, the warranty specification must be very clear as to what amount of coating failure, gloss reduction, fade, and percentage of corrosion and rust bleed require the contractor to remobilize and make repairs.

Alternatively, instead of warranty requirements the owner can perform ongoing inspections. This inspection can be full-time or part-time, depending on resources available. Qualified independent inspection agencies can also provide full- and part-time inspection services. The advantage here is that the inspector is there to ensure proper, as specified, surface preparation and coating application. Once the prepared surface is covered by the coating system, without destructive testing it is not possible to determine if it was properly prepared, and even then it is too late to make any cost-effective changes. Inspection costs can increase the overall cost of the contract, but are typically less than the cost of warranty provisions of over 5 years. In high-profile cases, owners sometimes specify both an extended warranty and independent inspection services.

Summary

A basic understanding of field- and shop-applied paint and coating costs is necessary to properly choose the painting system that provides maximum benefits for a given structure. The corrosiveness of the service environment must be known as well as the expected plant life of the structure.

At the one time in the life of a new structure when a proper protective coating system can be selected, justified, and applied, poor decisions are frequently made. Usual reasons are initial “cost” considerations or failure to use life-cycle cost and service-life data. The ability to effectively communicate with management in economically justifying a painting system requires the corrosion engineer to have a basic knowledge of cash flow, discounting practices, and tax benefits.

This chapter presents elements of field painting costs, current cost data, an expected service life table, cost worksheets, justification procedures, and a definition of contract forms to assist the specifier in making sound decisions.

Acknowledgments

The authors and SSPC wish to acknowledge the previous authors of this chapter, from which these revisions were based: G.H. Brevoort, S.J. Oechsle, and M.R. Sline. Other acknowledgements include those who contributed to *Costing Considerations for Maintenance and New Construction Coating Work* published through NACE International at *Corrosion ‘98:* M.P. Reina, K.R. Shields, R.P. Negrey, and Ken Trimber. Portions of this chapter text copyrighted 1998 by NACE International. All Rights Reserved by NACE; Reprinted by Permission.

About the Authors

L. Brian Castler
Brian Castler has been with the Connecticut Department of Transportation since 1966. In 1991, he assumed his current position of manager of construction operations in the office of construction for the state. In this capacity, Mr. Castler is responsible for planning, coordinating, and administering field operations for the construction of all highways, bridges, aviation, and railroad facilities. He also directs and oversees the disposition of claims and interprets and administers pertinent laws regulating these activities.

Jayson L. Helsel, P.E.
Jayson Helsel is a senior consultant with KTA-Tator, Inc. He holds an MS in chemical engineering from the University of Michigan, is a registered professional engineer, and a NACE coatings inspection technician. At KTA, Mr. Helsel has managed numerous coating failure investigations and has been involved with coating surveys and inspections of industrial structures. He previously served as a Lieutenant Commander in the U.S. Coast Guard with extensive experience in marine vessel inspection.

Michael F. MeLampy
Michael MeLampy is the northeast region manager with KTA-Tator, Inc., where he is responsible for project management and business development in all of New England and northern New York. He holds an Executive MBA from the University of Pittsburgh and has over 15 years of experience as an executive in the manufacturing industry. Mr. MeLampy is a co-author of the NACE Corrosion ‘98 publication referenced here.

Eric S. Kline
Eric S. Kline is vice president/senior consultant with KTA-Tator, Inc., where he has been involved in dozens of bridge projects and serves as an instructor in many KTA training programs. An SSPC certified protective coatings specialist (PCS) and past president of the SSPC Pittsburgh Chapter, he is chair of the SSPC subcommittee on contractor certification and co-chair of the SSPC task force for the certificatin of inspection agencies as well as a member of several other SSPC committees. Among other industry groups, Mr. Kline is also a member of NACE International; the American Railway Engineering and Maintenance of Way Association (AREMA) committee 15, subcommittee 8, painting and special construction; and the AASHTO/NSBA Collaboration, where he chairs committee TG-8 on coatings.

Chapter 10.3
Using Plant Surveys to Maintain Coating Protection of Structures

Richard W. Drisko

Introduction

Plant maintenance personnel often ask:

• How can I best develop a program for maintaining coating protection for different plant structures?
• How can I determine whether localized repair of damaged substrate and coating or substrate repair and total coating replacement is the better choice?
• What coatings systems should be used in each case?
• When is the best time to take the necessary actions?

This chapter will attempt to show how information obtained by field surveys can be used to answer these and other maintenance questions. Information is provided from actual field experiences.[1]

Minimum Walk-Through Survey

A minimum walk-through survey consists of a visual assessment of the overall conditions of substrates and coatings on plant structures. It is a relatively fast and inexpensive method to prepare general information on the overall conditions and establish times when maintenance actions can be anticipated. A simple numerical rating system (e.g., priority ratings of 1 through 5) can establish work priorities should limited funds not permit all of the desired work to be done. This method may also provide data for establishing a logical approach to subdividing the facilities into smaller units for a systematic collection of data in more detail.

Mid-Level Survey

In a mid-level survey, facilities are subdivided into smaller units in order to obtain more information about individual components. Alternatively, these components can be subdivisions related to function (e.g., architectural, electrical, mechanical, etc.). This survey level provides more detailed data. The types and extents of substrate and coating deterioration are made in accordance with industry standards:

• Definitions for defects are found in Reference 2 and depicted pictorially in References 3 and 4. The latter two references can be used very effectively to identify types of defects.
• The extent (percent) of defects in localized areas can be determined using SSPC-VIS 2 (Reference 5). A series of pictures visually depicts different levels of deterioration for more precise estimation.
• The general distribution of defects in large areas can be determined using Reference 6, which presents a series of pictures with known distributions levels of deterioration.

It should be noted that natural deterioration occurs more rapidly at edges and other irregular areas where cleaning and coating is more difficult or in localized areas where the environmental forces are more severe. Exterior water traps (where rain water collects) present an especially severe environment.

Detailed Survey

In a detailed survey, the individual components are further subdivided, and actual physical tests are conducted, notably dry film thickness and adhesion. These values are critical in establishing whether the existing coating has adequate properties for localized repair rather than total replacement.

Defects should be identified and quantified using ASTM rating standards (e.g., size and density of blisters). If appearance is important, the extent of chalking, color fading, discoloration, loss of gloss, etc. should be measured using standard ASTM procedures. If the identity of the existing coating is not known, it may be necessary to submit a sample for analysis to find a compatible repair material.[1] If pitting corrosion is present, measuring the pit depths may be very important.

A detailed survey is required to provide the necessary data to define work requirements for a specification. The additional expense for a detailed survey is well justified by minimizing risks associated with maintenance painting.

Analysis of Survey Data

The survey data must be collected systematically using a standard printed form in a complete and quantitative manner to obtain sufficient data for reliable decisions. There are seldom too much data available.

While it would be nice to establish deterioration levels at which maintenance work should be undertaken (e.g., 10% substrate or coating deterioration), there are many other factors that affect decision making. Those related to the coating survey are discussed here.

Type and Extent of Substrate Damage and Coating Defects

The nature of any corrosion (e.g., uniform, pitting, filiform, etc.) is very important in determining best corrective actions. Thus, pitting corrosion may be critical to a storage tank, if penetration of a steel wall or floor is threatened. Concrete deterioration is described in SSPC's book *The Fundamentals of Cleaning and Coating Concrete.*

Reference 2 describes causes and corrective actions for coating defects. The extents of damage to substrates and coating is critical in determining whether spot repair of substrate and coating or more extensive substrate repair and a total replacement of coating is more appropriate. To determine the total extent of coating deterioration, it may be necessary to scrape with a dull putty knife to expose all of the damaged areas. Visually sound coating may have poor adhesion to its substrate.

Distribution of Substrate and Coating Damage

The distribution of substrate and coating damage can determine whether only localized damage repair will be necessary.

Loss of Coating Function

Some coatings have functions other than substrate protection. These include non-slip, reflective, or electrical conductive properties. If these properties have been significantly reduced, it may be necessary to restore them by total repainting.

Rate of Increase of Defects

An important part of a deterioration control program is the periodic survey of the component structures. Navy shore facilities receive annual condition inspections. By establishing the current rate of deterioration, the likelihood of further significant deterioration with deferred maintenance can be deduced.

Identity of Surface Coating

The identity of the surface coating is important in determining the compatibility of the existing coating with the system selected for localized repair. All localized-repair coatings must not only cover the damaged areas but also overlap onto the sound existing coating. If compatibility cannot be established, a test patch of the proposed system must be applied to the existing coating.

Adhesion

Topcoating a coating with limited substrate adhesion may actually accelerate total coating deterioration.

Film Thickness

It is important to determine if chalking erosion or some other mechanism has significantly reduced the film thicknesses of the existing coatings. This may, in turn, significantly reduce the barrier protection of the substrate.

Appearance

Appearance may be an important factor in selecting the types of corrective actions. Localized repair may produce an unsightly patchy appearance. A thin, total finish coat may be applied to remove this. However, the finish coat may increase the rigidity of the total system and associated stresses to reduce overall adhesion.

Other Factors Affecting Decisions

Unfortunately, there are sometimes factors unrelated to survey data that affect the choice of maintenance actions. Some of these factors are described here.

Limited Funding

Maintenance funds may be not be available in sufficient quantity to cover all of the desired work. To avoid this problem, surveys should be taken periodically, so that future funding requirements can be determined and requested to meet anticipated maintenance requirements in future years.

At times, it may be necessary to prioritize the

desired work to address the areas with the greatest deterioration. However, prioritization may also be based on those areas that have the greatest effect on operations.

Risk of Deferred Maintenance

If only localized repair is conducted, there is a risk that the protection provided will be short term, and a total coating replacement will be necessary. This will result in a considerable loss of money.

Effects of Maintenance Actions on Plant Operations

Maintenance work of any kind is likely to affect continuing operations. It may be necessary to conduct the maintenance work at night, on weekends, or at a time of total operational shut down. Obviously, interference with plant operations and the work of other trades must be minimized.

Contamination of Products

If substrate and/or coating deterioration is causing contamination of products, immediate corrective action is usually necessary. This is particularly true for food products or sophistic electronic instrumentation.

Summary

Preparing plans for maintenance work on coated structures is not an easy matter. Necessary actions must be determined by a plant survey, but other factors come into play. The best approach to such problems is to establish a total maintenance program for all plant facilities. Periodic condition surveys will permit detailed planning for present work and more general planning for future work. The latter should include requests to management for funding for anticipated future work and permit maintenance decisions to be based on survey data.

References

1. Drisko, Richard W. Total Protective Coatings Program. In *Proceedings of SSPC '96,* pp 283-289.
2. *Protective Coatings Glossary;* Drisko, Richard W., ed., SSPC: Pittsburgh, 2000.
3. *Techdata Sheet 82-08: Paint Failures—Causes and Remedies;* Naval Facilities Engineering and Service Center: Port Hueneme, CA, 1982.
4. Munger, Charles G. *Corrosion Prevention by Protective Coatings;* NACE: Houston, 1984.
5. SSPC-VIS 2. *Standard Method of Evaluating Degree of Rusting on Painted Steel Surfaces;* SSPC: Pittsburgh.
6. ASTM F 718. *Standard for Shipbuilders and Marine Paints and Coating Product/Procedure Data Sheet;* ASTM: West Conshohocken, PA.

About the Author

Dr. Richard W. Drisko

Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society for Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy's center of expertise on coatings for shore structures. He is a professional corrosion engineer in the state of California, an SSPC certified protective coatings specialist (PCS), and a NACE International certificated corrosion specialist. Dr. Drisko received his BS, MS, and PhD degrees from Stanford.

Chapter 10.4
Preparing a Specification for a Coating Project

Richard W. Drisko

Introduction

Purpose of Specification

A job specification is defined as a written, legal document, usually part of a contract, that precisely describes an item of work that is to be accomplished.[1] It defines the quality of materials, mode of construction, and desired amount of work. There are many purposes for a specification:

- To obtain a specific desired product
- To assure quality materials and work
- To assure completion of work
- To avoid delays and disputes
- To obtain minimum or reasonable costs
- To avoid costly change orders and claims
- To meet all safety, environmental, and legal requirements

In addition to making bidding fair, government job specifications usually have the additional requirement of making it available to as many contractors as possible.

Types of Specification

The term "job specification" is used in this chapter to avoid confusion with other types specifications used in the coatings industry. Many technical organizations prepare documents called specifications that describe products, procedures, or conditions. *SSPC Painting Manual Volume 2, Systems and Specifications* includes dozens of specifications covering surface preparation, abrasives, paints and paint systems, and paint application.

Background

Earlier Practices

At one time, previously used painting specifications were kept on file and used over and over again. This did not permit the incorporation of new technologies, new governmental requirements, and recent structural changes, or the correction of errors in earlier documents. Specifiers with limited time or experience often followed the bad practice of "cutting and pasting" previous specifications. This is much easier to do today using computer programs with standard forms and/or recommendations. The Construction Specifications Institute (CSI), the American Institute of Architects (AIA), and several commercial firms have such programs. Although they can be very helpful, none of them will tailor a specification to a particular job or convert novices instantly into professional specifiers.

Often, painting comprises only a small part of construction work. Since structural aspects of construction projects are stressed, the painting portion frequently receives less time or consideration than is necessary to describe its requirements satisfactorily.

Another approach still used occasionally today, especially on smaller jobs, is to have suppliers prepare specifications for painting. As might be expected, the supplier's products were required by the document. Problems frequently arise from this approach because few suppliers are skilled in preparing specifications.

Results from Specification Deficiencies

Poorly or incompletely prepared specifications can result in bidding concerns that may require cancellation of the bid invitation and rewriting the specification for a new bid invitation. Some of the more common bidding concerns are:

- Bids from unqualified contractors
- Fewer bids from qualified contractors
- Unrealistically high or low bids

Job specifications are further complicated in that they are legal documents and must contain the legal as well as the technical requirements. Inadequacies in paint specifications, or other specifications, may permit bidders to interpret the described requirements to their advantage to provide lesser work or use cheaper materials. This, in turn, may give rise to disputes and litigation. Thus, it is extremely important that painting job specifications or other construction

specifications be prepared systematically and thoroughly and conform to all applicable regulations.

Basics of Contracting

An understanding of the general nature of contracting is necessary to achieve an understanding of how specifications are used because most painting and other construction work is accomplished by contract. Thus, participants in the contracting process and types of contracting will be discussed briefly. The types of payment will also be discussed because of possible confusion between types of contracting and types of payment.

Contract Participants

A contact is a written agreement between an owner and a contractor. However, other personnel are usually involved in the contracting process. An owner can be an individual or an organization. The owner may be from the private sector or be a governmental organization. It is the responsibility of the owner to initiate the project and secure sufficient funding for all phases of it. The owner may also have an office-based project manager, who is responsible for most of the planning, and a field manager who oversees work at the job site.

Contractor and owner agree to complete the specified work with the contractor's workforce or subcontracted forces in a specified time for a particular amount of money. Materials and equipment suppliers are often involved through contracts with the contractors or subcontractors. However, in all cases the responsibility for successful completion of the contract work resides with the contractor.

The specifier (specification writer) is usually an architect/engineer (in-house or contracted) used by the owner to design the project work and to prepare job specifications and related documents. This person may in turn hire coating consultants or other specialists to assist with special phases of the work. Because of the nature of specifications, the specifier must have a combination of skills:

• Proficiency in use of language. Ability to produce clear, precisely worded documents.
• Research and reading skills. Ability to work with voluminous quantities of information to procure precise data.
• Ability to work with others, consulting and coordinating with other specialists.
• Knowledge of coatings operations, including an understanding of and ability to generate cleaning/coating requirements.
• Legal knowledge. A clear fundamental understanding of the legal principles involved in specifications and the contracting procedure.

The specifier's selection of coating systems should based on how well they satisfy the owner's requirements. Four important factors in their selection are:

• **System Properties.** Is it adequate for the specific needs? How does it compare to alternative systems? What service life can be expected? What are its limitations? Does it meet all local regulations? Is it readily available and in the desired color?
• **Manufacturer.** Is the manufacturer's product on a "Qualified Products" list? Is the manufacturer reputable? Does this manufacturer provide field service for product use? How well does the manufacturer respond to field problems?
• **Application.** Do the manufacturer's data sheets provide all necessary information for proper application? Should alternative application methods be described? Are special workers or equipment required for successful application? Do workers require certification?
• **Costs.** What long-term (life cycle) costs will be associated with the system? What maintenance costs can be expected with the system?

Coating inspectors are usually required to monitor the work and conduct testing to establish and document whether all specification requirements have been met. They may be employees of the owner or contractor or preferably certified specialists hired from an independent inspection firm.

Contracting and Payment Methods

There are two general types of construction contracts: competitive bidding and direct selection. Each type has its own advantages and limitations. The competitive bidding method is used to determine the least cost for accomplishing the work defined by the specification. A bid, also called a proposal, states the price that the bidder will charge to accomplish the work. Bids are prepared in confidence and submitted in sealed envelopes for the owner to examine and compare with other bids. The owner usually selects the lowest qualified bidder to do the work.

In the direct selection (also called negotiated) method, the owner, usually with the advice of the specifier, selects the prospective contractor from a pre-qualified list based upon experience, dependability, financial stability, and necessary skills. This method is not normally allowed for projects in the public sector. There are several bases of payment for contract work. These include but are not limited to stipulated or lump sum, unit price, cost plus fee, and guaranteed maximum price.

In the stipulated or lump sum method of stating the cost, a specified amount is quoted for completing all the described work. In competitive bidding, lump sums are quoted by the bidders; in direct selection, the lump sum is negotiated between the owner and the contractor. The stipulated or lump sum method is used when all items of work can be accurately defined.

The unit price method is used when the items of work cannot be accurately defined in advance. A price is quoted for each unit measure of each portion of work to be done. After completing each portion of work, the actual amount of work done is measured and recorded by the contractor who is paid according to the agreed upon unit price. This payment method is appropriate for both competitive bidding and direct selection contracts.

In the cost-plus-fee method of payment, the contractor is paid for the actual materials and labor plus an additional amount for profit and overhead. This additional amount may be an agreed upon percent of the actual costs or a fixed amount. This method is used almost exclusively for direct selection contracts. Tight management is necessary because there is no incentive to control costs. To control costs, the bidder may be required to state a guaranteed maximum price that will not be exceeded.

Contracts may include incentive clauses that provide additional payment for early completion of work or good performance or penalty clauses for late completion of work. Such clauses are included when a timely completion is very important.

Job Specification Format

Field problems with painting contracts can best be avoided with a systematically prepared specification that uses a standard format. This makes it easier to avoid overlooking any important item. A standard format also makes it easier for those preparing bids or executing the contract to accomplish their work, because all the requirements can be found in the same part of the document, as in all previous documents from the organization.

