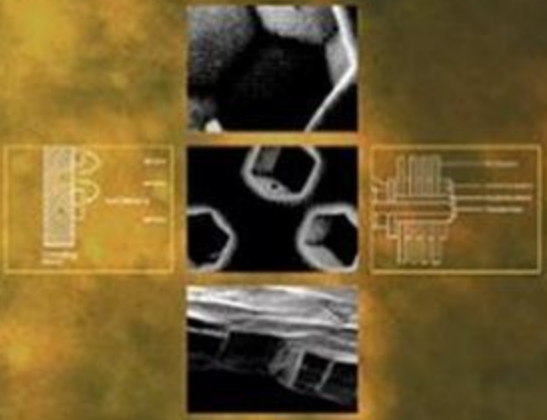
# Encyclopedia of CORROSION TECHNOLOGY

Second Edition, Revised and Expanded



Philip A. Schweitzer

# *Encyclopedia of*
# *CORROSION TECHNOLOGY*

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# CORROSION TECHNOLOGY

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3. *Corrosion Resistance of Elastomers*, Philip A. Schweitzer
4. *Corrosion Resistance Tables: Metals, Nonmetals, Coatings, Mortars, Plastics, Elastomers and Linings, and Fabrics: Third Edition, Revised and Expanded (Parts A and B)*, Philip A. Schweitzer
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ADDITIONAL VOLUMES IN PREPARATION

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# CORROSION TECHNOLOGY
## Second Edition, Revised and Expanded

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**Library of Congress Cataloging-in-Publication Data**
A catalog record for this book is available from the Library of Congress.

**ISBN: 0-8247-4878-6**

This book is printed on acid-free paper.

**Headquarters**
Marcel Dekker, Inc.
270 Madison Avenue, New York, NY 10016, U.S.A.
tel: 212-696-9000; fax: 212-685-4540

**Distribution and Customer Service**
Marcel Dekker, Inc.
Cimarron Road, Monticello, New York 12701, U.S.A.
tel: 800-228-1160; fax: 845-796-1772

**Eastern Hemisphere Distribution**
Marcel Dekker AG
Hutgasse 4, Postfach 812, CH-4001 Basel, Switzerland
tel: 41-61-260-6300; fax: 41-61-260-6333

**World Wide Web**
http://www.dekker.com

The publisher offers discounts on this book when ordered in bulk quantities. For more information, write to Special Sales/Professional Marketing at the headquarters address above.

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Current printing (last digit):

10 9 8 7 6 5 4 3 2 1

**PRINTED IN THE UNITED STATES OF AMERICA**

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# Preface

Corrosion is expensive and can be hazardous. It is costly to replace and/or repair equipment, structures, and other miscellaneous items that have been damaged as a result of corrosion. It can be hazardous when corrosion has weakened a portion of a vessel, bridge, or other structure causing it to fail, resulting in injury to persons and/or fires or explosions.

Materials are capable of corroding as the result of prolonged exposure to the atmosphere as well as contact with aggressive media. It is the purpose of this encyclopedia to explain the many terms associated with corrosion, including the various types and forms of corrosion, and metallurgical and other terms as they relate to the corrosion process.

All the most commonly used materials of construction have been included because the various forms and types of corrosion affect different materials in different ways.

Methods whereby corrosion can be controlled or prevented are explained. Information regarding areas of application, conditions of protection, and conditions under which they are useful have been included.

Ample references are supplied to permit more detailed study of many of the topics.

This encyclopedia will provide insight into the causes and problems of corrosion and offer some assistance in solving these problems.

*Philip A. Schweitzer, P.E.*



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# A

## ABRASION CORROSION

See "Erosion Corrosion."

## ABSORPTION

See also "Sheet Linings."

Unlike metals, polymers will absorb varying quantities of the corrodents they come into contact with, especially organic liquids. This can result in swelling, cracking, and penetration to the substrate. Swelling can cause softening of the polymer. If the polymer has a high absorption rate, permeation will probably occur. An approximation of the expected permeation and/or absorption of a polymer can be based on the absorption of water. Some typical rates are shown in Table A.1. Table A.2 shows the absorption of selected liquids by FEP, and Table A.3 shows the absorption of selected liquids by PFA.

## ACID

Any chemical compound containing hydrogen capable of being replaced by positive elements or radicals to form salts. In terms of the dissociation theory, it is a compound which on dissociation in solution yields excess hydrogen ions.

**Table A.1** Water Absorption Rates of Polymers

| Polymer | Water absorption 24 h at 73°F (23°C) (%) |
|---|---|
| PVC | 0.05 |
| CPVC | 0.03 |
| PP (Homo) | 0.02 |
| PP (Co) | 0.03 |
| PE (EHMW) | <0.01 |
| E-CTFE | <0.1 |
| PVDF | <0.04 |
| Saran | nil |
| PFA | <0.03 |
| ETFE | 0.029 |
| PTFE | <0.01 |
| FEP | <0.01 |



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**Table A.2** Absorption of Selected Liquids[a] by FEP

| Chemical | Temperature (°F/°C) | Range of weight gains (%) |
|---|---|---|
| Aniline | 365/185 | 0.3–0.4 |
| Acetophenone | 394/201 | 0.6–0.8 |
| Benzaldehyde | 354/179 | 0.4–0.5 |
| Benzyl alcohol | 400/204 | 0.3–0.4 |
| *n*-Butylamine | 172/78 | 0.3–0.4 |
| Carbon tetrachloride | 172/78 | 2.3–2.4 |
| Dimethyl sulfoxide | 372/190 | 0.1–0.2 |
| Nitrobenzene | 410/210 | 0.7–0.9 |
| Perchlorethylene | 250/121 | 2.0–2.3 |
| Sulfuryl chloride | 154/68 | 1.7–2.7 |
| Toluene | 230/110 | 0.7–0.8 |
| Tributyl phosphate | 392/200[b] | 1.8–2.0 |

[a]168-hour exposure at their boiling points.
[b]Not boiling.

**Table A.3** Absorption of Representative Liquids by PFA

| Liquid[a] | Temperature (°F/°C) | Range of weight gains (%) |
|---|---|---|
| Aniline | 365/185 | 0.3–0.4 |
| Acetophenone | 394/201 | 0.6–0.8 |
| Benzaldehyde | 354/179 | 0.4–0.5 |
| Benzyl alcohol | 400/204 | 0.3–0.4 |
| *n*-Butylamine | 172/78 | 0.3–0.4 |
| Carbon tetrachloride | 172/78 | 2.3–2.4 |
| Dimethyl sulfoxide | 372/190 | 0.1–0.2 |
| Freon 113 | 117/47 | 1.2 |
| Isooctane | 210/99 | 0.7–0.8 |
| Nitrobenzene | 410/210 | 0.7–0.9 |
| Perchlorethylene | 250/121 | 2.0–2.3 |
| Sulfuryl chloride | 154/68 | 1.7–2.7 |
| Toluene | 230/110 | 0.7–0.8 |
| Tributyl phosphate | 392/200[b] | 1.8–2.0 |
| Bromine, anhydrous | –5/–22 | 0.5 |
| Chlorine, anhydrous | 248/120 | 0.5–0.6 |
| Chlorosulfonic acid | 302/150 | 0.7–0.8 |
| Chromic acid 50% | 248/120 | 0.00–0.01 |
| Ferric chloride | 212/100 | 0.00–0.01 |
| Hydrochloric acid 37% | 248/120 | 0.00–0.03 |
| Phosphoric acid, concentrated | 212/100 | 0.00–0.01 |
| Zinc chloride | 212/100 | 0.00–0.03 |

[a]Liquids were exposed for 168 hours at the boiling point of the solvents. The acidic reagents were exposed for 168 hours.
[b]Not boiling.

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## ACID BRICK

Acid brick is brick made from selected clays having a higher silica content than ordinary firebrick and containing little acid-soluble components. It is used to line vessels to impart corrosion resistance against hot acid or erosion–corrosion attack. It is fired at higher temperatures and for longer periods of time than the same clay when used to make "common" brick. Acid-resistant brick is covered by ASTM Specification C-279. The two most commonly used bricks are red shale and fireclay. These are used for all applications except those where the exposure is to strong alkali or hydrofluoric acid. Of the two, the most frequently used is red shale.

### Red Shale Brick

Red shale brick is usually described as meeting type L in ASTM C-279. These bricks provide a lower absorption rate than fireclay and are usually somewhat more brittle. They are applied in those areas where lowest absorption masonry is desired.