The format of the Construction Specifications Institute (CSI) is used by the federal and many state governments, as well as private industry.[2-4] The CSI format divides all construction work into 16 divisions by the building trade involved with the work. Finishes are always in Division 9 and paints and protective coatings in section 09900 of Division 9. All sections have five digit numbers. Each CSI section is divided into three basic parts:

- Part 1. General
- Part 2. Products
- Part 3. Execution

Part 1. General

The following sections are listed under headings in broad agreement with the CSI specification format. They are defined and discussed from a coatings viewpoint. It is not necessary to use those sections that are not applicable for a particular job specification. Additional sections may be added to include appropriate general information that does not fit into other sections.

- Summary (Introduction)
- References
- Definitions
- Submittals
- Quality assurance
- Delivery, storage, and handling
- Project/Site conditions
- Sequencing and scheduling
- Warranty

Summary (Optional)

A summary or introduction section at the start may present the scope and purpose of the work. Care must be taken to avoid inclusion of any requirements described elsewhere in the document, because slightly differing descriptions can result in problems of interpretation. Thus, many organizations prefer to use only the title of the specification to introduce the document.

References

The reference section, sometimes called "Applicable Documents," should include a listing of all documents used in the specification and no others.

Others included only for general information may be interpreted as requirements. Listed references form a part of the specification to the extent indicated.

All standards referenced in the document should be complete with designations and titles. Any test variations and compliance requirements should be listed elsewhere in the specification. Industry specifications and standards such as those of SSPC are preferred to government standards for equivalent products or processes. In all cases, issuing organization, number, and latest issue are normally listed. Unless otherwise indicated, the issue in effect on the day of invitation for bids applies. Where alternative standards occur, the normal order of precedence is:

1. Industry Documents
2. Federal Documents
3. Military Documents

This should not be confused with the order in which they are normally sequenced in the specification reference listing—alphabetically by organization name, or by document category name. For example:

1. American Society for Testing and Materials (ASTM)
2. Federal Specifications
3. Society for Protective Coatings (SSPC)

Within each of the above categories, individual documents are listed numerically. References should be listed only for items described in the body of the specification to minimize error. Where alternative standards or practices are available, only one of them should be used. Thus, both SSPC-PA 2, *Measurement of Dry Coating Thickness with Magnetic Gages* and ASTM D 1186, *Standard Test Methods for Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to a Ferrous Base* should not be referenced in a specification.

Definitions

The definition section is used when necessary to define unusual terms or unique methods of using them. An understanding of terms used in painting operations may vary widely in different geographical locations and even between different people in the same location. Definitions for such words may prevent costly disputes over different interpretations.

Submittals

Specification submittals are documents or samples to be provided by the contractor to the owner. They are provided to assure the owner that specific requirements will be met. Submittals may be required before, during, or upon completion of the work. They may include:

- Samples of coatings to be used
- Drawdown coating films (cured films of uniform thicknesses applied to cardboard or other substrates)
- Blast-cleaned reference panels
- Laboratory test results
- Certificates of conformance
- Product data sheets
- Material safety data sheets
- Manufacturer's instructions
- Supplier's field reports
- Shop drawings
- Warranties

Complete laboratory testing of paint for conformance to specification can be very expensive and thus is not often done except where very large areas are coated or where the coating provides a critical function. More often, the owner accepts certificates of conformance. These are basically statements that a previous representative batch of the same formulation has met specification requirements, and a few quick laboratory tests by the supplier indicate that the present batch does also.

Sometimes, authenticated wet samples of coating are retained for later laboratory testing should early failure occur. They are normally retained for only one year, the normal warranty period. The specification should also permit field sampling of coatings being applied.

For large or critical batches of paint, factory-witnessed manufacture or testing is sometimes done. These and first article (pre-production) tests can be very expensive and so should be used only where the expense is justified. Manufacturer's data sheets and instructions may be used to define under what conditions and by what methods their products can be successfully applied to produce a quality film. Inspection and safety procedures may be required in order to obtain information on how these aspects will be handled.[5]

Quality Assurance

The quality assurance part includes prerequisites, standards, limitations, and criteria that define the

quality of materials and work. They may include the following:

- Qualifications
- Certifications
- Regulatory requirements
- Field sampling requirements
- Pre-construction conference

Qualification or certification statements may be requested to establish the capabilities of the contractor and those employed by the contractor. SSPC-QP 1, *Standard Procedure for Evaluating Painting Contractors (Field Application to Complex Industrial Structures)* may help assess a contractor's ability to complete the work in a satisfactory and timely manner. Additional certification may also be required, e.g., if asbestos or lead-based paint complicate the work.

It is desirable to include a clause permitting the contracting officer to procure at any time a sample of the paint being applied. Local air pollution personnel usually have this authority. All prevailing regulations should be included in the submittals, so that they are on-site. The contractor must be familiar with all of them. Material Safety Data Sheets for all paints, solvents, and other materials to be used should also be submitted and kept on site.

A pre-construction conference of owner and contractor personnel should be held before the work begins. At this time, any differences of opinion or uncertainties should be resolved. Any agreements reached that affect the specification should be written down and signed by both parties so that it becomes a part of the contract. Any differences not resolved may result in costly change orders.

Delivery, Storage, Handling, and Disposal

Special requirements for packing and shipping of products, equipment, and components should be stated here. Conditions for acceptance of these items at the project site should also be included. Special storage and handling requirements necessary to prevent contamination or damage to products during storage or use should also be included. Spill kits and procedures established to clean up spills may be required.

Project Site Conditions

Any physical or environmental limitations or criteria at the project site should be stated. These may include temperature, weather, humidity, or ventilation. The site conditions must be completely and correctly defined. Existing structural and geophysical reports should be referenced.

Variations from the description of the site conditions may cause costly modifications to the specification. They may concern the size or scope of the work, the extent of corrosion or coating deterioration, the construction or coating materials, or other things that affect the work to be done.

Some specifiers do not examine the job site but rely on drawings on file that may not be current. Structural additions or changes significantly increasing the level of effort may have occurred since the drawing was made. Another common error is to underestimate the amount of loose, deteriorated coating that must be removed in maintenance painting. Loose paint is generally not well defined. The best definition is probably paint that can be readily removed with a dull putty knife.

Sequencing and Scheduling

The requirements for coordinating work that must be done in special sequence with, or at the same time as, work with other trades should be clearly stated. Any other special scheduling requirements should also be stated.

Warranty

Special or extended warranty or bonding covering the conformance or performance of the work should be stated. Warranties for coating work are typically for one year.

Maintenance (Optional)

Provisions for maintenance service, if any, should be listed. These should include items difficult to obtain such as matching colors.

Part 2. Products

This part provides information about all products to be used. These products include:

- Cleaning materials
- Coating materials, including thinners
- Support materials
- Equipment

Products may be named in Division 9 or other divisions of the specification.

Materials

All materials to be utilized on a job must be well defined. These include cleaning, coating, and support materials such as scaffolding and other systems required for safety.

Paint products can be specified by several options:

- By government or industry specification
- By qualified products list
- By brand name
- By properties

Federal, military, state, and industry coating specifications can often provide the best source of information concerning a particular generic coating system. They are usually based upon materials with well-documented performances. These specifications often have qualified product lists of materials that have been tested in the laboratory and field and have been found to perform well for the intended service. Names and addresses of manufacturers are listed for each listed product. The names of products that have the capability to supply the desired properties can be listed and supplemented by brand names or other proprietary designations. It is especially wise to specify products that have provided previous good service on the actual structures or equipment to be coated. Specifying “Brand X or equal” is another dangerous method of describing a product. There is no specific definition of “equal” or procedure to determine such equality.

If commercial products are specified, their colors should be selected from the manufacturer’s list of available colors. Whatever the method of specifying products, it is best to require that all products for a multiple-coat system be procured from the same supplier. This will avoid compatibility problems and eliminate disputes as to which manufacturer may be liable for coating defects. Products used to coat items in a fabrication shop offsite should be specified as fully as those to be applied onsite.

Substitution products are frequently requested by a contractor, subcontractor, or material manufacturer during the bidding, before beginning the work, or while doing it. Some of the reasons for considering substitutions are:

- To encourage a more open and competitive bidding process
- To allow the use of products that the contractor is more familiar with or from a manufacturer that provides field support
- To allow the contractor to procure more readily available products
- To use cheaper products to reduce work costs

Some of the concerns about substitute products include:

- Substitution products may be inferior to the specified products
- Some aspects of the substitute product may not be suitable (e.g., loss of gloss, color fading, ease of maintenance etc.)
- Significant time may be required for the specifier to evaluate the substitution product
- Significant time may be required for accelerated testing of the substituted product.

Equipment

Information describing the function, operation, and other important aspects of required equipment should be included. Each article of required equipment should be specifically named in this part of the specification and this name used throughout.

Part 3. Execution

The execution part of the specification describes the use of the materials described in the products part. It should include sufficient sections and subsections to adequately describe all the work to be accomplished.

Much of the detailed information for execution of a specification may be found in drawings or other referenced documents that form a part of the specification. Drawings are used to provide a graphic representation of the work to be done. They define the areas to be coated and provide a schedule of coating systems and colors to be used. To prevent problems resulting from variations between descriptions found in the body of the specification and those found in associated documents, it should be stated that where such duplication occurs, requirements found in the body of the specification pre-empt those found elsewhere. It is always best to describe a desired product rather than tell how to achieve it. It is sometimes advantageous to permit a contractor to use creativity and experience to determine the best means to meet a requirement.

It is usually very difficult to define the desired quality of the work. Quality requirements should be readily attainable and measurable and never greater

than is actually needed for the particular service. Ambiguous statements such as “best quality work” should be avoided. It is better to refer to refer to trade or industry standards such as SSPC-PA 1, *Shop, Field, and Maintenance Painting of Steel*.

Examination

Before actually beginning the work, the contractor should be required to examine the work site to determine that all prevailing conditions are acceptable for the specified coating operations. Even if the contractor had examined the site before bidding, it is necessary to conduct a more detailed examination. Variations from expected conditions can prove to be very costly. Requirements should be stated for actions to be taken to prevent coating overspray onto structures or equipment that are not intended to be coated.

The contractor’s examination of the work site may also reveal any apparent deviations from the written description of the work to be done. If the inspection reveals that more work is required than initially believed from simply reading the specification, or if the specified work will not adequately meet the owner’s needs, these concerns should be resolved before beginning the work.

Pre-Surface Preparation

The requirements for preparing the facility or equipment for surface preparation and coating should be stated. These include structural modifications (e.g., grinding of welds, rounding of sharp edges, etc.) as well as masking and containment work.

Surface Preparation

Surface preparation requirements should be well defined. They should include immediate priming of metal surfaces after acceptance of cleaned surfaces and require reblasting when flash rusting occurs.

As discussed earlier in this (Execution) part, it is illegal to both describe a product and how it is to be achieved. Thus, if the specification calls for a specific abrasive be used to blast clean steel by holding a venturi nozzle with 90 to 100 psi 8 inches from the surface and slowly moving it across the surface, there can be no requirement for the resulting degree of cleanliness (e.g., SSPC-SP 6/NACE 3, *Commercial Blast Cleaning*).

Application

All application requirements for primary products (e.g., coatings) should be stated. Permitted variations in tolerance (e.g., ranges of wet and/or dry film thickness) should be specified. Specifications may permit the use of brush, roller, or spray to apply coatings, as the contractor prefers. However, some materials can only be applied satisfactorily by one or two of these methods. Thus, zinc-rich coatings should be applied by spray equipment using an agitated pot and following the instructions of the coating supplier. The specification should state that any thinning of coatings should be limited to the thinner type and the amount specified. Thinning should also be specified as being within the limits set by local air pollution authorities.

Field Quality Control (Inspection)

All test and inspection requirements before, during, and upon completion of work must be defined completely. The individual or firm responsible for this work must also be specified. While use of an independent inspection firm is typical for large or critical jobs, material suppliers often provide field service instruction, supervision, or training in use of their products.

Industry standard test procedures should be described whenever possible. For example, SSPC-PA 2, *Measurement of Dry Coating Thickness with Magnetic Gages*, should be used to determine whether dry film thickness requirements have been met.

Site Clean-Up

Requirements for the final actions for completed work should be fully described. This includes clean-up of waste products and proper disposal of hazardous materials. Requirements for collecting, handling, and storing these materials during their generation should also be specified.

Changes to Specification

Addenda

Addenda are additions made to the documents during the bidding period to correct errors or omissions, clarify questions made by bidders, or issue new requirements, including the scope of the work. Typical addenda items:

- Change time, date, or location for receipt of bids
- Change the quality of the work

• Change the method of work sequence
• Add, delete, or revise the bidding documents
• Include additional qualified products

Before making addenda, the value of the work should be considered. It may be more advantageous to defer non-critical items until after completion of the contract.

Contract Modifications

Contract modifications are additions, deletions, or changes of the work requirements after the contract agreement has been assigned. This can be accomplished by change order, supplemental instruction, or field order at any time after the contract signing.

Language To Be Used In Specifications

For a specification to result in all needs being met, it must be:
• Clear—Use correct wording and grammar to avoid ambiguity or confusion
• Correct—Write accurately and precisely
• Complete—Do not omit any important items
• Concise—Eliminate unnecessary words without sacrificing clarity, completeness, or correctness

The language of a specification must describe exactly the product that is desired. The contractor is required to provide only the product described and no more. Thus, the specification writer must be very precise describing contractor requirements. The following recommendations should be helpful:
• Use short, specific words (avoid vague terms)
• Use short sentences
• Use common words that are clearly understood
• Place the action words at the beginning
• Use strong verbs
• Use the imperative (preferred) or indicative mood
• Do not repeat descriptions or requirements

Concise Words and Sentences

Words in the specification should be relatively short, specific, and easily understood. Avoid words that are ambiguous, vague, or otherwise not readily understood. Such expressions as “high-performance coatings” and “quality work” are too vague to be of any value.

Short sentences are more readily understood than longer ones. Also, the action words (subject and verb) should go up front. Thus, do not write: “After the steel has been properly cleaned and after the weather conditions have been verified to be acceptable, apply one coat of the specified primer.” Instead, write: “Apply one coat of the specified primer after . . .” Strong verbs such as “blast,” “clean,” and “prime” are more precise than weaker verbs such as “make,” “build,” and “establish.” Strong verbs are also more easily understood.

Grammar

Either the imperative or the indicative mode can be used to prepare specifications. The same mode should be used throughout the document. Use of the imperative is preferred to the indicative, because it is more direct, concise, and less likely to be misinterpreted. Examples of the imperative are:
• Blast clean the steel to SSPC-SP 10/NACE 2.
• Apply two coats of SSPC-Paint 16; each coat at 7 to 9 mils dry film thickness.
• Determine coating dry film thickness by method described in SSPC-PA 2.

The same examples in the also acceptable indicative mode are:
• The steel shall be blast cleaned to SSPC-SP 10/NACE 2.
• Two coats of SSPC Paint 16 shall be applied; each at 7 to 9 mils dry film thickness.
• The coating dry film thickness shall be determined by the method described in SSPC-PA 2.

Parallel construction should be used. Good and bad examples are shown below:
• **Incorrect:** Conduct tests to determine adhesion and measuring dry film thickness.
• **Correct:** Conduct tests to determine adhesion and measure dry film thickness.
• **Incorrect:** Cleaning, application, and inspection
• **Correct:** Cleaning, applying, and inspecting

Unnecessary Words

Unnecessary words such as “the,” “a,” and “all” should be avoided, as indicated below:
• **Poor:** Apply the epoxy primer with a spray gun to the concrete wall.
• **Better:** Apply epoxy primer with spray gun to concrete wall.

• **Poor:** Coat all metal components protected from the weather.
• **Better:** Coat metal components protected from the weather.

The word “contractor” should not be the subject of a sentence. It is better to say “The zinc-rich coating shall be applied by airless spray” rather than “Contractor shall apply zinc-rich coating by airless spray.” It should be noted that imperative mode automatically eliminates the use of the word “contractor” as the expressed subject of a sentence, although it is implied.

No information in the specification should be repeated in a second place because of the greater possibility of errors or because slight differences in description may receive different interpretations.

Vocabulary

Care must also be taken to use only standard terms such as “Brush-Off Blast Cleaning” (SSPC-SP 7/NACE 4), rather than “brush blast,” “sweep blast,” “shower blast,” or some other undefined term.

Summary

Every painting job to be done by a contractor or in-house should be written up as a specification. This will avoid disputes and result in the desired product. The specification should be clear, correct, complete, and concise. Otherwise some of these deficiencies may occur:
• Variation in site conditions
• Vague or incomplete wording of requirements
• Portions not legal or readily achievable

This, in turn, may result in the following work or working problems:
• Lower quality products than desired
• Lower quality work than desired
• Less work than desired
• Change orders
• Disputes
• Defaulted contracts
• Claims
• Litigation

By using a standard format and proper language and by including all the necessary information, problems with contract painting will be greatly reduced.

References

1. *Protective Coatings Glossary;* Richard W. Drisko, ed., SSPC: Pittsburgh, 2000.
2. *CSI Manual Practices;* Construction Specifications Institute: Alexandria, VA.
3. CSI MP-2-1. *Masterformat-Master Lit of Section Titles and Numbers;* Construction Specifications Institute: Alexandria, VA.
4. CSI MP-2-2. *Three-Part Section Format for Construction Specifications;* Construction Specifications Institute: Alexandria, VA.
5. *Inspection of Coatings and Linings,* Bernard R. Appleman, ed., SSPC: Pittsburgh, 1997.

About the Author

Dr. Richard W. Drisko
Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society for Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy’s center of expertise on coatings for shore structures. He is a professional corrosion engineer in the state of California, an SSPC certified protective coatings specialist (PCS), and a NACE International certificated corrosion specialist. Dr. Drisko received his BS, MS, and PhD degrees from Stanford.

Chapter 10.5
Maintenance Painting Programs

Richard W. Drisko and Joseph H. Brandon

Introduction

It is seldom that coating system components break down uniformly over a structure. By routinely evaluating the condition of coatings and designing and performing remedial actions in a planned fashion, it is often feasible to keep a coating system working to provide cost-effective corrosion protection and desired aesthetic features long after initial signs of degradation. This chapter describes the elements of a maintenance painting program—when to start and how to accomplish the steps. Other chapters of this book address maintenance painting issues specific to various industries.

Maintenance painting is defined in broad terms as all painting on industrial structures conducted for protection or aesthetics or as any coating work conducted subsequent to the coating work associated with construction to ensure continuous protection of coated surfaces.[1] Both of these definitions are used throughout this chapter.