### Fireclay

Fireclay brick is usually described as meeting type H in ASTM C-279. It contains a higher proportion of alumina and lower percentages of silica and iron than does shale brick. Fireclay bricks have a higher absorption rate than shale bricks, although some manufacturers provide a denser brick that will meet type L for absorption. These bricks are usually selected for outdoor exposures where rapid thermal changes occur, since they are less brittle than the shale brick. Since they also have a low iron content, they are used in process equipment where this characteristic is important in maintaining product purity.

### Carbon Brick

Carbon brick is used in areas exposed to strong alkali (pH 12.5+) and hydrofluoric acid, or fluoride salts in an acid medium. These bricks are more shock resistant than either red shale or fireclay brick, permitting them to be used in areas where rapid pressure changes take place, a condition that can cause shale or fireclay to spall.

### Silica Brick

All silica brick is used in very high acid concentrations, particularly in phosphoric acid.

See Ref. 1.

## ACID MINE WATERS

These are waters that are present in some underground coal mines. They are extremely corrosive because of their free acidity and the presence of high concentrations of ferric and sulfate ions. Their corrosiveness is a result of the aerial and microbial oxidation of pyrite sulfur present in the coal seams or related strata.

## ACID RAIN

When rain has a pH less than 5.6 it is classified as acid rain. It is the result of atmospheric moisture coming into contact with sulfur dioxide gases from industrial emissions and/or with nitrogen oxide gases from car exhausts. See "Atmospheric Corrosion."

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## ACRYLATE-BUTADIENE RUBBER (ABR) AND ACRYLIC ESTER–ACRYLIC HALIDE (ACM) RUBBERS

Acrylate-butadiene and acrylic ester–acrylic halide rubbers are very similar to ethylene-acrylic rubbers.

### Physical and Mechanical Properties

The ABRs and ACM rubbers exhibit good resilience and tear resistance but poor impact resistance. Abrasion resistance and compression set are good. The maximum temperature rating is 340°F (170°C), the same as for the EA rubbers.

Table A.4 lists the physical and mechanical properties of the ACM rubbers.

### Resistance to Sun, Weather, and Ozone

Acrylate-butadiene and acrylic ester–acrylic halide rubbers exhibit good resistance to sun, weather, and ozone.

### Chemical Resistance

The acrylate-butadiene and ACM rubbers have excellent resistance to aliphatic hydrocarbons (gasoline, kerosene) and offer good resistance to water, acids, synthetic lubricants, and silicate hydraulic fluids. They are unsatisfactory for use in contact with alkali, aromatic hydrocarbons (benzene, toluene), halogenated hydrocarbons, alcohol, and phosphate hydraulic fluids.

### Applications

These rubbers are used where resistance to atmospheric conditions and heat is required.

See Refs. 2 and 3.

## ACRYLIC ESTER–ACRYLIC HALIDE RUBBERS

See “Acrylate-Butadiene Rubber.”

**Table A.4** Physical and Mechanical Properties of Acrylic Ester–Acrylic Halide (ACM) Rubbers[a]

| | |
|---|---|
| Specific gravity | 1.1 |
| Hardness range, Shore A | 45–90 |
| Tensile strength, psi | 2175 |
| Elongation, % at break | 400 |
| Compression set, % | Fair |
| Tear resistance | Good |
| Maximum temperature, continuous use | 340°F (170°C) |
| Electrical properties | Poor to fair |
| Abrasion resistance | Fair to good |
| Permeability to gases | Low |
| Resistance to sunlight | Good |
| Resistance to heat | Excellent |

[a]These are representative values since they may be altered by compounding.

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**Table A.5** Physical and Mechanical Properties of ABS

| | |
|---|---|
| Specific gravity | 1.03 |
| Water absorption 24 h at 73°F (23°C), % | 0.2–0.4 |
| Tensile strength at 73°F (23°C), psi | 5350 |
| Modulus of elasticity in tension at 73°F (23°C) × $10^5$ | 2.4 |
| Flexural strength, psi | 9400 |
| Izod impact strength, notched at 73°F (23°C) | 8.5 |
| Coefficient of thermal expansion | |
| in./in.–°F × $10^{-5}$ | 5.6 |
| in./10 °F/100 ft. | 0.056 |
| Thermal conductivity, Btu/h/sq ft/°F/in. | 1.7 |
| Heat distortion temperature at 66 psi, °F/°C | 204/94 |
| Resistance to heat at continuous drainage, °F/°C | 140/60 |
| Limiting oxygen index, % | 19 |
| Flame spread | Not applicable |
| Underwriters lab rating (Sub 94) | 94 HB |