According to the second definition, any coating work after the initial coating is maintenance coating; however, there are two distinctly different situations that may be encountered, each requiring different techniques:

• Existing coating system is considered to have served its useful life and should be removed to bare metal

• Existing coating system is performing its function to a significant degree, but requires either spot (localized) repair or spot repair and overcoating to extend its useful life. The situation where the existing coating is to be removed to bare metal is relatively simple to design in that the selection of surface preparation and coating system can be made without the constraints of having to respect the requirements of the existing coating system. Much is written on selecting surface preparation and coating systems for this situation, and it generally involves matching the coating system to the service conditions to be encountered, and then selecting the surface preparation to complement the coating system selection.

The remainder of this chapter will address the situation in which it is determined that spot repair or spot repair and overcoating may be economically feasible.

Why Maintenance Painting Might Be Valuable

The typical exterior protective coating system serves at least two primary functions: corrosion protection and aesthetics.

In the industry-standard zinc-rich epoxy, epoxy, aliphatic polyurethane coating system, the first two coats provide corrosion protection for the steel substrate, and since the epoxy is not resistant to UV radiation from sunlight, the aliphatic topcoat provides both protection of the underlying epoxy coats and aesthetic features (color and gloss).

There are many formulations of polyurethane and other UV resistant topcoat materials, and even though they are significantly more resistant to UV radiation than epoxies, all organic coating materials will eventually suffer from sunlight exposure and require replacement or “rejuvenation,” which might consist of a simple overcoat. Likewise, many combinations of circumstances can adversely affect the corrosion protection coats, including damp or wet conditions, steel surface contaminants, daily and seasonal thermal cycling, and strain from structural loading/unloading.

In an ideal situation, the corrosion protection coats and the aesthetic/protective topcoats would all fail simultaneously, after a significant number of years of service. This situation does not occur very often, especially since most UV topcoat materials are not capable of providing suitable protection for the anticipated lifespan of the epoxy corrosion protection coats. Typical behavior will find that the topcoat may be replaced one to three times before the corrosion protection requires replacement. Even so, it is likely that some corrosion protection will fail prematurely in small areas and require treatment.

As most coatings have finite life-spans, it periodically becomes necessary to either rejuvenate

the coating system or replace it. Rejuvenation can involve any combination of spot repair and overcoating to restore damaged areas to an acceptable condition and provide additional years of protection from any combination of sunlight, water, or chemical intrusion. Although coatings are sometimes replaced for aesthetic purposes only, and some are replaced on a fixed schedule, such actions are unlikely to be cost effective, due to the many variables involved in determining the useful life of a coating system. It is highly unlikely that the useful life of any coating system can be predicted with any accuracy, therefore, a methodology for identifying the specific needs of a coating system in service is required.

Because the cost of surface preparation for painting can easily exceed the cost of coating materials and coating application, any corrective action that does not require significant preparation to bare metal may be cost effective. To achieve the most timely and cost-effective actions, maintenance painting must be planned and accomplished systematically, using the latest available technologies. There are many examples of dramatic coating failures resulting from good intentions that were improperly planned or executed. The most notable failures are those caused by coating incompatibility related to:

- Differential coefficients of linear expansion between coats
- Attack of topcoat solvent on undercoat
- Limited adhesion between coats or to substrate

Early coating failures result in double payment, in that the service life extension that was recently executed is not realized, and the premature failure probably necessitates additional surface preparation and coating application to correct the failure. Such a failure is often addressed by complete removal because the owner does not want to risk further premature failure.

When viewed from a risk-management perspective, any maintenance effort other than complete removal and replacement seems to carry some additional risks over those of normal coating preparation and application. The risk of incompatibility of repair and existing coating is an added factor. Even though some believe that this risk is not manageable, proper knowledge of coatings may reduce these risks to manageable levels. This allows for cost-effective maintenance painting with relatively low risks but does require an understanding of the properties and the condition of the existing coating system.

Personnel concerned with the protection of structures and equipment by coatings often ask the following questions:

- How can I best develop a program for maintaining coating protection for different plant structures or facilities?
- How can I define the point of failure of the existing coating system?
- How can I determine whether localized repair of damaged substrate and coating or substrate repair and total coating replacement is the better choice?
- What coatings systems should be used in each case?
- When is the best time to take the necessary actions?

SSPC PA Guide 5, currently under revision, provides a methodology for planning and executing a maintenance painting program for steel structures, and discussion in this chapter is based on the general outline of the revised document.[2] While SSPC PA Guide 5 is specifically limited to steel substrates, the processes outlined in it are applicable to many other substrates, including concrete. The significant differences in the maintenance practices are in surface preparation and coating selection.

Maintenance painting programs can be developed for a plant, a government facility, a group of structures, or a single structure. There is efficiency inherent in managing a large facility or group of facilities over managing a small facility, as inspections are more cost effective for larger facilities, and contracting is more efficient for larger projects.

The methodology outlined in SSPC PA Guide 5 is:

- Perform a condition assessment survey
- Determine necessary corrective action
- Evaluate economics of available options
- Establish procedures for corrective action
- Execute corrective action and follow-up activities

Condition Assessment Surveys

Specific information required for developing a painting program for existing structures is generally acquired by a survey that is sufficiently detailed to provide for the appropriate decisions. Surveys range from simple walk-through inspections, intended to establish general painting needs, to detailed

itemizations of painted components with an assessment of the type and condition of coatings present on each. The varying levels of surveys, when used in an iterative process of identifying defects and prescribing priorities, provide an efficient and effective methodology for developing a maintenance painting plan.

While the costs of implementing a condition assessment survey program can be significant, there may be viable options that make use of existing inspection assets, particularly for initial screening, as described in the general overview survey here. Reference 6 describes the use of federally mandated bridge safety inspections to collect data on coating condition. Bridge safety inspectors are given visual guides for identifying specific coating and corrosion-related problems, and are provided minimal training in identifying and reporting those problems for further evaluation. The incremental cost of collecting this data is very low compared to a specific inspection for that purpose, making full use of the mobilization and demobilization costs of the safety inspections.

In other cases where operators are routinely working in or inspecting large portions of a facility or plant, simply making operators aware of the signs of both sound and stressed coatings, and how to report appropriate deficiencies, has proven effective in providing initial screening for coating maintenance needs.

This discussion specifically addresses a plant survey, yet the principles are equally applicable to individual components of a structure, complete structures, and multiple structures. The three levels of surveys are general overview survey, detailed visual survey, and physical inspection survey.

General Overview Survey

A general overview survey consists of a visual assessment of the overall conditions of substrates and coatings on plant structures. It is a relatively fast and inexpensive method to prepare general information on the overall conditions and establish times when maintenance actions can be anticipated. A simple numerical rating system (e.g., priority ratings of 1 through 5 as shown in **Table 1**) can establish work priorities if limited funds do not permit all of the desired work to be done. This method may also provide data for establishing a logical approach to subdividing the facilities into smaller units for a systematic collection of data in more detail.

Table 1. Priority Rating System for Maintenance Painting.

Rating	Condition Evaluation
1	Slight or no damage to coating or substrate, requiring no maintenance in near future.
2	Slight localized damage to coating or substrate, requiring localized maintenance within one year.
3	Moderate localized damage to coating or substrate, requiring localized maintenance within one year.
4	Thin coating from erosion or application, requiring additional thickness for corrosion protection, often with slight or moderate localized coating or substrate damage, requiring overcoating within one year. This may also identify aesthetic requirements.
5	Extensive coating or substrate damage, requiring total coating replacement, often with substrate repair.

Detailed Visual Survey

In a detailed visual survey, facilities are subdivided into smaller units in order to obtain more information about individual components. Alternatively, these components can be subdivisions related to function (e.g., architectural, electrical, mechanical, etc.). This survey level provides more detailed data.

The types and extents of substrate and coating deterioration are made in accordance with industry standards. Definitions for defects are found in Reference 1 and depicted pictorially in References 3, 4, and 5. The latter three references can be used very effectively to identify types of defects. Additional assistance can be found in the chapter of this book that discusses coating failures and failure analysis.

The extent (percent) of defects in localized areas can be determined using SSPC VIS 2.[7] A series of pictures visually depicts different levels of deterioration for more precise estimation. The general distribution of defects in large areas can be determined using Reference 8, which presents a series of pictures of known distributions levels of deterioration.

It should be noted that natural deterioration occurs more rapidly at edges and other irregular areas where cleaning and coating is more difficult or in localized areas where the environmental forces are more severe. Exterior water traps (where rain water collects) present an especially severe environment.

Physical Inspection Survey

In a physical inspection survey, the individual components are further subdivided, and actual

physical tests are conducted on the coatings, notably dry film thickness and adhesion. These values are critical in establishing whether the existing coating has adequate properties for localized repair rather than total replacement.

Deterioration including film erosion, blistering, rusting, chalking, checking, cracking, peeling, flaking, and dirt and mildew accumulation should be identified and quantified using ASTM rating standards. In some cases, it may be necessary to inspect the surface for contaminants including grease, oil, and soluble salts. The inspection should determine the types, quantities, and locations of contaminants.

If appearance is important, the extent of color fading, discoloration, loss of gloss, etc., should be measured using standard ASTM procedures. Should the generic type of the existing coating be unknown, it may be necessary to submit a sample for analysis to find a compatible repair material.[9] When the composition of the existing coating is not known, it may be necessary to submit a sample for analysis to determine if any constituents (e.g., lead, chromium, cadmium, PCB, etc.) will require actions for health, safety, or environmental compliance.

When pitting corrosion is present, measuring pit depth may be very important. Ultrasonic measurements of substrate thickness are sometimes performed on steel that is subject to severe general or localized corrosion and subsequent loss of cross section. These inspections are performed because severe localized or general corrosion may affect structural integrity or the intended function of the structure, such as containing a fluid. Pit shape and aspect ratio also have a bearing on the type of surface preparation that will be required.

A physical inspection survey provides the necessary data that defines the work requirements for a specification. The additional expense for a detailed survey is well justified by minimizing risks associated with maintenance painting.

Performing a Hazardous Content Assessment

If the composition of the coating system is unknown, then samples should be submitted for laboratory evaluation for hazardous materials such as lead, chromium, cadmium, polychlorinated biphenyls (PCBs), and other materials controlled by federal, state, or local laws or regulations. The existence of hazardous materials may be a major factor in determining both short and long-term strategies for management.

Determine Corrective Action Required

Analysis of Survey Data

The condition of the existing coating system, which may vary from area to area, and component to component, will dictate the approach that is required to restore functionality. The survey data should be collected systematically using a standard printed form in a complete and quantitative manner to obtain sufficient data for reliable decisions. There are seldom too much data available.

While it would seem appropriate to establish deterioration levels at which maintenance work should be undertaken (e.g., 10% substrate or coating deterioration), there are many other factors that affect decision making. Those related to the coating survey are discussed here.

Type and Extent of Substrate Damage and Coating Deterioration. The nature of any corrosion (e.g., uniform, pitting, filiform, etc.) is very important in determining the best corrective actions. Thus, pitting corrosion may be critical to a storage tank, if penetration of a steel wall or floor is threatened.

Concrete deterioration should be described separately. Conditions such as efflorescence, laitance, cracking, and spalling, and appropriate corrective actions for each, are described in Reference 10.

The nature of the coating deterioration is important in order to determine the causes and thus appropriate corrective actions. Reference 1 describes causes and corrective actions for coating deterioration.

Judging the extent of damage to substrates and coating is critical in determining whether spot repair of substrate and coating or more extensive substrate repair and a total replacement of coating is more appropriate. To determine the total extent of coating deterioration, it may be necessary to scrape with a dull putty knife to expose all of the damaged areas. Visually sound coating may have poor adhesion to its substrate.

Distribution of Substrate and Coating Deterioration. The distribution of substrate and coating damage can determine whether only localized damage repair will be necessary. For example, at a coastal airfield at a

tropical location, all of the metal corrosion and coating deterioration on a group of hangars was limited to the exposure facing the ocean.

Loss of Coating Function. Some coatings have functions other than substrate protection. These include non-slip, reflective, or electrical-conductive properties. If these properties have been significantly reduced, it may be necessary to restore them by total repainting.

Rate of Increase of Deterioration. An important part of a deterioration control program is the periodic survey of the component structures. (Navy shore facilities receive annual condition inspections.) By establishing the current rate of deterioration, the likelihood of further significant deterioration with deferred maintenance can be deduced.

Type of Coating. The type of coating is important in determining compatibility with the system selected for localized repair as well as the type of surface preparation necessary prior to overcoating. All localized-repair coatings must not only cover the damaged areas but also overlap onto the sound existing coating.

If compatibility cannot be established from historical records, a test patch of the proposed system may be applied to the existing coating to establish this. Additionally, a laboratory technique, Fourier Transform Infrared Spectroscopy (FTIR), is frequently used to determine the generic coating type. This requires only a tiny sample paint chip to identify the coating type, and is available at a nominal price.

Adhesion. Coatings with limited adhesion, either to their substrates or between coats, are likely to have their adhesion further reduced. Thus, topcoating may actually accelerate total coating deterioration. This situation is frequently seen on newly overcoated structures, where the coating comes off in sheets.

ASTM test methods provide for both qualitative and quantitative methods of testing adhesion. Adhesion generally becomes more of an issue as the thickness of the coating system increases, although intercoat delamination due to application deficiencies can occur at any thickness. *SSPC TU 3: Overcoating* discusses the significance of adhesion testing in maintenance overcoating.

Film Thickness. It is important to determine if the existing coating system is sufficiently thick to provide the required barrier protection. Unusual thinness could be a result of improper application, or from chalking erosion or some other mechanism that has significantly reduced the film thicknesses of the existing coatings. This may, in turn, significantly reduce the barrier protection of the substrate. It is also important to know if there is excess coating thickness, as this can cause premature failure if the thickness overstresses the adhesion to the substrate, or between coats. SSPC TU 3, *Overcoating* discusses the significance of high film thickness in maintenance overcoating. SSPC PA 2 describes a standard process of determining the coating thickness on a structure.[11]

Appearance. Coating appearance may be an important factor in selecting the types of corrective actions. This is especially true for structures in public view and where worker morale is important. Localized repair may produce an unsightly patchy appearance. A complete finish coat may be applied to remove this.

Hazardous Materials in Paint. There are numerous issues involved in evaluating coatings containing hazardous materials, most of which are detailed in References 12 and 13. While deciding how to treat coatings containing hazardous materials, it may be advantageous to consider that the hazardous materials may be an integral part of the corrosion protection mechanism (e.g., inhibiting effects of lead pigments). Depending on the condition of the coating system, it may be possible to achieve additional use from that corrosion protection mechanism through timely and appropriate maintenance.

Other Factors Affecting Decisions

Unfortunately, there are some factors unrelated to survey data that affect the choice of maintenance actions. Some of these factors are described here.

Limited Funding. Maintenance funds may not be available in sufficient quantity to cover all of the needed work. In these cases, work should be prioritized to maximize the overall economic benefit. To avoid funding shortfalls, take surveys periodically, so that future funding requirements can be determined and requested to meet anticipated maintenance requirements in future years.

Risk of Deferred Maintenance. If needed repairs are deferred, then it is possible that future coating repairs will need to be more extensive.[14] In extreme cases, deferred maintenance may lead to severe substrate damage and subsequent loss of structural functionality. This may result in significantly increased life-cycle maintenance costs and other unintended economic losses from things like environmental contamination, service outages, and various emergency repairs.

Effects of Maintenance Actions on Plant Operations. Maintenance work of any kind is likely to affect continuing operations. It may be necessary to conduct the maintenance work at night, on weekends, or at a time of total operational shut down. Obviously, interference with plant operations must be minimized.

At times of total operational shut down, other maintenance work is often undertaken as well. In such cases, schedules must be established to minimize interference between trades.

In some instances, the indirect cost of an outage far exceeds the cost of the maintenance painting itself. This is especially true of systems that produce large revenue streams, such as processing, manufacturing, transportation, and power production equipment. Here coating repairs are sometimes scheduled to coincide with other repairs.

Sometimes the scheduled outage is short lived and coating repairs must be rapid, sacrificing thoroughness for speed. This may be an economical approach where periodic maintenance outages are fairly frequent, such as in paper plants. In other situations it is more economical to ensure that coating repair life is as long as possible to minimize the frequency of repair outages. This is often true for power generating hydro turbines and chemical process tanks.

Contamination of Products. If substrate and/or coating deterioration is causing contamination of products, immediate corrective action is usually necessary. This is particularly true for such industries as food processing, pharmaceuticals, chemical production, electronics manufacturing, and sophisticated electronic instrumentation.

Maintenance Painting Strategies

There are four approaches to maintaining a structure in satisfactory condition, generally in the order of increasing cost:

- **Cleaning—**Pressure washing or steam cleaning may satisfactorily restore structure to an acceptable condition.
- **Spot repair—**Repairing areas with localized damage but otherwise sound paint should be done before the damage becomes more extensive.
- **Localized spot repair—**Combine localized spot repair with complete topcoat refinishing only when localized repair would produce an unacceptable aesthetic finish or where localized repairs plus added film build are needed to repair eroded coating.
- **Complete removal—**Remove all existing paint and then totally repaint only when the damage is so extensive that spot repair or overcoating are not economical.

These strategies may be used individually or in combination, based on the requirements of the specific structures. The objective is to provide complete corrosion protection and suitable aesthetics with the least amount of paint, and the least number of painting/repair/repainting evolutions. This requires that each situation be considered on its merits.

Economics of Maintenance Painting Options

Regardless of the needs of the coating system, economics generally is the most important variable, and it frequently dictates the characteristics of the chosen action. Periodic structural condition assessments should be performed in advance of the budgeting process; however, even that does not guarantee that necessary funds will be available when needed.

The fact that properly executed maintenance painting plans will provide a basis for evaluating all viable alternatives is advantageous to the owner, and should not be overlooked as a valuable tool for both protective coating maintenance in both routine and “lean” times.

Establishing Procedures for Corrective Action

As a result of surveys and analysis, deficiencies should be identified and the need for corrective action should be apparent. The next step is to match potential solutions to the deficiencies in a manner that

is both achievable by the prospective workforce and addresses the deficiencies appropriately.

Coating Selection

Numerous factors may require attention, such as compatibility with any existing coatings, exposure environment, surface preparation and application conditions, surface preparation limitations, and health, safety, or environmental requirements.

Surface Preparation Method and Coating Materials for Complete Recoat Strategy

This is generally the easiest maintenance strategy in terms of selecting surface preparation methods and coatings, since compatibility with existing coatings is not involved, and the surface preparation requirements can be properly matched to those of the chosen coating system. Much guidance exists on selecting these items for specific structures and service and work conditions, including numerous chapters of this book.

Surface Preparation Method(s) and Coating Materials for Spot Repair or Spot Repair and Overcoat Strategy

This is a matter of matching the needs of the existing coating system with compatible and suitable coatings that can be applied under the specific field conditions using appropriate and achievable surface preparation. The process can become a multi-dimensional equation and it is frequent that sacrifices must be made to accommodate certain limitations.

Surface preparation requirements may also vary from area to area, or component to component, and should be chosen to provide the required surface conditions and a useful repair but not be so onerous as to be impossible or impractical to achieve.

Although abrasive blasting is a recognized surface preparation method for bare steel surfaces, the use of abrasive blasting for spot repairs may not be suitable in all cases, due to controls on dust and grit, or the potential for damage to surrounding coatings, equipment, or other sensitive parts or surfaces. Spot repairs, particularly where there is a paint build-up, will generally require feathering the old paint to provide for a transition to the new paint.

Select Method of Work Accomplishment

There are numerous methods of accomplishing coating work, and owners generally have one or more methods that suit their needs. The first decision is whether to perform the work in-house or by contract, and if by contract, which form of contract, and so on. This is typically a decision that the owner makes after evaluating the needs of the coating work with respect to in-house capabilities, if any.

Prepare Specifications and Execute Work

Reference 15 provides guidance for preparing protective coating specifications for atmospheric service. An extremely important part of any coating project is competent inspection. There are multiple sources of such inspection, including those certified by the National Association of Corrosion Engineers International (NACE) under the Coating Inspection Program (CIP), and from inspection companies certified by SSPC to the requirements of SSPC QP 5.[16] It is most important to try to maintain inspector independence from the contractor operations to avoid undue influence on the inspection results.

If an extended warranty is desired, the precise details of that warranty should be delineated, such as term, identification of warrantor (contractor, manufacturer, other), definition of failure, and allowance for manufacturer/contractor to inspect at regular intervals and make appropriate repairs.

It is quite typical for an owner to rely heavily, even to the point of eliminating the owner's inspection, on a warranty that is subsequently found to be unenforceable due to the manner is which it was written. This situation significantly increases the life-cycle cost of coating maintenance.

Follow-up Actions

Regular inspections are an important part of any maintenance program. All inspections should be documented for warranty and latent-defect purposes. An inspection should be made prior to the end of the warranty, if only a one-year general warranty was required, or at appropriate intervals if an extended warranty was required. The American Waterworks Association, for instance, recommends that water storage facilities be inspected at an interval not exceeding 3 years, for safety, sanitation, and cost-effective maintenance.[17] Guidance is provided for inspecting the coating system.

Life-cycle costs may be significantly reduced by identifying and implementing preventive measures

to reduce stresses on coatings, such as timely removal of chemical spills, deicing salts, etc.

Summary

Generally speaking, it is easier to design for maintenance coating by requiring complete removal of all coating material to bare steel rather than evaluating the existing coating system for repair and/or overcoating. However, this is often the most expensive option. Other options that might be much more cost-effective will require competent evaluation.

Yet such evaluations are frequently overshadowed by the savings when considered in a life-cycle cost analysis. By implementing a complete coating maintenance program that includes routine inspections and appropriate evaluations, an owner may be able to significantly reduce the life-cycle costs of corrosion protection and functional aesthetics in addressing the specific needs of coating systems as they occur.

References

1. *Protective Coatings Glossary;* Richard Drisko, ed.; SSPC: Pittsburgh, 2000.
2. SSPC PA Guide 5. *Guide to Maintenance Painting Programs*; SSPC: Pittsburgh, 1990.
3. *Techdata Sheet 82-08: Paint Failures: Causes and Remedies;* Naval Facilities Engineering Service Center: Port Hueneme, CA, 1982.
4. *Visual Comparison Manual: Application and Coating Defects;* Fitzsimons, Brendan, ed.; SSPC: Pittsburgh, 1999.
5. Munger, C.G.; Vincent, Lou. *Corrosion Prevention by Protective Coatings;* NACE: Houston, 2000.
6. Melewski, Peter M.; Kline, Eric S.; and MeLampy, Michael F. *Protective Coating Analysis and Bridge Maintenance;* SSPC: Pittsburgh, 1997, p 1.
7. SSPC VIS 2. *Standard Method of Evaluating Degree of Rusting on Painted Steel Surfaces;* SSPC: Pittsburgh.
8. ASTM F 718. *Standard for Shipbuilders and Marine Paints and Coating Product/Procedure Data Sheet;* ASTM: West Conshohocken, PA.
9. Drisko, Richard W. *Total Protective Coating Program: Technologies for a Diverse Environment;* SSPC: Pittsburgh, 1996, pp 283-289.
10. *The Fundamentals of Cleaning and Coating Concrete;* Randy Nixon; Richard Drisko eds., SSPC: Pittsburgh, 2001.
11. SSPC PA 2. *Measurement of Dry Coating Thickness with Magnetic Gages;* SSPC: Pittsburgh, 1996.
12. *Industrial Lead Paint Removal Handbook;* SSPC: Pittsburgh, 1993.
13. *Industrial Lead Paint Removal Handbook, Volume 2;* SSPC: Pittsburgh, 1995.
14. *SSPC Technology Update No. 3: Overcoating;* SSPC: Pittsburgh, 1997.
15. SSPC-TR 4/NACE 80200. *Preparation of Protective Coating Specifications for Atmospheric Service;* SSPC: Pittsburgh and NACE: Houston, 2000.
16. SSPC QP 5. *Standard Procedure for Evaluating Qualifications of Coating and Lining Inspection Companies;* SSPC: Pittsburgh, 1999.
17. *AWWA Manual M42: Steel Water Storage Tanks;* AWWA: Denver, 1998.

Bibliography

ASTM D 610-01 *Standard Test Method for Evaluating Degree of Rusting on Painted Steel Surfaces;* ASTM: West Conshohocken, PA.
ASTM D 4214-98 *Standard Test Methods for Evaluating the Degree of Chalking of Exterior Paint Films;* ASTM: West Conshohocken, PA.
ASTM D714-87(2000) *Standard Test Method for Evaluating Degree of Blistering of Paints;* ASTM: West Conshohocken, PA.
ASTM D 3359-97 *Standard Test Methods for Measuring Adhesion by Tape Test;* ASTM: West Conshohocken, PA.
ASTM D 661-93(2000) *Standard Test Method for Evaluating Degree of Cracking of Exterior Paints;* ASTM: West Conshohocken, PA.
ASTM D 662-93(2000) *Standard Test Method for Evaluating Degree of Erosion of Exterior Paints;* ASTM: West Conshohocken, PA.
ASTM D 4541-95e1 *Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers;* ASTM: West Conshohocken, PA.
ASTM D 6677-01 *Standard Test Method for Evaluating Adhesion by Knife;* ASTM: West Conshohocken, PA.
FAA Advisory Circular AC 70/7460-1K *Obstruction Marking and Lighting;* FAA: Washington, DC, 2000.
Generic Coating Types: An Introduction to Industrial Maintenance Coating Materials; Lloyd M.Smith, ed., SSPC: Pittsburgh, 1995.

Protective Coatings: Fundamentals of Chemistry and Composition; Clive H. Hare, ed., SSPC: Pittsburgh, 1994.
Vincent, L.D. *Failure Modes of Protective Coatings and Their Effect on Management;* SSPC: Pittsburgh, 1998.

Acknowledgements

The authors and SSPC gratefully acknowledge the participation of Harold Clem and Tim Race in the peer review process for this document.

About the Authors

Dr. Richard W. Drisko
Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society of Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy's center of expertise on coatings for shore structures. He is a professional corrosion engineer in the state of California, an SSPC certified protective coatings specialist (PCS), and a NACE International certificated corrosion specialist. Dr. Drisko received his BS, MS, and PhD degrees from Stanford.

Joseph H. Brandon
Joseph H. Brandon, a protective coating specialist with the Naval Facilities Engineering Service Center (NFESC), specializes in industrial coatings for both steel and concrete. A member of the International Concrete Repair Institute (ICRI) and several SSPC and NACE committees, he holds protective coatings specialist certifications from both SSPC and NACE, and is a NACE certified corrosion inspector. He has a BS degree in structural engineering.

Chapter 11
Quality Control for Protective Coating Projects

Thomas A. Jones

Scope

The purpose of this chapter is to provide an overview for individuals involved in quality control inspection for protective coating projects. Many times inspection is considered the primary quality control activity, when in fact inspection is only one part of the quality control process. Equally important are the activities of document control, calibration verification, and identifying nonconformances and recommending corrective actions. This chapter concentrates on quality control performed by individual inspectors on the project level and not an overall quality program.

Terminology

• Quality control (QC) is gathering and documenting information that verifies that the work performed meets or exceeds some minimum standard as required by project specifications.[1]
• Quality assurance (QA) is defined as the process to verify that the quality of the work performed is actually what is claimed on the basis of the quality control performed. Quality control is not synonymous with quality assurance. Quality assurance is meant to protect against failures of quality control.[1]
• The quality program or quality system establishes and controls the level of QA and QC that may be required to show conformance to a specification or industry accepted standard.
• The Quality Control Manual is the governing document of written procedures used to implement the quality program.
• The QC manager or supervisor is the qualified person designated by upper management with the full support and authority to oversee the quality program. The overall quality program is maintained and evaluated on an annual basis by the QC manager who is responsible for issuing corrective actions and implementing revisions to the quality program. [2]
• The QA or QC inspector is the qualified person designated by the QC manager to perform individual inspections and verify that work is being performed according to the predetermined criteria. The QC inspector should have the authority and support of upper management to identify nonconformance, recommend corrective actions, and stop work if required.[2]

Standards and Guidelines

In addition to this volume, the following SSPC publications provide standards, procedures, and guidelines to better understand the quality control process:
• SSPC-QP 1. *Standard Procedure for Evaluating Painting Contractors (Field Application to Complex Industrial Structures)*
• SSPC-QP 3. *Standard Procedure for Evaluating Qualifications of Shop Painting Applicators*
• SSPC-QP 5. *Standard Procedure for Evaluating Qualifications of Coating and Lining Inspection Companies*
• *The Inspection of Coatings and Linings*

Pre-Job Review

Contract and Specification Review

Prior to beginning any job the specification and all supporting documents should be reviewed by the designated individuals responsible for overseeing the job. Written acknowledgement of the specification, revisions, supporting documents, and correspondence should be provided. Ambiguous specifications and uncertainties and differences of opinion should be documented in writing and maintained in the job file. The quality control section of the specification may require verification of conformance of certain requirements prior to starting the job.

Quality Control and Inspector Requirements

All persons designated as inspectors may be required to have sufficient documentation or records available for:
• Formalized training or certification of the inspector
• Experience in the type of structure to be inspected

• Inspection equipment required by the job specification available to the inspector
• Records of calibration for all inspection equipment used by the inspector
• Standards and procedures required to show conformance to job specifications are available to the inspector
• Approved copies of material supplier technical data sheets, application instructions, and Material Safety Data Sheets (MSDSs)

Inspection Plan

A written inspection plan to show conformance to the specification may be required. The inspection plan should list inspection hold or work-stoppage points that conform to the individual specification requirements or industry standards and procedures. The following listed inspection hold points are considered basic for most work.[3] Additional inspection hold points may be added if necessary:
• Prior to the start of work
• Immediately following surface preparation
• Immediately prior to the coating or lining application
• Following the application of each coat
• Following the curing of the coating or lining
• Final inspection and sign off, in accordance with job specifications

Document Control

The inspector should have sufficient inspection forms and records to show verification to the specification. Specific items required for documentation may vary depending on the job specification. Some specifications require the use of specified forms or approved standard forms. The frequency of recording and reporting all documented information should be determined and understood by the inspector prior to beginning the inspection assignment. Forms should have their own unique numbering system along with a filing system for efficient control. Several examples of different types of reporting forms may be found at the end of this chapter.

Pre-Job Conference

The inspector, owner representatives, applicator, and supplier should attend a pre-job conference. At this time, the inspector should identify any missing, incomplete, unclear, or ambiguous statements and communicate this information to the owner's representative. All uncertainties and differences of interpretation should be resolved and documented in writing. Prior to starting the job, the inspector, applicator, and owner's representative should have a clear understanding of the work requirements. In addition the degree of the inspector's authority to stop work or make any other managerial decisions should be established in writing by the owner and communicated to the applicator. An inspector must be careful to never overstep this degree of authority.[4]

Daily Inspection Activities

Daily inspection activities vary according specification requirements and the level of inspection performed by the inspector. In order to show conformance to specifications the inspector should prepare detailed documentation of work performed by the applicator. Inspection records provide a means of ensuring that deviations from the specification are corrected prior to final acceptance. In the event that more than one inspector inspects the work, the records provide a history of what has transpired and of the current status of the project.

Revision Log

The revision log should document the receipt of all revisions and changes to the specifications and inspection procedures. Issuance of all revised specifications should be documented along with verification that all persons involved in the inspection process and the applicator are properly informed of any changes. The removal of obsolete specifications and procedures should be verified.

Technical Resources Availability

The inspector should have available at the job site all necessary standards, quality control inspection procedures, and technical references required to verify conformance to the job specification. The inspector may be required to have some the following available:
• *SSPC Painting Manual Volume 2: Systems and Specifications*
• SSPC-PA 2. *Measurement of Dry Coat Thickness with Magnetic Gages*
• SSPC Visual Standards applicable to the specified work
• *ASTM Protective Coating Inspection Standards for Field and Shop Applications*
• Updated material supplier technical data sheets and

written recommendations.
• Applicable required copies of SSPC, NACE, ASTM, NAVSEA, AWWA, API, and ISO standards, procedures, and guidelines.

Calibration Verification

Calibration of inspection equipment is usually performed by a qualified individual using industry accepted standards and issuing a certification that the equipment is properly calibrated. The inspector in the field can only verify that the equipment used to perform inspections is calibrated according to industry accepted standards and procedures. The inspector should document the verification of all calibrations according to specifications and procedures. Normally the following information is required to show verification:
• Equipment type and serial number
• Required frequency and calibration method
• Record of calibration data
• Signature and date of person performing calibration verification

Daily Work Log

A description of the inspector's daily duties should be recorded in the daily work log. Supplemental data that cannot be recorded on standard forms should also be recorded in the daily work log. These should be objective observations, not "intuition" or "guesswork." They should be independent, not reflecting bias for or against the applicator or owner.[4]

Daily Inspection Report

The inspection daily report is probably the single most important document. The inspector should record observations and measurements on the coating job conditions as required, and note any hold points. This may include the following:
• Weather and site conditions
• Pre-surface condition and cleanliness
• Surface preparation monitoring
• Post-surface preparation and monitoring of cleanliness and profile
• Pre-application surface cleanliness
• Coating material preparation and application
• Physical film properties or appearance properties
• Dry film thickness measurements according to specifications or industry standard such as SSPC-PA 2, *Measurement of Dry Coat Thickness with Magnetic Gages*
• Verification of corrective actions prior to final approval
• Drawings, sketches, or photographs indicating where work occurred and to document the cumulative work progress
• Record of instruments used to obtain measurements and calibration verification
• Record of applicator's equipment and workforce

Nonconformance and Corrective Actions

Deviations or nonconformances from specifications and stop-work orders should be documented and corrective actions issued. Corrective actions taken to resolve deviations from specifications and procedures should be approved prior to restarting work. Follow up on the corrective actions should be verified prior to final approval. Any specification issues that were not resolved should be further documented to show nonconformance to the specification.

Photographic Record

Photographs of the coating inspection work taken by the inspector should be documented in such a manner that pictures can be properly identified. When possible the inspector should try to use the time/date stamp available on many cameras. A record showing location, area, and conditions along with corresponding number of the photograph should be noted. Undeveloped film should be properly stored and labeled until the film is developed.

Management Review

In process review should be scheduled and performed by management on an ongoing basis. Inspection documentation and records should be checked for accuracy, identifying problems that may need to be resolved. The review should be recorded and brought to the attention of the person responsible for the problem.

Post Job Activities

Recordkeeping

After completion of the inspection activities, verify that all required entries and supporting notes have been made and are legible. Signatures and dates required in documentation should be verified. Furnish any photographs (with date taken and other

identification on back of photo) and other supplemental documentation. Deliver or retain all documentation as required by contract or specification.

Traceability

Many times inspection records and documentation are required to be properly stored for a set period of time. Completed inspection records and documentation should be filed and organized in a manner that makes them easily accessible.

Summary

Quality control for protective coating projects begins prior to project start-up and continues after project completion. Many times inspection is considered the primary quality control activity. Specification review, documentation issuance, calibration verification, and corrective action follow-up are equally important. Standards and procedures needed to perform proper inspection need to be available and understood by all inspection personnel. A written inspection plan should be developed and followed by the inspector.

Records and support documents required to verify conformance with specifications should be filled out in a consistent and timely matter. Inspection equipment should be properly maintained and calibration verified as required. Deviations or nonconformance from specifications must also be properly documented and all corrective actions verified prior to final approval. All records and documents should be reviewed and organized in a consistent filing system. Proper storage of all records and documents allows for easy access should they be required at a latter date for review.

References

1. Glossary. In *The Inspection of Coatings and Linings;* Bernard R. Appleman, ed; SSPC: Pittsburgh,1997; p 429.
2. Windler, Frank J. Quality Control: A Necessary Factor in SSPC Contractor Certification. *Journal of Protective Coatings and Linings,* April 1988, pp 32-37.
3. Bechtel Power Corp. *Coating and Lining Inspection Manual;* SSPC: Pittsburgh, 1991; Chapter 2.
4. Drisko, Richard W. Reviewing and Preparing Inspection Documents. In *The Inspection of Coatings and Linings;* Bernard R. Appleman, ed; SSPC: Pittsburgh, 1997; pp 13-32.

Acknowledgements

The author and SSPC gratefully acknowledge Austin Paint Inspection for providing samples of their quality control and inspection forms and Bruce Rutherford for his peer review of this chapter.

About the Author

Thomas A. Jones
Thomas A. Jones is the senior technical auditor at SSPC, performing audits for the painting contractor certification program (PCCP). He has over 25 years experience in the protective coatings industry working in quality control inspection, project management, and technical service. He is the co-founder of the SSPC South Texas Chapter and is certified as a SSPC protective coatings specialist (PCS), NACE coatings inspector, and a NAVSEA paint inspector. Mr. Jones received his BA degree from Texas A&M-Corpus Christi.