## ACRYLONITRILE-BUTADIENE-STYRENE (ABS)

ABS is a vast family of compounds whose properties can be varied extensively, depending on the ratio of acrylonitrile to other components. Higher strength, better toughness, greater dimensional stability, and other properties can be obtained at the expense of other characteristics. Typical physical and mechanical properties that can be obtained are shown in Table A.5. The ABS material has limited heat tolerance, with a maximum operating temperature of approximately 195°F (90°C), with relatively low strength and limited chemical resistance. But its low price and ease of fabrication and joining make it attractive for use as distribution piping for gas, water, and waste. It also finds application for vent lines, automotive parts, and other consumer items.

ABS plastic will be attacked by oxidizing agents and strong acids, and will stress crack in the presence of certain organic compounds. The compatibility of ABS plastic with selected corrodents is shown in Table A.6. Because manufacturers can vary the properties so greatly, the corrosion resistance of the specific material to be used should be verified with the manufacturer.

## ADSORPTION

Adsorption is a surface phenomenon exhibited by solids which consists of the adhesion in an extremely thin layer of the molecules of gases, of liquids, or of dissolved substances with which they are in contact. There are two types depending on the nature of forces involved. In chemisorption, a single layer of molecules, atoms, or ions is attached to the surface by chemical bonds and is essentially irreversible. In physical adsorption, attachment is by the weaker Van der Waal's forces, whose energy levels approximate those of condensation.

Compare with "Absorption."

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**Table A.6** Compatibility of ABS with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | x | x | Benzyl chloride | x | x |
| Acetic acid 10% | 100 | 38 | Borax | 140 | 60 |
| Acetic acid 50% | 130 | 54 | Boric acid | 140 | 60 |
| Acetic acid 80% | x | x | Bromine liquid | x | x |
| Acetic acid, glacial | x | x | Butadiene | x | x |
| Acetic anhydride | x | x | Butyl acetate | x | x |
| Acetone | x | x | Butyl alcohol | x | x |
| Acetyl chloride | x | x | Butyric acid | x | x |
| Adipic acid | 140 | 60 | Calcium bisulfite | 140 | 60 |
| Allyl alcohol | x | x | Calcium carbonate | 100 | 38 |
| Allyl chloride | x | x | Calcium chlorate | 140 | 60 |
| Alum | 140 | 60 | Calcium chloride | 140 | 60 |
| Aluminum chloride, aqueous | 140 | 60 | Calcium hydroxide, sat. | 140 | 60 |
| Aluminum fluoride | 140 | 60 | Calcium hypochlorite | 140 | 60 |
| Aluminum hydroxide | 140 | 60 | Calcium nitrate | 140 | 60 |
| Aluminum oxychloride | 140 | 60 | Calcium oxide | 140 | 60 |
| Aluminum sulfate | 140 | 60 | Calcium sulfate 25% | 140 | 60 |
| Ammonia gas dry | 140 | 60 | Carbon bisulfide | x | x |
| Ammonium bifluoride | 140 | 60 | Carbon dioxide, dry | 90 | 32 |
| Ammonium carbonate | 140 | 60 | Carbon dioxide, wet | 140 | 60 |
| Ammonium chloride, sat. | 140 | 60 | Carbon disulfide | x | x |
| Ammonium fluoride 10% | x | x | Carbon monoxide | 140 | 60 |
| Ammonium fluoride 25% | x | x | Carbon tetrachloride | x | x |
| Ammonium hydroxide 25% | 90 | 32 | Carbonic acid | 140 | 60 |
| Ammonium hydroxide, sat. | 80 | 27 | Cellosolve | x | x |
| Ammonium nitrate | 140 | 60 | Chloracetic acid | x | x |
| Ammonium persulfate | 140 | 60 | Chlorine gas, dry | 140 | 60 |
| Ammonium phosphate | 140 | 60 | Chlorine gas, wet | 140 | 60 |
| Ammonium sulfate 10–40% | 140 | 60 | Chlorine, liquid | x | x |
| Ammonium sulfide | 140 | 60 | Chlorobenzene | x | x |
| Amyl acetate | x | x | Chloroform | x | x |
| Amyl alcohol | 80 | 27 | Chlorosulfonic acid | x | x |
| Amyl chloride | x | x | Chromic acid 10% | 90 | 32 |
| Aniline | x | x | Chromic acid 50% | x | x |
| Antimony trichloride | 140 | 60 | Citric acid 15% | 140 | 60 |
| Aqua regia 3:1 | x | x | Citric acid 25% | 140 | 60 |
| Barium carbonate | 140 | 60 | Copper chloride | 140 | 60 |
| Barium chloride | 140 | 60 | Copper cyanide | 140 | 60 |
| Barium hydroxide | 140 | 60 | Copper sulfate | 140 | 60 |
| Barium sulfate | 140 | 60 | Cresol | x | x |
| Barium sulfide | 140 | 60 | Cyclohexane | 80 | 27 |
| Benzaldehyde | x | x | Cyclohexanol | 80 | 27 |
| Benzene | x | x | Dichloroacetic acid | x | x |
| Benzene sulfonic acid 10% | 80 | 27 | Dichloroethane (ethylene dichloride) | x | x |
| Benzoic acid | 140 | 60 | Ethylene glycol | 140 | 60 |
| Benzyl alcohol | x | x | Ferric chloride | 140 | 60 |