FORM 1

DOCUMENTATION ACKNOWLEDGEMENT

PROJECT:	PROJECT:	COPY
LOCATION:		OFFICE ESTIMATING
	START DATE:	QC MGR HSO
CONTACT:	FINSH DATE:	Proj Mgr Inspector

THIS IS TO ACKNOWLEDGE RECEIPT OF ONE OR MORE OF THE FOLLOWING DOCUMENTS

SPECIFICATIONS REVISIONS CORRESPONDENCE REPORTS TEST RESULTS DRAWINGS OTHER _____

RECEIPT OF ALL DOCUMENTATION IS TO BE RECORDED IN THE PROJECT DOCUMENTATION LOG

DATE	DOCUMENTATION, SPECIFICATIONS, PRINTS & REVISIONS	DESCRIPTION & TITLE

UPDATE ALL SPECIFICATIONS & PROCEDURES AND RECORD IN APPROPRIATE REVISION LOGS

ISSUED TO: _____

COMPANY: _____

RECEIPT ACKNOWLEDGED BY: _____

SIGNATURE REQUIRED DATE

RETURN THIS FORM WITH SIGNATURE TO:

FORM 2

INSPECTION EQUIPMENT CALIBRATION RECORD

PROJECT:		PROJECT:	COPY
LOCATION:			Office QC Mgr
ISSUED TO:		START DATE:	Proj Mgr Client
CONTACT:	RETURN DATE:	FINSH DATE:	

DOCUMENT AS REQUIRED FOR EQUIPMENT REQUIRING CALIBRATION

TYPE/MODEL	SERIAL #	DATE OF CALIBRATION	CALIBRATION REQUIREMENTS	VERIFIED	VERIFIED BY

FORM 3

INSPECTION EQUIPMENT ISSUANCE SHEET			COPY Office Employee File QC Mgr Proj Mgr Inspector
PROJECT:		PROJECT #:	
LOCATION:			ATTACHMENTS Calibration Record
ISSUED TO:	ISSUED DATE:	START DATE:	
ISSUED BY:	RETURN DATE:	FINISH DATE:	

INSPECTION EQUIPMENT					
ITEM	MODEL #	SERIAL #	DATE OF CALIBRATION	VERIFIED BY	CALIBRATION REQUIREMENTS
TEMPERATURE/HUMIDITY					
SURFACE PREPARATION					
WET/DRY FILM THICKNESS					
OTHER TOOLS					

SPECIFICATION & STANDARDS	

ACKNOWLEDGEMENT OF RESPONSIBILITY

The following designated inspector has been issued the above listed inspection equipment, certification and calibration standards required to perform the intended inspection as required by contract. The inspector is required to keep all equipment in a safe place and in good working order. The inspector will document required calibrations and maintain all records per job specifications. Upon completion of the project, the inspector will return all equipment to the QC Mgr. The inspector is responsible for negligence and understands and accepts to replace damaged or stolen equipment.

ISSUED BY:		ISSUED TO:	
QUALITY CONTROL MANAGER'S SIGNATURE	DATE	INSPECTOR'S SIGNATURE	DATE

FORM 4

DAILY COATING INSPECTION REPORT

DATE: M T W R F S SU | # Pg of

PROJECT#:

INSPECTOR:

COPY
Office Client
Proj Mgr _____

PROJECT/CLIENT:

LOCATION:

DESCRIPTION:

REQUIREMENTS:

ATTACHMENTS
DFT SHEET NCR/CAR

CONTRACTOR: | SPEC#: | REVISION#:

DESCRIPTION OF AREAS & WORK PERFORMED

HOLD POINT INSPECTIONS PERFORMED

1. WEATHER AND SITE CONDITIONS
2. PRE SURFACE PREPARATION/CONDITION & CLEANLINESS
3. SURFACE PREPARATION MONITORING
4. POST SURFACE PREPARATION/CLEANLINESS & PROFILE
5. APPLICATION MONITORING/WET FILM THICKNESS (WFT)
6. POST APPLICATION/APPLICATION DEFECTS
7. POST CURE/DRY FILM THICKNESS (DFT)
8. CORRECTIVE ACTIONS FOLLOW UP & FINAL INSPECTION

APPROVED BY: _____

SURFACE CONDITIONS

NEW MAINT PRIMER/PAINT AGE/DRY/CURE_____
STEEL GALVANIZE CONCRETE _____
HAZARD_____ SAMPLE REPORT #_____
DEGREE OF CONTAMINATION:_____
TEST: Cl_____µg/cm²/ppm Fe_____ppm pH_____ppm
DEGREE OF CORROSION:_____
SCALE PITTING/HOLES CREVICES SHARP EDGES
WELD_____ MOISTURE OILS _____
PAINTED SURFACE CONDITION:_____
DRY TO/TOUCH_____HANDLE_____RECOAT_____
DRY/OVERSPRAY RUNS/SAGS PINHOLES HOLIDAYS
ABRASION FALL OUT _____

AMBIENT CONDITIONS

AREAS:

TIME				
DRY BULB TEMP° C/F	°	°	°	°
WET BULB TEMP° C/F	°	°	°	°
% RELATIVE HUMIDITY	%	%	%	%
SURF TEMP° C/F MIN/MAX	/ °	/ °	/ °	/ °
DEW POINT TEMP° C/F	°	°	°	°
WIND DIRECTION/SPEED				

WEATHER CONDITIONS:

SURFACE PREPARATION

START TIME FINISH TIME AREA ft²/m²

SOLVENT CLEAN HAND TOOL POWER TOOL_____
HP WASH PSI_____ _____
ABRASIVE BLAST ABRASIVE TYPE SAMPLE
BLAST HOSE SIZE_____ NOZZLE SIZE/PSI_____
AIR SUPPLY CFM_____ AIR SUPPLY CLEANLINESS
WATER/OIL TRAP CHECK EQUIPMENT CONDITION CHECK
_____

APPLICATION

START TIME FINISH TIME AREA ft²/m²

PRIMER INTERMEDIATE TOPCOAT TOUCH UP

GENERIC TYPE	QTY MIXED
MANUF	MIX RATIO
PROD NAME	MIX METHOD
PROD #	STRAIN/SCREEN
COLOR	MATERIAL TEMP
KIT SIZE/COND	INDUCTION TIME
SHELF LIFE	POT LIFE
BATCH NUMBERS	REDUCER #
(A)	QTY ADDED
(B)	% BY VOLUME %
(C)	Specified WFT mils/µm
REDUCER	Achieved WFT mils/µm

SURFACE CLEANLINESS & PROFILE MEASUREMENT

JOB SPEC NACE/SSPC-SP-_____
NACE/SSPC SPEC/ VISUAL STDS _____
PROFILE CHECK: DISC_____ TAPE_____ GAUGE_____
SPECIFIED_____mils/µm ACHIEVED_____mils/µm
SURFACE EFFECT ON D.F.T. GAUGE/BMR/_____mils/µm

AIRLESS/CONV BRUSH ROLLER PRIMER

PUMP/POT	HOSE dia.	AIR CHECK
RATIO/SIZE	HOSE Lng.	TRAP
GPM/CFM	SPRAY GUN	FILTER
PSI	TIP SIZE	AGITATOR

MEASUREMENTS

D.F.T. GAUGE CALIBRATION

GAUGE TYPE MODEL	GAUGE SERIAL #	GAUGE CALIB. VERIFIED	SPECIFIED AVERAGE D.F.T.	AVERAGE D.F.T THIS COAT	AVERAGE D.F.T LAST COAT	TOTAL AVERAGE D.F.T

_____
INSPECTOR'S SIGNATURE DATE

FORM 5

DFT MEASUREMENT WORKSHEET

DATE: M T W R F S SU | # Pg of

PROJECT#:

INSPECTOR:

COPY
QC Mgr Client
Proj Mgr

PROJECT/CLIENT:

LOCATION: SPEC#:

DESCRIPTION: REVISION#

ITEM:

LOCATION	AREA	SPOT READINGS 1	2	3	Total	%Min	Avg
	A						
	B						
	C						
	D						
	E						

Approx. ft^2/m^2 Specified DFT mils/μm Total Avg. mils/μm

Reference Inspection Report # for application record

ITEM:

LOCATION	AREA	SPOT READINGS 1	2	3	Total	%Min	Avg
	A						
	B						
	C						
	D						
	E						

Approx. ft^2/m^2 Specified DFT mils/μm Total Avg. mils/μm

Reference Inspection Report # for application record

ITEM:

LOCATION	AREA	SPOT READINGS 1	2	3	Total	%Min	Avg
	A						
	B						
	C						
	D						
	E						

Approx. ft^2/m^2 Specified DFT mils/μm Total Avg. mils/μm

Reference Inspection Report # for application record

ITEM:

LOCATION	AREA	SPOT READINGS 1	2	3	Total	%Min	Avg
	A						
	B						
	C						
	D						
	E						

Approx. ft^2/m^2 Specified DFT mils/μm Total Avg. mils/μm

Reference Inspection Report # for application record

ITEM:

LOCATION	AREA	SPOT READINGS 1	2	3	Total	%Min	Avg
	A						
	B						
	C						
	D						
	E						

Approx. ft^2/m^2 Specified DFT mils/μm Total Avg. mils/μm

Reference Inspection Report # for application record

D.F.T. GAUGE CALIBRATION RECORD

GAUGE TYPE MODEL	GAUGE SERIAL #	PLATE/ SHIM mils/μm	BMR	ADJUST +/-	SPEC. AVERAGE COAT	D.F.T THIS COAT	D.F.T LAST COAT

INSPECTOR'S SIGNATURE DATE

FORM 6

CORRECTIVE ACTIONS REPORT	DATE: M T W R F S SU	# Pg of
	PROJECT#:	COPY
	INSPECTOR:	QC Mgr Client Proj Mgr
PROJECT/CLIENT:		
LOCATION:		ATTACHMENTS
DESCRIPTION:		STOP WORK ORDER
REQUIREMENTS:		
CONTRACTOR:	SPEC#:	REVISION#:

TIME & LOCATION	NAME/COMPANY/TITLE

DESCRIPTION OF NONCONFORMING ITEM	DESCRIPTION OF NONCONFORMANCE

REFERENCED: SPECIFICATION/PROCEDURE/STANDARD	ACTION LEVEL

DISCUSSION & RECOMMENDATIONS

APPROVAL & CORRECTIVE ACTIONS

CORRECTIVE ACTIONS FOLLOW UP

FINAL APPROVAL:				
SIGNATURE	TITLE	DATE	INSPECTOR'S SIGNATURE	DATE

FORM 7

PHOTOGRAPH RECORD			DATE: M T W R F S SU # Pg of
			PROJECT#: COPY
			INSPECTOR: QC Mgr Client
			Proj Mgr
PROJECT/CLIENT:			
LOCATION:			CAMERA:
CAMERA TIME/DATE VERIFIED: YES NO N/A		PERMISSION REQ: YES NO	EXPOSURES:
FILM DEVELOPER:		# DATE	ROLL#:

#	LOCATION	AREA	COMMENT
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			
24			
25			
26			
27			
28			
29			
30			
31			
32			
33			
34			
35			
36			

NUMBER ON FORM MUST MATCH WITH PICTURE FILL OUT ONE FORM PER ROLL	INSPECTOR'S SIGNATURE DATE

Chapter 12
Coating Failures

Richard W. Drisko

Introduction

All coatings have limited service lives. Unfortunately, there are occasions when coatings fail much sooner than they should. When this occurs, it is necessary to determine the causes of the failure and what actions must be taken to correct this condition and prevent its recurrence.

There are numerous causes of coating failure. These may be related to structural design, the substrate, the coating itself, surface preparation, coating application, or coating curing, or combinations of these basic causes. Historically, improper or inadequate surface preparation has been the most commonly reported cause of coating failure; more recently, governmental restrictions on coating VOCs and toxic constituents (e.g., solvents, pigments, and biocides) have restricted coating formulations and made them more difficult to apply successfully. This chapter will address the common causes of coating defects on industrial structures and the associated preventative or corrective actions.

Commonly Used Failure Terms

Many different terms commonly used to describe coating failures mean different things to different people. SSPC's *Protective Coatings Glossary* defines failure terms and these definitions are used for all failure terms in this chapter.[1] Some of the definitions of general terms commonly associated with coating deterioration/degradation are:

Catastrophic Coating Failure. A coating failure that is sudden, very dramatic, and serious.

Defect. A surface or film imperfection (flaw), deficiency, or incompleteness that deviates from a specification or industry-accepted condition.

Degradation. A gradual loss of coating materials and/or properties resulting from service conditions and weathering.

Deterioration. See degradation above.

Failure of Coating. Loss of a coating's function or purpose, i.e., when it no longer protects the substrate, provides an attractive appearance, or serves some other function such as providing a non-slip surface. The time of failure is considered to occur when some action is needed to restore its properties to the level necessary to again provide its intended purpose(s).

Failure Analysis. Systematic investigation conducted to determine the causes and responsibilities of coating defects, loss of function, and/or corrosion, if present.

Premature Failure. Failure that occurs significantly before a coating's life expectancy.

Service Life of Coating. The period of time during which a coating provides its intended function(s). This will vary with different exposures and services.

Effects of Structural Design on Metal and Coating Deterioration

It has been shown that structural design may be an important factor in metal and coating deterioration.[2-3] It is important that these design factors be recognized and corrected at the planning stage rather than later when their adverse effects have become apparent. Although each of the major design factors leading to early coating deterioration will be discussed separately, they often occur in conjunction with other factors that further aggravate the deterioration.

Contact of Dissimilar Metals Resulting in Galvanic Corrosion

When two dissimilar metals are in physical contact with each other in an electrolyte (electrically conductive medium), the more active metal will corrode preferentially, while protecting the other metal from corrosion. The greater the difference in electrochemical activity between the metals, the greater will be the rate of dissimilar metal corrosion. The relative surface areas of the touching metals may also greatly affect the corrosion of the more active metal (the

anode in the reaction). A small anode area and a much larger cathode (protected) area may result in extremely rapid corrosion of the smaller anode area. Thus, in painting, care should be taken to ensure that all cathode areas are especially well covered. Galvanic corrosion may also be minimized by using metals of similar composition, or using a non-conductive insulator between them.

Crevices

Crevices are likely to occur in structural components that are bolted, riveted, or skip-welded together. Inside crevice areas, there is invariably a lower concentration of oxygen as compared to the air outside the crevice. This results in a corrosion cell with accelerated corrosion occurring within the crevice area. Thus, continuous welding is the preferred method of joining metal components. Welds should be ground smooth and weld spatter removed before coating in order to obtain good coating adhesion in these areas. Also, back-to-back angle designs should be avoided because they have crevices between them.

Water Traps

Water traps are design features, such as upward facing angle iron, that collect the rain that accelerates deterioration of coatings and corrosion of metals. Such designs should be oriented downward so that the water drains. Drill weep holes into existing water traps to permit collected water to drain.

Sharp Edges

When sharp edges are coated, the paint tends to draw back from the edge to leave a much thinner coat of paint there than on flat areas. In order to produce a coating film of more equal thickness (and thus equal barrier protection) on all surfaces, edges are usually striped (brushed with an additional coat of primer) before or after applying a full coat to the substrate. Relatively recently, new edge-retentive coatings (usually amine-cured, solvent-free epoxies) have been developed to address this problem.

Faying Surfaces

Faying surfaces are contacting surfaces where joints in steel structures are formed by riveting or by the use of high-strength bolts. Most coatings are unsuitable for use in the joint itself, because they do not provide the proper coefficient of friction to maintain the joint in a static state. However, inorganic zinc-rich silicate coatings have adequate coefficient of friction to perform well in this service.

Limited Access to Work

Limited access to surfaces to be cleaned and coated often results in poor quality work and consequently early coating deterioration. Thus, structures should be designed for access both for the original work and for subsequent maintenance painting.

Effects of Substrate Properties on Coating Performance

It has been shown that the chemical and physical natures of a surface to be coated may have a very profound effect on the performance of the coating system.[4] It should be noted that, in general, textured surfaces provide more bonding sites and thus have greater coating adhesion than smooth areas of similar composition.

Hot-Rolled Steel

Most structural steel is made by the hot-rolling process. This process results in a loosely bonded layer of iron oxide called mill scale. Mill scale must be removed before the steel is coated, or its subsequent loss with time will result in coating deterioration.

Coatings on metal structures are susceptible to underfilm corrosion. Undercutting of a coating film by corrosion at breaks or pinholes in the barrier film may result in rapid loss of coating and its protection.

Cold-Rolled Steel

Cold-rolled steel is used more for manufacturing office furniture, appliances, and automobile bodies than for applications where structural strength is required. Cold rolling produces a denser, smoother surface than hot-rolling. Coatings do not bond as well to these surfaces. Thus, chemical treatments such as phosphating are often used to promote coating adhesion. Abrasive blasting can also be used to produce a profile to improve coating adhesion.

High-Strength Alloy Steels

In some environments, high-strength alloy steels may require a coating system to supplement its natural corrosion resistance. In these cases, the

cleaning requirements are similar to those of conventional steels, but harder abrasives (e.g., silicon carbide, aluminum oxide, or garnet) may be necessary to produce the desired surface profile. Because of their inherent corrosion resistance, they will normally have less corrosion and undercutting of coating at film holidays.



Figure 1. Corrosion undercutting of coating at scratch.

Zinc-Coated Surfaces

Zinc-coatings, both galvanizing and zinc-rich, always have alkaline surfaces created by the natural corrosion of zinc. This alkalinity will saponify (hydrolyze) alkyds and other coatings that cure by oxidation of drying oils.

New galvanized surfaces are sometimes given a thin coat of oil or chromate conversion coating to protect them from corrosion called wet storage stain or white rust during exterior storage. These treatments must be removed prior to coating to permit good coating adhesion. The oil is best removed by solvent cleaning (i.e., SSPC-SP 1), and the chromate conversion coating can be removed chemically or by prolonged weathering.

Aluminum

Epoxies normally bond quite well to aluminum. For other coatings that do not, one the following treatments may be used:

- Chemical treatment such as phosphating
- Wash priming (good with alkyds)
- Blasting with a soft abrasive (e.g., plastic) to produce a suitable profile

Aluminum is susceptible to exfoliation, an advanced stage of intergranular corrosion characterized by a delamination of metal along grain boundaries. Rolled metal products such as aluminum alloy plate are especially susceptible to exfoliation due to their longitudinal grain structure.

Coated aluminum is particularly susceptible to a form of corrosion called filiform. It is characterized by threadlike directional growths proceeding away from damaged areas. In the past, chromate inhibitive pigments were widely used to control filiform corrosion; chromate-free inhibitive pigments are now used.

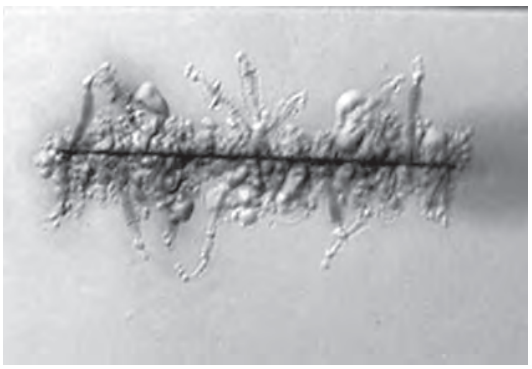


Figure 2. Filiform corrosion.

Concrete

Concrete has unique properties (e.g., alkalinity and porosity) that make its coatings especially susceptible to certain defects. These are described extensively in SSPC's *The Fundamentals of Cleaning and Coating of Concrete*.[5]

Wood

The properties of woods vary greatly with the types of tree from which they came. Soft woods such as redwood and fir are penetrated by coatings to permit good bonding much more easily than are hard (dense) woods such as ash and oak.

Pine and fir have variable grain structures, while redwood and cedar have uniform grain and brown color. The brown color of the latter two woods comes from water-soluble dyes that may bleed through latex coatings to cause staining, unless sealed

before painting. An oil-based or water-borne stain-blocking primer can be used for this purpose.

Resinous materials in some trees, such as lower grades of pine, may seep to the wood surface after painting to cause staining and paint deterioration. This can be minimized by using weathered wood and sealing it before use.

Woods are very sensitive to moisture so that they swell during periods of high humidity and shrink during periods of low humidity. Rigid coatings on wood may crack when they are unable to expand and contract with dimensional changes.

Coatings hide wood grain and greatly reduce water permeability. However, water that enters into the wood interior may try to escape through impermeable coatings to cause blistering and/or delamination. For this reason, latex coatings that permit the passage of water vapor (sometimes called breathing) may minimize this problem. Many people prefer to use semi-transparent stains that do not seal the surfaces of wood.

Defects/Failures Associated with the Coating Itself

Some coating defects and failures are directly related to the coating itself. These include:

- Errors by the manufacturer in production of the coating
- Coatings that have exceeded their shelf life
- Inherent limitations of properly formulated coating
- Incompatibility of a coating with its substrate or undercoat

Coatings with Errors in Manufacture or that Have Exceeded Their Shelf Life

Errors in coating manufacture do not occur very often. They can usually be detected in the field before use by testing for condition in container, as described in Federal Test Method Standard 141. If the viscosity does not appear to be at the proper level, it can be checked in the field using a viscosity cup. Also, a test patch of coating can be applied to the intended substrate to check for such properties as ease of application, hiding, leveling, and complete curing.

If a stored coating has exceeded its shelf life, it may have deteriorated to the extent that it can no longer be successfully utilized. Such coatings should be checked for condition in container before use.

Limitations of Coating Formulations

All coating formulations have some limitations that restrict their uses to appropriate environments and services. In this section, some of the more important limitations are addressed.



Figure 3. Chalking.

Chalking. Chalking is the formation of loose powder on the surface of coatings. It is typically caused by deterioration of the organic coating binder by ultraviolet light (usually from the sun) to leave a loose residue of pigment and oxidized binder. All organic coating binders chalk to some extent, but those containing aromatic chemical groups (e.g., epoxies and phenolics) chalk much faster than others.

Some pigments such as the anatase form of titanium dioxide chalk very freely, while other pigments such as rutile, another crystalline form of titanium dioxide, are quite chalk-resistant. Opaque pigments, of course, reduce chalking of underlying organic binders by shielding them from sunlight. Leafing aluminum pigments formulated to float to coating surfaces protect underlying binders especially well.

Chalking of finish coatings can best be controlled by proper selection of pigments and binders and by use of additives such as ultraviolet light absorbers.

Erosion. Erosion is the gradual loss of coating by wear or weathering. Thus, coatings that chalk freely are more susceptible to erosion than are coatings that are more chalk-resistant. Erosion may also be caused by wind-blown sand or rain.

Accelerated erosion may significantly reduce coating thickness and even expose undercoats. Erosion may be minimized by selecting a

chalk-resistant coating with good leveling properties.



Figure 4. Erosion of topcoat on deck of a ship.

Discoloration. Discoloration is the change in coating color after application (usually an undesirable darkening), normally caused by exposure to sunlight or chemical atmospheres. Thus, lead pigments are blackened by the attack of hydrogen sulfide gas. To minimize discoloration, coating formulations should have stable pigments and binders.

Fading. Fading is the reduction of color intensity, usually by sunlight. This adverse cosmetic effect can also be minimized by using formulations with stable pigments or binders.

Loss of Gloss. Loss of gloss is still another defect that is caused by sunlight and can best be minimized by selecting ultraviolet-resistant coating components. All coatings lose gloss in sunlight to some extent, but some do much more than others. This cosmetic defect, as well as discoloration and fading, is especially distracting when it occurs on the side of a structure that is partially shaded so that there is an uneven loss of gloss or color.

Mildew Defacement. Mildew defacement is an unsightly appearance on coated or uncoated structures caused by the growth of micro-organisms, particularly fungi. This is more of a cosmetic effect than one that adversely affects coating film properties. Mildew defacement may be controlled in architectural coatings (i.e., drying oil and water-borne latex coatings) by using EPA-approved mildewcides. Also, smooth, chalk-free coating surfaces in dry locations exposed to sun light are less susceptible to mildew than other coated surfaces.



Figure 5. Uneven loss of gloss.



Figure 6. Mildew defacement.

Moisture Blushing. Moisture blushing is the formation of a milky opalescence that may occur in humid environments where solvent evaporation reduces the temperature of an uncured coating to the dew point so that moisture condensation occurs on it. This cosmetic defect most commonly occurs with fast evaporating coatings such as vinyl lacquers. Moisture blushing may also occur by the reaction of moisture in the air with polyurethanes and other moisture sensitive coatings on humid days. Moisture blushing can best

be prevented by avoiding the application of moisture-sensitive coatings on humid days.



Figure 7. Moisture blushing.

Amine Blushing. Amine blushing is the formation of a milky opalescence on the wet-film surfaces of amine-cured epoxies by the reaction of the amine with carbon dioxide and water in the air to form an amine carbamate. This film may cause adhesion problems for topcoats if not removed as recommended by the epoxy manufacturer.

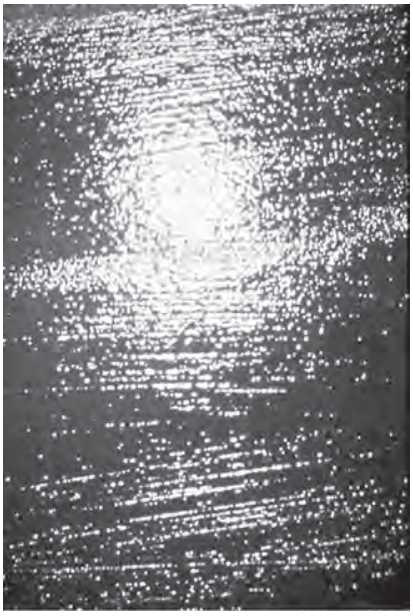


Figure 8. Brush marks.

Brush Marks. Brush marks may occur in brush-applied coatings with insufficient leveling for the wet film to flow together to form a film of uniform thickness. Localized areas of lesser film thickness almost always exhibit deterioration before areas of greater film thickness.

Orange Peel. Orange peel is similar to brush marks in that it is caused by insufficient leveling of the wet film. However, this defect occurs with spray rather than brush application of coatings.

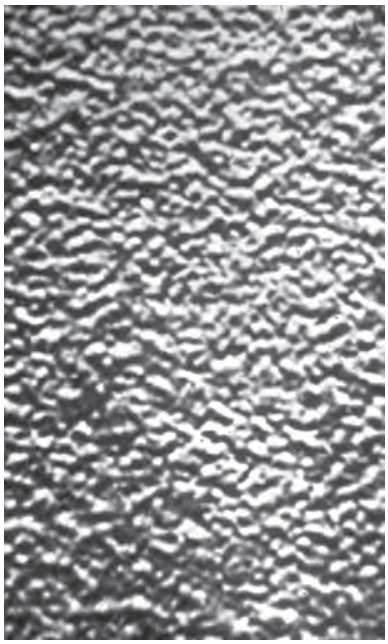


Figure 9. Orange peel.

Wrinkling. Wrinkling is a defect that results in the formation of small furrows or ridges in coating films. It occurs most commonly with thick films of alkyds and other drying oil-curing coatings. In these cases, curing by air oxidation occurs much more rapidly at the coating surface than below it, and a surface skin is formed that prevents further curing of the underlying binder. Contraction of the surface skin causes the wrinkling. Through-dry metal driers will help accelerate complete film curing, but the use of lead driers (some of the best through-driers) is now greatly restricted. Wrinkling can also be minimized by avoiding thicker film than recommended by the manufacturer.

Chemical Attack on Coatings. Chemical attack on coatings will occur when the coating system is not resistant to the environment. This most commonly occurs to linings in storage tanks where they come into contact with stored chemical liquids. Chemical attack may also occur in atmospheric service where harsh chemical fumes or vapors come into contact

with the coating.

High-Temperature Attack on Coatings. High-temperature attack is likely to occur to organic coatings even during intermittent high-temperature service. Thus, heat-resistant inorganic coatings are usually used at temperatures above 450°F (230°C).

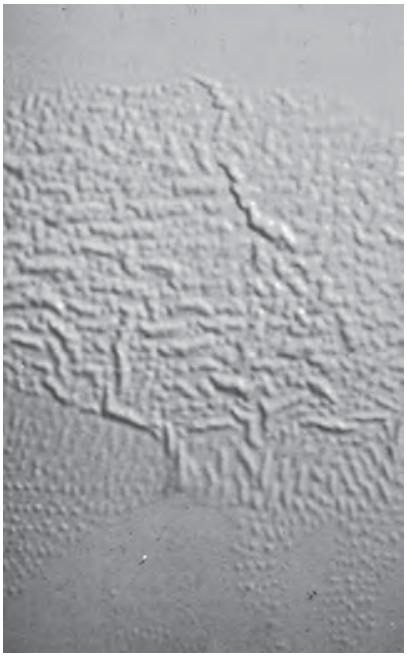


Figure 10. Wrinkling.



Figure 11. Mottling.

Mottling. Mottling is the presence of differently colored spots or blotches on a painted surface. It is commonly caused by pigment overload (using more pigment than can be completely wetted by the limited amount of resin present).

Osmotic Blistering by Soluble Pigments. Osmotic blistering may occur to coatings with primer pigments having significant water solubility. This is especially likely to occur during water immersion service. These pigments can be detected during a laboratory failure analysis of the water (sometimes colored) in filled blisters.

Osmotic blistering may also occur if soluble salt contaminants are not completely removed from substrates during surface preparation.

Flooding and Floating. Flooding and floating are two cosmetic formulation defects that are sometimes confused with each other. Flooding is the segregation of pigments in a coating system caused by different rates of settling in the wet film to form a uniform appearance different from that expected. Floating is the segregation of individual pigments in a coating system during curing related to differential movement in the surface tension currents caused by solvent evaporation to produce a varigated paint surface.



Figure 12. Cracking.

Cracking. Cracking is a general term for the splitting of a coating film to relieve stresses. Most of these stresses originate by shrinking during curing, by solvent evaporation, and/or polymerization. Stresses increase with further polymerization and weathering. When stresses exceed the cohesive strength of the coatings, they crack to relieve the stress.

The greater the coating thickness, the more rigid it is and thus the greater its tendency to crack. Different types of cracking, other than common cracking, include hairline cracking, checking, crazing,

alligatoring, other intercoat cracking, and mud cracking. Cracking usually occurs all the way through the coating to expose the substrate.



Figure 13. Checking.

Checking. Checking is the fine surface cracking that develops in coating films during prolonged curing and/or weathering that does not penetrate to the underlying substrate. Wetting and drying, heating and cooling, and exposure to sunlight all contribute to checking.

Alligatoring. Alligatoring is a type of crazing or surface cracking with a definite pattern, as indicated by its name. The effect often occurs when a relatively rigid coating is applied over a more flexible undercoat. The resulting stresses cause the topcoat to crack to expose the undercoat but not the substrate.

Intercoat Cracking. Cracking from intercoat stresses may occur when a relatively rigid topcoat is applied over a more flexible undercoat. These stresses are similar to those previously described for alligatoring, but cracking does not always occur in such a regular pattern.

Mud Cracking. Mud cracking is a cracking pattern that resembles the irregular cracking of drying mud. It typically occurs when a rigid coating is applied too thickly. This defect often happens with inorganic zinc-rich coatings, which are very rigid.



Figure 14. Alligatoring with bleeding.

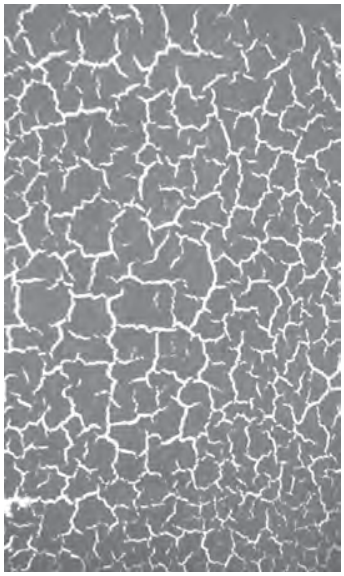


Figure 15. Mud cracking of inorganic zinc-rich coating.

Coating Incompatibilities

Incompatibilities may occur between individual coats in a total coating system or between an existing system and a topcoat to be applied over it. It is wise to obtain all coatings for a total system that are known to be compatible with each other and that are produced by the same manufacturer. Five types of

incompatibility between coatings are described here.

Topcoat Solvent Attack on Undercoat Binder. Topcoat solvent attack on undercoat binder may cause the latter to soften, swell, or disbond. In any case, the intercoat adhesion is significantly diminished. An example of this is a chlorinated rubber or an epoxy coating with a strong solvent being applied over a vinyl dispersion (latex) coating.



Figure 16. Bleeding of alkyd coating on asphalt pavement.

Bleeding. Bleeding often occurs when a topcoat with a strong solvent is applied to a coal-tar or asphalt coating. The solvent dissolves some of the colored material in the existing coating and allows it to migrate through the topcoat to impart a brown surface discoloration. This defect is somewhat similar to the previously described bleeding from an asphalt pavement and migration of water-soluble dyes from wood through latex coatings.

Limited Adhesion. Limited adhesion and subsequent peeling may occur to a water-dispersed (latex) coating applied over a smooth oil-based enamel. There is often insufficient solvent in the topcoat to penetrate the existing coating to achieve good intercoat adhesion.

Intercoat Cracking. Cracking from intercoat stresses was described earlier in the discussion of different forms of cracking.

Saponification (hydrolysis). Saponification may occur to an alkyd or other drying oil applied over a zinc-rich primer. As with concrete, the surface alkalinity on the zinc-rich primer causes this chemical degradation.



Figure 17. Saponification of alkyd coating.

Incompatibilities with Cathodic Protection

There are three basic mechanisms by which coatings may be deteriorated by cathodic protection systems. Coatings to be used in conjunction with cathodic protection to control the corrosion of steel must be resistant to these problems.

Saponification of Coatings. Alkalinity is always produced on cathodically protected surfaces. If coatings on these surfaces are not alkali-resistant, they are subject to saponification.

Blistering of Coatings by Hydrogen Gas Evolution. Blistering of coatings by hydrogen gas evolution may occur on cathodically protected surfaces where the voltages are excessively high (e.g., in excess of –1.1 volts). This seldom occurs if steel-to-soil or

steel-to-water potentials are regularly monitored.

Electroendosmosis. Electroendosmosis is a mechanism of coating deterioration in which excessive cathodic potentials causes electrolyte to penetrate rapidly through a coating film. It normally results in coating blistering and peeling.

Coating Defects/Failures from Inadequate Surface Preparation

Inadequate surface preparation is generally recognized as being the chief source of coating defects and failures. Surface preparation inadequacies are either caused by inadequate removal of contaminants or by improper profile height. Each commercially available primer has a surface preparation recommended by its manufacturer. These recommendations should be carefully followed.

One of the best ways of minimizing adverse effects of surface preparation is by careful inspection of the cleaned surfaces and immediate correction of any deficiencies found. These deficiencies cannot be corrected after coating application.

The coating manufacturer also provides the recommended ranges of ambient conditions suitable for successful application of each company product. These recommendations may be as important as any other manufacturer recommendation.

Inadequate Surface Cleanliness

Inadequately cleaned surfaces are very difficult to wet with coatings, because the remaining contaminants reduce the number of bonding sites. Intimate contact between coating and substrate is necessary for good adhesion.

Disbonding, Peeling, and Blistering. Disbonding, peeling, and/or blistering may result from incomplete removal of rust, mill scale, dirt, or other loosely held contaminants from the substrate surface or from the presence of moisture. Flash rusting of properly cleaned steel before coating is another source of these defects.

Incomplete removal of contaminants from an existing coating before topcoating may result in intercoat disbonding, peeling, and/or blistering.

Crawling (Fisheyes). Crawling, sometimes called fish eyes, is the drawing back of a liquid film from a uniformly thick layer to form areas of little, if any, thickness. It occurs when the surface tension of a coating is greater than the surface tension of the substrate. Crawling is caused by substrate contamination with oil or some other low surface energy contaminant.

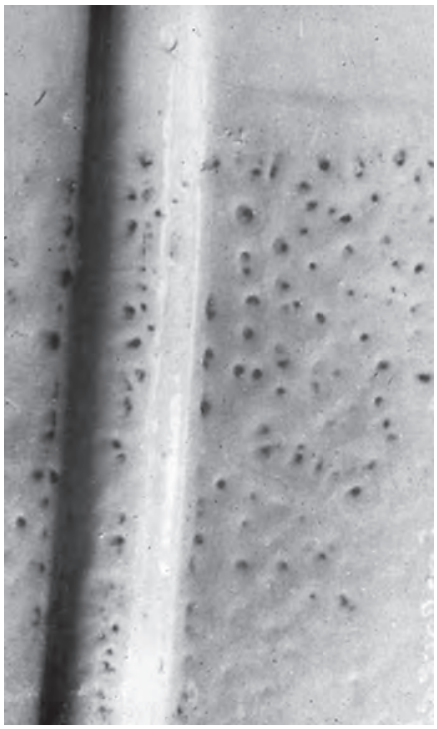


Figure 18. Crawling (fish eyes).

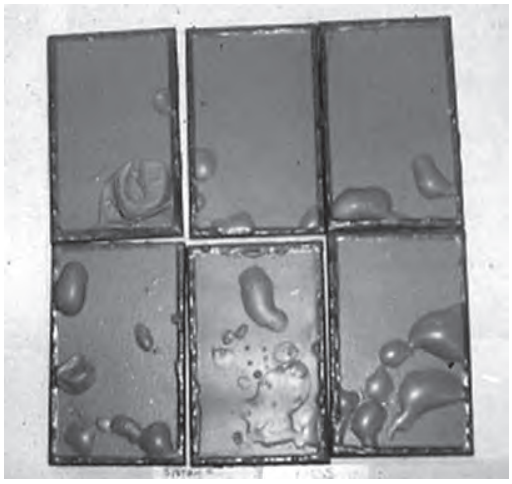


Figure 19. Osmotic blistering caused by inadequate removal of soluble salts.