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**Table A.6** Compatibility of ABS with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Ferric nitrate 10–50% | 140 | 60 | Phosphoric acid 50–80% | 130 | 54 |
| Ferrous chloride | 140 | 60 | Picric acid | x | x |
| Fluorine gas, dry | 90 | 32 | Potassium bromide 30% | 140 | 60 |
| Hydrobromic acid 20% | 140 | 60 | Sodium carbonate | 140 | 60 |
| Hydrochloric acid 20% | 90 | 32 | Sodium chloride | 140 | 60 |
| Hydrochloric acid 38% | 140 | 60 | Sodium hydroxide 10% | 140 | 60 |
| Hydrofluoric acid 30% | x | x | Sodium hydroxide *50%* | 140 | 60 |
| Hydrofluoric acid 70% | x | x | Sodium hydroxide, concentrated | 140 | 60 |
| Hydrofluonc acid 100% | x | x | Sodium hypochlorite 20% | 140 | 60 |
| Hypochlorous acid | 140 | 60 | Sodium hypochiorite, concentrated | 140 | 60 |
| Ketones, general | x | x | Sodium sulfide to 50% | 140 | 60 |
| Lactic acid 25% | 140 | 60 | Stannic chloride | 140 | 60 |
| Magnesium chloride | 140 | 60 | Stannous chloride | 100 | 38 |
| Malic acid | 140 | 60 | Sulfuric acid 10% | 140 | 60 |
| Methyl chloride | x | x | Sulfuric acid 50% | 130 | 54 |
| Methyl ethyl ketone | x | x | Sulfuric acid 70% | x | x |
| Methyl isobutyl ketone | x | x | Sulfuric acid 90% | x | x |
| Muriatic acid | 140 | 60 | Sulfuric acid 98% | x | x |
| Nitric acid 5% | 140 | 60 | Sulfuric acid 100% | x | x |
| Nitric acid 20% | 130 | 54 | Sulfuric acid, fuming | x | x |
| Nitric acid 70% | x | x | Sulfurous acid | 140 | 60 |
| Nitric acid, anhydrous | x | x | Thionyl chloride | x | x |
| Oleum | x | x | Toluene | x | x |
| Perchloric acid 10% | x | x | White liquor | 140 | 60 |
| Perchioric acid 70% | x | x | Zinc chloride | 140 | 60 |
| Phenol | x | x | | | |

The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x.

*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. l-3. New York: Marcel Dekker, 1995.

## ALIPHATIC HYDROCARBONS

Aliphatic hydrocarbons are straight chain organic compounds that are either alkanes, alkenes, alkynes, or their derivatives. All moncyclic organic compounds are aliphatic and cyclic aliphatic compounds are alecyclic.

## ALKALINE

Alkaline describes a solution with an excess of hydroxyl ions having a pH greater than 7.

## ALLIGATORING

Alligatoring is a rupture of an organic coating film, usually caused by application of a hard brittle film over a more flexible film, having an appearance similar to an alligator hide. It is a form of checking in which the surface hardens and shrinks at a much faster rate than the body of the coating. See "Organic Coatings."

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## ALLOY

An alloy is a mixture of two or more metallic elements to produce a single phase. Alloys can be either heterogeneous, where the alloy is a mixture of two or more separate phases, or they may be homogeneous, where the components are completely soluble in one another.

The term alloy is also used to describe resin, polymer, and plastic mixtures formed from two or more immiscible polymers united by another component and having improved performance properties.

## ALLOY B-2

Alloy B was originally developed to resist hydrochloric acid up to the atmospheric boiling point. However, because of the susceptibility to intergranular attack in the heat-affected zone after welding in some environments, a low-carbon variant, alloy B-2, was developed and is replacing alloy B in most applications. The chemical composition is shown in Table A.7.

This alloy is uniquely different from other corrosion-resistant alloys because it does not contain chromium. Molybdenum is the primary alloying element and provides significant corrosion resistance to reducing environments.

Alloy B-2 has improved resistance to knifeline and heat-affected zone attack. It also resists formation of grain boundary precipitation in weld heat-affected zones.

Alloy B-2 has excellent elevated-temperature (1650°F/900°C) mechanical properties because of its high molybdenum content and has been used for mechanical components in reducing environments and vacuum furnaces. Because of the formation of the intermetallic phase $Ni_3Mo$ and $Ni_4Mo$ after long aging, the use of alloy B-2 in the temperature range 1110–1560°F (600–850°C) is not recommended.

Alloy B-2 is recommended for service in handling all concentrations of hydrochloric acid in the temperature range 158–212°F (70–100°C) and for handling wet hydrogen chloride gas as shown in Fig. A.1.

Alloy B-2 has excellent resistance to pure sulfuric acid at all concentrations and temperatures below 60% acid and good resistance to 212°F (100°C) above 60% acid, as shown in Fig. A.2. The alloy is resistant to a number of phosphoric acids and numerous organic acids, such as acetic, formic, and cresylic. It is also resistant to many chloride-bearing salts (nonoxidizing), such as aluminum chloride, magnesium chloride, and antimony chloride.

Since alloy B-2 is nickel rich (approximately 70%), it is resistant to chloride-induced stress corrosion cracking. Because of its high molybdenum content, it is highly resistant to pitting attack in most acid chloride environments.

**Table A.7** Chemical Composition of Alloy B-2

| Chemical | Weight percent |
|---|---|
| Molybdenum | 26.0–30.0 |
| Chromium | 1.0 max. |
| Iron | 2.0 max. |
| Nickel | Balance |

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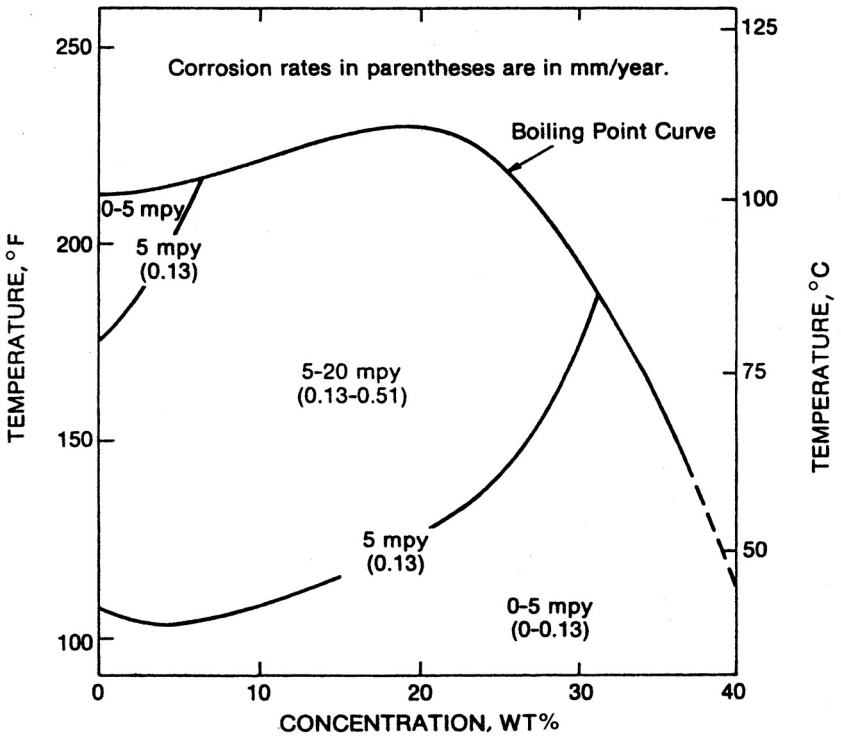