Osmotic Blistering by Incomplete Removal of Soluble Salts. Incomplete removal of soluble salts during

surface preparation may result in osmotic blistering of coatings subsequently applied. These salts are usually not readily visible and so must be removed and analyzed using special techniques.[6] The adverse effects of soluble salts are much greater on coatings in immersion service than in atmospheric service.

Improper Surface Profile

Each primer has a profile height recommended by its manufacturer for best performance. Any significant deviation from this recommendation may result in reduced coating system performance. In general, recommended profile heights vary directly with the primer film thickness. Thus, primers with greater film thickness usually have higher recommended surface profiles.

Insufficient Profile Height. Insufficient profile height of cleaned surfaces may provide insufficient bonding areas for adequate coating adhesion. This, in turn, usually results in early coating loss by disbonding and peeling.



Figure 20. Pinpoint rusting.

Excessive Profile Height. Pinpoint rusting may occur on coated steel structures where abrasive blast cleaning has produced so high a profile that it is not adequately protected by a relatively thin primer. Pinpoint rusting may also occur when erosion significantly reduces coating film thickness.

Coating Defects/Failures from Improper Coating Application

As with surface preparation, the best way to avoid coating failures resulting from improper coating application is by (1) carefully following the coating manufacturer's recommendations for application and (2) carefully inspecting the work to permit early detection of defects and their immediate correction. It is much easier to prevent coating problems associated with improper spray application than to correct them after application.

When applying two-component thermosetting coatings, careful attention must be paid to the manufacturer's recommendations for induction, pot life, and recoat times. If this is not done, catastrophic failure may occur.

Mixing Coatings

Although coatings are prepared ready to apply, settling of the heavier pigment portion may occur during storage. Thus, all paints should be thoroughly mixed before application to ensure that the material being applied is the homogeneous blend originally manufactured. Improper mixing can lead to uneven color in cured paint, inadequate film thickness, poor coating adhesion, and checking or cracking of the paint film.[7]

Coatings should not be overmixed to avoid entrapping air into them. Thus, a mechanical mixer should be used at a speed set so that a small rather than a large vortex or depression on the paint surface is created in the center of the can. Use of paint shakers is not recommended. Allowing stirred paint to set for several minutes before application may permit the release of entrapped air.

Two-component coatings such as thermosetting epoxies and polyurethanes are normally supplied in kits composed of Component A and Component B. The components of each kit must be properly proportioned for mixing together to achieve proper curing and optimum coating performance. Therefore, use of complete kits rather than partially filled kits are recommended. Each component should be mixed separately and then mixed together in the order specified by the coating manufacturer.

Plural-component spray application systems combine Components A and B together automatically in a specific ratio. However, the proportions should be checked before beginning coating application to be sure that the proportions are those specified by the manufacturer. When spraying with plural-component equipment, it is common practice not to use the triggering technique commonly used with other spray equipment because the ratio of components may vary significant at the start and stop of each trigger stroke. Skilled applicators are required for the successful use

of plural-component application equipment.

Thinning

Coatings are manufactured for application as received without thinning. However, low temperatures or other conditions may necessitate thinning to reduce the viscosity for effective application. When necessary to use a thinner, it should be of the type and in the amount recommended by the coating manufacturer. Thinner should be added to the coating slowly and with thorough mixing to avoid overthinning one portion of the paint and the possibility of curdling the coating or flocculation of the pigment.

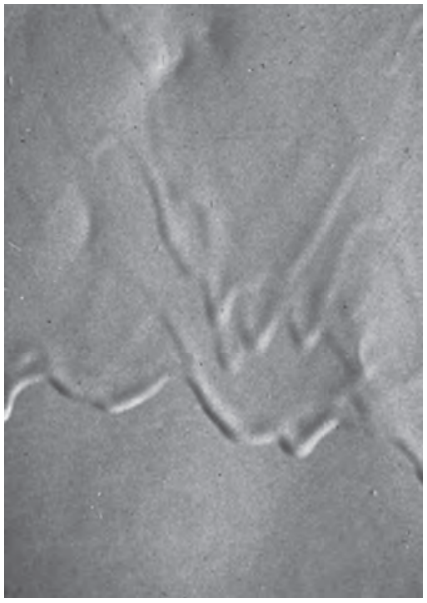


Figure 21. Sagging.

Straining

Coatings should be strained after mixing to eliminate any skins, lumps, or other foreign matter to avoid clogging spray equipment. Inorganic zinc-rich coatings are especially susceptible to clumping.

Effects of Improper Coating Thickness

It is important that coatings be applied uniformly, holiday-free, and in the thickness range specified by the manufacturer. Otherwise, maximum coating performance will not be achieved. Use of a wet film thickness gauge, as described in ASTM D 4414, *Practice for Measurement of Wet Film Thickness by Notch Gages,* will help ensure that the desired dry film thickness is achieved.

Insufficient Coating Thickness. If a coating is applied with less than the specified minimum thickness, its barrier protection will be lessened, and thus its service life will be reduced. As discussed earlier, a thinner than desired coating may contribute to pinpoint rusting on steel surfaces.

Excess Coating Thickness. If a coating is applied too thickly, its weight may cause the wet coating to flow downward to form sags, runs, or curtains. Such defects should be detected and corrected as soon as observed.

Excessive coating thickness may lead to the acceleration of common cracking, mud cracking, and/or disbondment of relatively rigid coatings. As described earlier, thicker films have more rigidity than thinner films and thus are less able to expand and contract with substrate dimensional changes.

Excess coating thickness may be gradually built up by application of additional coats to an existing coating system during periodic maintenance painting. When the total stress built up in the coating system exceeds the adhesion at its weakest point (usually primer to substrate), disbondment will occur. Disbondment may take the form of chipping, flaking, peeling, or delamination.

As described earlier, wrinkling occurs more often with thicker than thinner coatings that cure by oxidation of drying oils. Excess thickness may also result in other types of incomplete or improper curing.

Non-Uniform Coating Thickness. If coating thicknesses vary significantly outside the specified range, the first signs of deterioration invariably occur in areas of low film thickness. Thus, low thickness areas limit the performance of the total coated area.

Coatings with variable film thicknesses tend to be resin-rich in localized areas of greater thickness. This often results in unsightly glossy areas sometimes called hot spots.

Effects of Improper Spray Techniques

The most uniform coating application and the best looking finishes are achieved by spray application. Deviation from the recommended gun-to-substrate distance, constant rate of gun travel, proper spray pattern, and standard triggering can results in defects and early coating failure.



Figure 22. Dry spray.

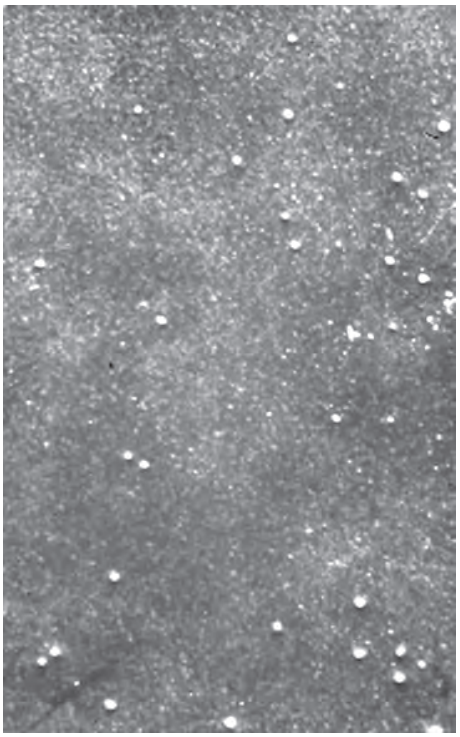


Figure 23. Pinholing.

Dry Spray. Dry spray is a rough, powdery, non-coherent film produced when an atomized coating partially dries before reaching the intended surface so that the coating cannot flow to form a uniform continuous film. This condition most commonly occurs with fast drying coatings. Holding the spray gun too far from the substrate may also contribute to dry spray. Dry spray film have little, if any, protective value.

Dry spray should not be confused with overspray. Overspray consists of atomized paint particles that deflect from or miss the surface being sprayed and fall on unintended surfaces.

Pinholing. Pinholing is the formation of small holes that extend through the entire thickness of a coating. It occurs most often with lacquers and other coatings that contain fast evaporating solvents. Solvent imbalance is an important source of pinholing.

Pinholing is sometimes caused by holding the spray gun too close to the surface with excessive atomization pressure or a combination of a low atomization pressure and excessive material pressure.

A special case of pinholing often occurs during the topcoating of inorganic zinc-rich coatings on warm days. Topcoat solvent that enters the naturally porous film of the inorganic zinc-rich coating evaporates in the warm environment, and the resulting vapors rise to the surface of the uncured topcoat to form pinholes. This phenomenon is somewhat similar to outgassing of wet coatings on concrete, in which, during periods of rising temperature, interior air and solvent vapors rise to the concrete surface to form small bubbles in the topcoat.

Cratering is a special form of pinholing caused by foreign matter in or deposited on the wet film.

Coating Holidays. A holiday is a pinhole, skip, discontinuity, or void in a coating film that exposes the substrate. Unless detected and corrected, holidays constitute a source of early electrolyte penetration and coating deterioration. Holidays in coatings are best discovered using holiday detectors, as described in the chapter of this book on coating inspection.

Topcoating Outside of Recommended Recoat Window

Manufacturers of two-component thermosetting coatings specify a window of time during which

their coatings can be successfully topcoated. If topcoated too soon, the curing of both coats may be adversely affected. If topcoated too late, the topcoat will have limited adhesion to the undercoat.

Coating Defects/Failures from Improper Curing

Most coatings require special conditions for proper curing. These include ranges of temperature and relative humidity. Curing wet coatings at temperatures significantly above or below the recommended range may result in improper or incomplete curing.

Moisture-curing polyurethanes and alkyl silicate inorganic zinc-rich coatings cure to a solid film by reaction of their binders with moisture from the air. They must cure within a specific relative humidity range to achieve complete and proper curing.[8] Moisture-blushing of coating surfaces during periods of high humidity was discussed earlier in this chapter.

Coatings applied in confined spaces such as storage tanks may require both heating and ventilating to remove coating solvents and permit complete curing or curing to the extent required for topcoating. Otherwise, osmotic blistering may be caused by the entrapped solvent.

Summary

There are many causes of coating deterioration. In order to avoid or minimize deterioration, the following actions should be taken:

- Proper selection of a high-performance coating system appropriate for the particular environment and service
- Preparation of a job specification that includes all requirements necessary to achieve long-term coating performance
- Appropriate surface preparation for the environment, service, and coating system, as recommended by the coating manufacturer
- Appropriate application of the coating system, as recommended by its manufacturer
- Thorough inspection of all phases of the work to ensure that all specification requirements are met
- Rapid corrective actions to address any deviations from recommendations or early signs of coating defects.

References

1. *Protective Coatings Glossary;* Richard W. Drisko, ed; SSPC: Pittsburgh, 2000.
2. Drisko, Richard W.; Jenkins, James F. *Corrosion and Coatings;* SSPC: Pittsburgh, 1998.
3. Munger, Charles G.; Drisko, Richard W. A Review of Common Failures of Paint Coatings: Part I, Design Factors. *Journal of Protective Coatings and Linings;* July 1989, pp 36-41.
4. Munger, Charles G.; Drisko, Richard W. A Review of Common Failures of Paint Coatings: Part II, Factors of Uncoated and Coated Substrates that Affect Coating Performance. *Journal of Protective Coatings and Linings;* May 1990, pp 62-66.
5. *The Fundamentals of Cleaning and Coating Concrete;* Randy Nixon and Richard W. Drisko,eds.; SSPC: Pittsburgh, 2001.
6. SSPC-TU 4. *Field Methods for Retrieval and Analysis of Soluble Salts on Substrates;* SSPC: Pittsburgh.
7. Skinner, Jim. *Applicator Training Bulletin: Mixing and Thinning;* Technology Publishing Company: Pittsburgh, 1992, pp 65-68.
8. Hare, Clive H. *Protective Coatings, Fundamentals of Chemistry and Composition;* Technology Publishing Company: Pittsburgh, 1994.

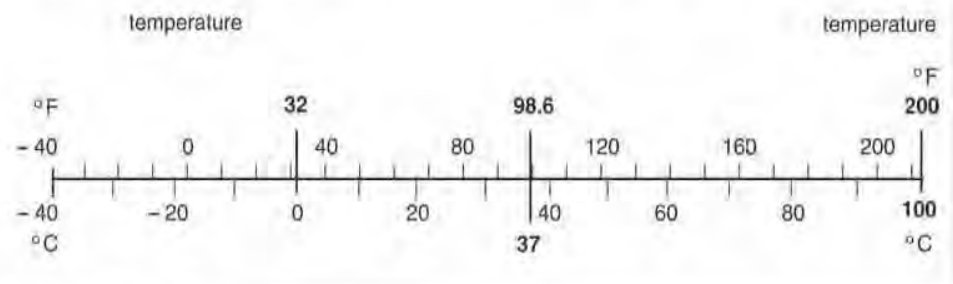
About the Author

Dr. Richard W. Drisko

Dr. Richard W. Drisko has been the senior technical advisor to SSPC: The Society for Protective Coatings since January 1995. Prior to this, he was employed for over 40 years at the Naval Civil Engineering Laboratory, Port Hueneme, California, where he conducted research, evaluation, and testing, and served as the Navy's center of expertise on coatings for shore structures. He is a professional engineer in the state of California, an SSPC certified protective coatings specialist (PCS), and a NACE International certificated corrosion specialist. Dr. Drisko received his BS, MS, and PhD degrees from Stanford.

SI* (Modern Metric) Conversion Factors

	Approximate Conversions to SI Units					Approximate Conversions from SI Units				
	Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
Length	in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
	ft	feet	0.3905	meters	m	m	meters	3.28	feet	ft
	yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
	mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
Area	in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
	ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
	yd^2	square yards	0.836	meters squared	m^2	ha	hectares	2.47	acres	ac
	ac	acres	0.405	hectares	ha	k^2	kilometers squared	0.386	square miles	mi^2
	mi^2	square miles	2.59	kilometers squared	k^2					
Volume **	fl oz	fluid ounces	29.57	millimeters	mL	mL	millimeters	0.034	fluid ounces	fl oz
	gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
	ft^2	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^2
	yd^2	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^2
Mass	oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
	lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
	T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
Temperature (Exact)	°F	Fahrenheit temperature	5 (F-32)/9	Celsius temperature	°C	°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement.

** Volumes greater than 1000 L shall be shown in m^3.

Index

A

Abrasive air/water parameters 112
Abrasive blast cleaning 64, 157, 212, 292, 398, 426-427
- concrete 194–195
- removing salts 127–128
- wet 111–112

Abrasives
- cast-steel 83–85
- characteristics 86–87
- chilled iron 85
- containment and recycling 87-88
- injected waterjetting 112
- manufactured 80
- metallic 83–90
- mineral 77–78
- nonmetallic 77–82
- paint waste 462–463
- slag by-products 78–80
- vegetable media 79–80

ACI 515.IR 304
Acid pickling 57
Acid cleaning (concrete) 197–198
Acrylics 222
- water-borne systems 215–216

Adhesion 24
- testing concrete 192

Adhesive patch cell 121–122
Aerial lift safety 430–431
AIM coatings rule 445–446
Air compressors 91–92, 397–398
Air line sizes 93
Air pollutants
- HAPs 441–442

Air quality
- lead 449–450
- particulates 450–452
- state and local regulations 452–453
- standards 441

Alkali resistance 50–51
Alkyd coatings 31, 213–214
Alligatoring 560
Aluminum
- alloys 203
- vessels 389

Amine blush 32, 558
Anemometers 276
Anode 2
ANSI B74.18 194
ANSI/AWWA standards
- C203 374
- C209 374
- C213 374
- C216 375

ANSI/AWS standards
- C2.18 242

Antifouling 387–389, 481–482
Application
- equipment 272
- methods 252–253

API
- 652 302
- 653 306
- 1631 302
- RP1631 479

Aquatic life
- water standards 467–468

ASTM standards
- A 123 58, 61
- B 117 296
- B 201 59, 61
- C 190 338
- D 512 122
- D 610 492
- D 822 339
- D 879 338
- D 1014 338
- D 1186 356
- D 1210 238
- D 1614 338
- D 1640 417
- D 1653 339
- D 2369 448

ASTM standards, cont.
D 2488 338
D 2792 338
D 3276 306
D 3359 416
D 3363 417
D 3960 447–448
D 4228 246–247
D 4260 199
D 4262 198
D 4258 198
D 4259 198
D 4285 156
D 4417 66, 202, 244, 276, 356
D 4514 245
D 4541 192, 196, 416
D 4752 417
D 5402 417
D 5894 338
D 6222 338
D 6386 59, 61
D 6687 416
E 11 84
E 307 339
E 337 184, 395
F 1869 219
G 8 51, 55, 371, 338
G 9 51, 55
G 15 11
G 19 51, 55
G 42 51, 55
G 80 51, 55
G 95 51, 55
ASTs 475–476
Atlas test cell 310–311
AWWA standards
D 101 306
D 102 239, 301
D 110 304
D 115 304
M 42 306

B

Baking 314–315
Baking soda blast cleaning 149, 153, 157, 208
cleaning rates and cost 151–152
defined 149
surface conditions 152
Ballast tank coating 382–383
Barrier protection 21–22
Bicarbonate of soda blast cleaning
See baking soda blast cleaning
Bids 507, 513–514
Bituminous coatings 29–30
Biofouling 25–26
Blast cleaning 64, 212, 398, 426–427
abrasive 157, 268–269, 292
baking soda 149-153, 157, 208
concrete 194–195
costs 501–502
dry ice 147, 157, 161–167, 208
hoses 96
equipment setup 101–103
nozzles 97-98, 399–400
paint waste 462–463
plastic media 204
pliant media 155–159
system components 91–98
wet 111–112
Bleeding 561
Bleed water 190
Blistering 21, 24, 561–562
Blushing,
amine 558
moisture 557–558
Breathing aids 98–99
Bresle test 121–122
Bridge
coatings 293–294
exposure environments 291
localized corrosivity 290–291
painting regulations 294–295
structure types 289–290
surface preparation 291–293
Brushes 180, 196
Brush marks 558
Bugholes 191–192
Bulk density 89

C

Carbonation 192
Carbon dioxide blast cleaning 147, 157, 161–167, 208
See also dry ice blast cleaning
Carbon monoxide monitoring 100
Cathodes 2–3

Cathodic protection 10, 23, 49–55, 201, 303–305, 371, 479, 492, 561–562
Caustic cleaning 57
Centrifugal blast cleaning 105–110, 269, 400
machine components 106
portable systems 108–109
shop 108
CERCLA 455–456, 467, 473–474
Chalking 556
Checking 560
Chemical cleaners 176
Chemical cleaning specifications 177
Chemical inhibition 22–23
Chemical plants
surface preparation 318–319
Chemical resistance 25
Chemical stripping 157, 205, 425
defined 145
cleaning rates and cost 147
Chisel scalers 72–73
Chloride ion analysis 125–126
Chlorinated rubber 222
Chlor-Test 122
Chromatography 125–126
Clean Air Act 441
Clean Water Act 467
Closed-loop dehumidification 186
Coal-tar enamel 362–363
Coal-tar epoxies 33, 214–215, 371–373, 363
Coal-tar mastic 363
Coatings
See also painting
alkyd 31, 213–214
application defects 563–565
application methods 405
bituminous 29–30
chemical attack 558–559
chemical resistance 321
coal-tar epoxies 33, 214–215, 371–373, 363
condition surveys 350–352
convertible 30–35, 45–46
cost factors 499–501, 505–507
defect analysis 518
economic analysis 504
epoxy 32–33, 213–214, 222–223, 364–365, 373–374, 379
failures defined 553
generic 29
gloss 557
Coatings, cont.
hydraulic structures 361–362
inaccessible areas 18–19
incompatibilities 560–562
inspector functions 393–394
latex 222
See also water emulsion
maintenance 19
metallic 23, 37
nonconvertible 29–30, 44–45
oleoresinous 31–32
organic 9–10, 41–42
performance 554–555
phenolic 31–32, 35
polyester 34–35
polyurea 34
polyurethane 33–34, 365–366
service life 502
shelf life 556
shop 285
systems 23–24, 355, 490–491
temperature problems 559
thermal spray 368
thickness 412–413, 564
vinyl 366–367
vinyl ester 34–35
water emulsion 30, 222
zinc-rich 23, 35–37, 502
Cofferdams 32
Corrosion
control 9–10, 21–22
cycle 1–3
filiform 555
forms 4–9
rate of reaction 3
undercutting 555
USTs 478–479
Compliance issues 433–434
VOCs 447–448
Composite materials 201, 207–208
Concrete
cleaning standards 198
coating 219–225
floor preparation 165
finishing 190
placement 189–190
properties 191, 219
surface preparation 220
curing 190–191

Condition assessment surveys 532–534
Conductivity 126–127
Confined space safety 432
Construction industry lead standard 436
Containment 23
  secondary 475–476
Contaminate tests 398
Contamination
  water 468–469
Contracts 507, 513–514
  process 522–523
  review 541
  warranties 514
Convertible coatings 30–35
Copper alloys 206
Couplings 96–97
Cracking 22, 559–560
Crawling 562
Crevices 16–17
Curing 45–46, 183, 314–315, 417
  concrete 190–192
  improper 566
  powder coatings 232

D

Dehumidification
  air flow capacity 186–187
  defined 183
  equipment 184–186
  desiccant systems 183, 185
Design
  steel structures 13
Destructive coating thickness instruments 413–414
Detergent
  cleaners 176
  machines 178–179
Dew point 396
Disbonding 562
DOD-P-15328 35
DOD-P-24441 130
Drinking water standards 467–468
Dry cell battery 3
Dry bulb temperature 395–396
Dry ice blast cleaning 147,157, 161–167, 208
  cleaning rates and cost 166
  defined 161
  equipment 162–163
  markets and applications 163–165
Dry film thickness 407–408
Dry oils 213–214
Dry spray 565
Dry voids 385
Dust 88, 158

E

Eddy current gauges 412
Edge treatments 16–17
Efflorescence 192, 195
Electric arc spraying 236
Electrochemical cell 2, 49–50
Electrochemical stripping
  advantages 170–171
  cleaning rates and cost 171–172
  defined 169
  surface conditions 172
Electroendosmosis 51
Electrostatic powder spray 229–230, 260–263
Embedment 88
Emission standards
  PM 10 451–452
Environmental
  condition measurements 184
  monitoring equipment 187–188
  regulations 487
  zones 216–217
EPA
  emission standards 451–452
  hazardous waste regulations 455–456
  lead hazard definitions 472–473
  lead monitoring criteria 449–450
  Title X 471–472
  TSCA Title IV 471–472
  VOC regulations 442–449
  waste regulations 459–460
  water standards 467–468
Epoxy coatings 32–33, 213–214, 222–223, 364–365, 373–374, 379
Erosion 556–557

F

Facility design 490
Failure analysis 553–554
Failure terms defined 553
Fall hazards 428–430
Fasteners 17–18

Faying surfaces 554
Ferrous ion analysis 126
Fiberglass 201, 207–208
Field
adhesion testing 416–417
coating cost worksheet 512
painting costs 495, 510
titration 125–126
Filiform corrosion 555
Film forming mechanisms 43–44
Film properties 24
Film thickness 405–408
Finish coats 346–347
Fire hazards 420–422
Fish eyes 562
Flame cleaning (concrete) 197
FlashJet· technology 208
Flash rust 115, 116, 183–184, 171
See also water bloom
Fluxing 57–58
Foam cleaning 179–180
Fossil fuels 344–345
FRP construction 479

G

Galvanic
corrosion 5–6, 203, 553–554
protection 23
Galvanizing 37, 502
bath 508
chemical treatments 59–60
coating systems 60–61
defined 57
inspection and repair 58–59
layers 57
maintenance 61
rusting and streaking 59
weathered 59–60
Gauges
constant pressure probe 410–412
Eddy current 412
pencil-pull off 409–410
magnetic pull-off 407–408
notch 405–406
Tooke (PIG) 412–414
ultrasonic 412–413
wet film 405–406
Generic coatings 29
Geometric design considerations 15–19
Gloss 557
Grit 84, 105

H

Hand tool cleaning 69–71, 128–129, 203, 270–271, 427
HAPs 441–446
Hazards,
health 422–425
in the coating industry 420–426
Hazardous
air pollutants *See HAPs*
EPA waste regulations 455–456
state regulations 463–464
substances 473
treatment and disposal 461–463
Heat-shrink sleeves 375–376
HEPA equipment 271, 472
Holidays 414-415, 555–565
Honeycombs 191–192
Hot dipping 57–58
HVLP spray systems 264–265, 285
Hydrochloric acid 141
Hydraulic structure design 361
Hygrometers 184
Hygrothermometers 396

I

Ice blast cleaning 147, 157, 161–167, 208
See also dry ice blast cleaning
ICRI Guidelines 03732 194, 199
Impact cleaning tools 72-73, 195–196
Impressed current systems 51–54
Infrared thermometers 396–397
Inhibitors 116
Inspection 19, 492
activities 542–543
functions 393–394
nonferrous materials 202
Inspector requirements 541–542
Ion detection tube 125
ISO standards
8501 69, 127, 277
8502-3 88
8502-5 125
8502-6 122, 127

ISO standards, cont.
8502-13 127
8502-11 126
8504 351
9223 378–379

J

Job cost elements 496–497
Job reference standard 241, 246
Job specifications 523–529
format 523–527
language 528–529
writing 521–522

K

Kitagawa tube 125

L

Lacquers 29, 45
Ladder safety 428
Laitance 190, 195
Laser stripping 208
Latex 222
See also water emulsions
Lead
exposure effects 424–425
hazards 472–473
monitoring exposure 449–450
soil 480–481
waste disposal 461–462
Lining materials 310–312
USTs 478–479
Liquid cargo 382

M

MACT 441–442
Magnehelic gauge 276, 283
Magnetic pull-off gauge 407–408
Maintenance painting 19, 354–355, 492–493, 503–504
bridges 297
corrective actions 536–538
defined 531
economics 536
power plants 345
Maintenance painting, cont.
pulp and paper mills 349
rating system 533
ships 380–381
tank linings 315–316
Materials selection 14–15
Metering valves 95
Metallic
abrasives 83–90
coatings 23
Metallizing 37–38
Mildew 194, 557
Micrometers 413
Microscopes 413–414
MIL-DTL-24441 364
MIL-P-85891 204
Mineral abrasives 77–78, 204
Mixing paint 402–404
Moisture
blushing 557–558
meters 207
separators 92
Monitoring water and soil 469
Mottling 559
Mud cracking 36, 560

N

NACE
See also SSPC for joint standards
RP 01 351
RP0178 18, 19, 305, 309, 394
RP0188 315
RPO288 306

NAQQS 441–444
Navy ships 378
Needle scalers 72, 196
NFPA 301
NIOSH 419–420
NIST standard 409
Nitrate ion analysis 126
Nonferrous surfaces 201–209
Nonmetallic abrasives 77–82
Notch gauge 406
Nozzle orifice gauge 399–400
NSF 61 301, 328, 382, 470
Nuclear plants 343–344

O

Oleoresinous coatings 31–32
Oil Pollution Act 476
Orange peel 558
Organic coatings 9–10, 41–42
OSHA 145, 340–341
  defined 419–420
  Injury and Illness Form 300 438
  PELs 425
  Process Safety Management 340–341, 420
  safety standards 434–436
  violations and fines 433
Osmotic blistering 21, 24, 559, 562–563
Overcoating 491–492
  bridges 294
  ozone 442–443

P

Painting
  See also coatings
  air monitoring 452
  bridges 289–297
  chemical plants 317–325
  costs 497–498, 508
  hazards 422–424
  hydraulic structures 359–370
  industrial structures 211–217
  lead hazards 472–473
  linings 309–316
  new construction 379–380
  petroleum refineries 335–341
  pipelines 371–376
  power generation facilities 343–347
  pulp and paper mills 349–357
  ships 377–391
  shop 281–287
  specifications 521–522
  tanks 299–308
  waste streams 455
  waste treatment plants 327–333
Paper chromatography 125–126
Particulate matter
  defined 450
  monitoring 450–452
Phenolic coatings 31–32, 35
Photochemical stripping 208–209
Peeling 562
Pencil pull-off gauge 409–410
Permeability 24–25, 337
  concrete 219
PELs 145, 425
Personal protective equipment (PPE) 100, 427
Petroleum refineries 335–341
Pickling 139
PIG gauges 412–414
Pigment characteristics 42–43
Pinhole detection 414–416, 565
Pipelines
  coating application 372–373
  coating properties 371
Pitot tubes 283
Pitting 7
Plant surveys 517–518
Plastic media blast cleaning 204
Pliant media blast cleaning
  applications 156
  cleaning rates and cost 158–159
  defined 155
  profile and cut rate 158
  surface conditions 159
Plural component spray 263–264
Point source discharge 469
Polyester coatings 34–35, 223–224
Polyolefins 374
Polyurea coatings 34
Polyurethane coatings 33–34, 214, 222–223, 365–366
Portland cement 189–190
Potable water 382, 470
Powder coatings 375
  application methods 229–232
  ASTM standards 233
  characteristics 228
  curing 232
  manufacture 227
  surface preparation 229
  types 227–228
Power plants 343–347
  ASTM standards 347
Power tool cleaning 71–76, 128–129, 203, 270–271, 427
  concrete 195–198
Pozzolans 189
Pre-cleaning 63
  concrete 193
  solvents and chemicals 175–181

Pre-construction primers 213, 379
Pre-surface preparation 394
Pressure blasting 93–94
Primers 346, 354
pre-construction 213, 379
steel 212–213
Process safety management 340–341, 420
Profile 66, 401–402, 563
Proposals 507, 513–514
Psychrometers 184, 395–396

Q

Quality control 276–277, 356, 541
Quantab 125–126

R

Refrigerant dehumidifiers 184
Rectifiers 52
Regulations
antifouling 481–482
ASTs 475–476
environmental 360–361, 432–434, 487
food and beverage facility coating 480
soil and lead 480–481
USTs 477–480
waste 459–460
Remote controls (on blast machines) 95–96
Replica tape 402
Resin-based composites 201
Respiratory protection 436–438
Rotary cleaning 73–76
Rotopeens 75
Rust bloom 183
Rust, flash 115–116
See also water bloom

S

Sacrificial anode system 51–53
Safety
blast cleaning 98–101
equipment 277–278
health responsibilities 420
work programs 438–439
Salts 116, 352–353
coating studies 130–131
contamination 24, 384, 398–399
Salts, cont.
corrosion-related problems 120–121
extracting from steel substrates 121–124
extraction efficiencies 123
levels on bridges 131
manufacturer recommendations 133
osmotic blistering 119–120, 562–563
safe and failure levels 132
removing from concrete 194
removing with baking soda 152
removing with specialty methods 129
various surface prep. methods 130
units and conversions 137–138
Sagging 564
Saponification 561
SARA strippers 145, 205
SARA Title III 474
Scaling hammers 73
Sealing
thermal spray 238–239
Seal weld 18
Secondary containment
ASTs 475–476
Service condition tables 330, 332
Service life 502, 505–506
hydraulic structures 369–370
Sharp edges 16–17, 554
Ships
painting systems 381–384
Shop
equipment 272
painting 211, 281–283, 509, 511
primers 379
surface preparation 283–284
VOCs 444–445
Shot gradations 84
Siloxanes 35, 215
Slag by-products 78–80
Slip resistance 482–483
Soda blast cleaning (SBC)
See baking soda blast cleaning
Soil quality 480–481
Solvents
cleaning 129
EPA exemptions 447
hazards 422–423
pre-cleaning 175–181
waste 463

Specifications 13–14
format 523–527
language 528–529
review 541
writing 521–522
Spray
application materials 403
guns 230, 253–260
techniques 564–565
SSPC standards and guidelines
AB 1 159, 244
AB 2 107
AB 3 86, 88, 244
CS 23 235, 236, 242
Guide 3 352
Guide 4 322
Guide 5 242, 306, 532
Guide 6 146, 449
Guide 10 447
Guide 14 61
Guide 61 352
Guide 71 352
PA 1 251, 284, 323, 397
PA 2 61, 323, 407, 409–410, 412, 528, 535, 542
PA 5 336
Paint 16 328, 363, 528
Paint 20 36
Paint 22 364
Paint 27 35, 60, 206
Paint 29 36
Paint 33 363
PS 12 302
QP 1 541
QP 3 541
QP 5 306, 541
QP 6 248
SP 1 59, 61, 63, 65–66, 69, 72, 127, 130, 268, 291, 351, 355, 386, 394
SP 2 61, 63–66, 69, 127, 130, 346, 351, 355, 386, 499
SP 3 61, 65, 71–72, 127, 129–130, 146, 212–213, 291, 346, 351, 386, 499
SP 5/NACE 1 65, 71, 111, 113, 128–129,159, 229, 242, 312, 344–345, 373
SP 6/NACE 3 65–66, 71, 111, 113, 130, 159, 211, 213, 283, 291–292, 319, 321, 330, 332, 339, 344–345, 351, 355
SP 7/NACE 4 65, 71, 111, 113, 159, 195, 204, 319, 529
SP 10/NACE 2 65, 71, 111, 113, 127, 130, 157, 211, 213, 229, 236, 242, 283, 291–293, 296, 330, 332, 339, 344, 351, 528
SP 11 65, 71–72, 128–130, 212–213, 292, 345–346, 351, 355
SP 12/NACE 5 63, 65, 111–113,130, 132–133, 197
SP 13/NACE 6 98, 159
SP 14/NACE 8 111,113, 159
SP 15 71-72, 351
SP-COMM 64
TR 2/NACE 6G198 111, 130
TR 3/NACE 6A192 313
TU 1 213
TU 3 294, 394, 535
TU 4 122, 125-127, 313
TU 5 338
TU 6 146, 425
TU 7 449, 451–452, 470
VIS 1 159, 203, 277, 356, 400
VIS 2 277, 318, 394, 492, 503, 517, 533
VIS 3 69, 203, 277, 351–352
VIS 4/NACE VIS 7 111, 113, 203, 277
VIS 5/NACE VIS 9 111, 203, 277
Stainless steel 206
Steam cleaning 177–178
Steam power plants 345
Steel
shot 105
stainless 206
structure design 13
structural paint preparation 165
Tank Institute 479
Stepwise procedure
thermal spray 240
Storm water discharge 469
Stray current corrosion 8–9
Stripe painting 294
Structural steel paint preparation 165
Substrate properties 554–555
Suction blasting 93
Sulfate ion analysis 126
Sulfuric acid 141
Superfund 455–456, 473–474

Surface
cleanliness standards 64–65
contaminant levels 133, 193–194
defects 63
temperature 184
Surface preparation 194–198, 268–271, 352, 400–403
concrete 189–199
defined 63
inadequate 562–563
methods compared 157
nonferrous materials 202–203
other methods 352
safety issues 426–427
specialized methods 208–209
steel 211–212
tank linings 312–313
Surface profile 66, 401–402, 563
Surface-tolerant
epoxy 379
primers 213
Sweep blasting 59

T

Tanks
applicable guidance 300
ASTs 475–476
ballast 382–384
exterior coatings 303–304
linings 309–316
liquid cargo 382
maintenance 306–307
USTs 477–480
waste water 215
Tape wraps 374
Tensile adhesion test kits 416
Thermal spray 37–38, 231–232, 368
bend test 245–246
defined 235–236
inspection 240–241
stepwise procedure 240
surface life 237–238
Thermocouple thermisters 397
Thermometers 395–396
Thermoplastic coatings 227, 375
Thermosetting coatings 228
Threshold limit concentrations 463
Titration 122, 125–126
Tooke gauges 412–414
Topcoating 354–355, 502, 565–566
thermal spray 238–239
Toxic metals 457
Toxic Substances Control Act 471–472
TT R 2218 205
Type 1 gauges 409
Type 2 gauges 410–412

U

Ultrasonic coating thickness gauges 412–413
Undercutting 555
Underwater hulls 386–387
Universal primers 213
USTs 477–480

V

Vegetable media 79–80
Venturi nozzles 97, 399
Vinyl coatings 34–35, 222, 366-367
Viscosity cups 404
Visual standards 400
See also SSPC detailed listings
VOC emissions 442–449

W

Wash primers 35
Waste
analysis 460–461
classifications 456–457
responsibilities defined 457–460
state regulations 463–464
treatment and disposal 327–328, 461–463
water tanks 215, 331
Water blasting 197
Water bloom 115–116
See also flash rust and rust bloom
Water-borne acrylic systems 215–216
Water cleaning
at various pressures 114–115
Water emulsion coatings 30, 45, 222
Waterjetting 64, 111–118, 127–128, 171, 157, 204, 212, 269–270, 339–340, 345, 352
production rates 117
recycling 116–117
safety 427–428

Water pollution 455
Water quality standards 467–468
Water tanks 214, 215, 331
failure 310
interior protection 301–302
Water traps 15–16, 554
Wet abrasive blast cleaning 111–112
Wet bulb temperature readings 395–396
Wet curing (concrete) 192
Weathering 25
Wet film thickness 405–406
Wet storage staining 59
Wheel blast cleaning 105–110, 269, 400
See also centrifugal blast cleaning
Wood substrates 206–207
Work mix 88
Work safety programs 438–439
Wrinkling 31, 558–559

Z

Zahn cup 404
Zinc-rich
coatings 23, 35–37, 215, 502, 560
primers 367–368