**Figure A.1** Isocorrosion diagram for alloy B-2 in hydrochloric acid (from Ref. 4).

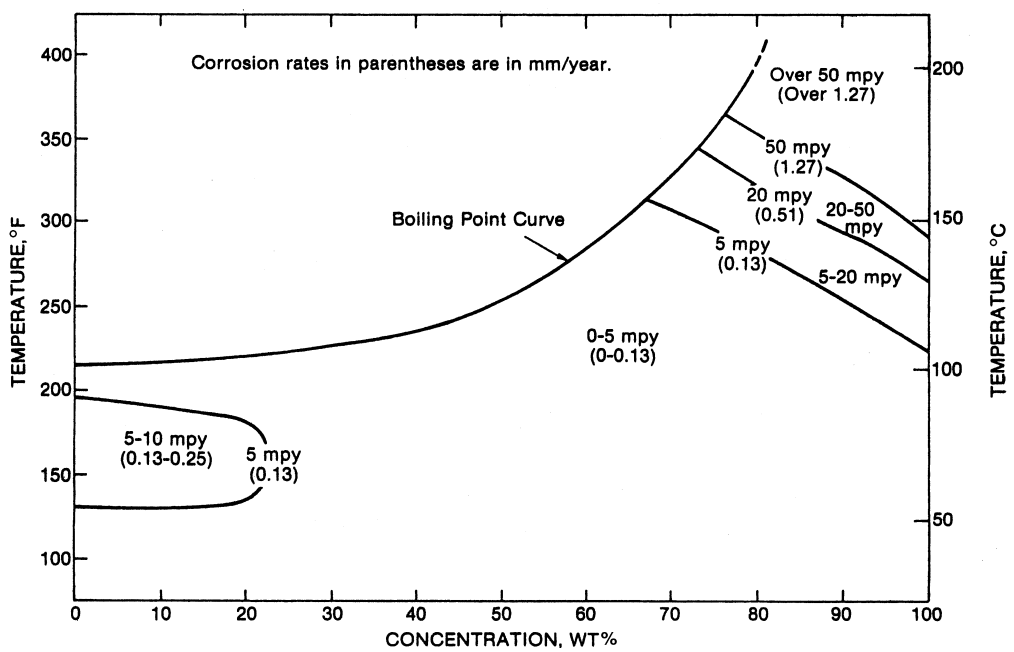



**Figure A.2** Isocorrosion diagram for alloy B-2 in sulfuric acid (from Ref. 4).

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Alloy B-2 is not recommended for elevated-temperature service except in very specific circumstances. Since there is no chromium in the alloy, it scales heavily at temperatures above 1400°F (760°C). A nonprotective layer of molybdenum trioxide forms and results in a heavy green oxidation scale. In a chloride-containing atmosphere alloy B-2 has demonstrated good resistance.

The major factor limiting the use of alloy B-2 is poor corrosion resistance in oxidizing environments. Alloy B-2 has virtually no corrosion resistance to oxidizing acids such as nitric and chromic or to oxidizing salts such as ferric chloride or cupric chloride. The presence of oxidizing salts in reducing acids must also be considered. Oxidizing salts such as ferric chloride, ferric sulfate, or cupric chloride, even when present in the parts-per-million range, can significantly accelerate the attack in hydrochloric or sulfuric acids as shown in Fig. A.3. Even dissolved oxygen has sufficient oxidizing power to affect the corrosion rates for alloy B-2 in hydrochloric acid. Alloy B-2 exhibits excellent resistance to pure phosphoric acid.

Stress corrosion cracking has been observed in alloy B-2 in 20% magnesium chloride solution at temperatures exceeding 500°F (260°C). Other environments in which stress corrosion cracking of this alloy has been observed include high-purity water at 350°F (170°C), molten lithium at 315°F (157°C), oxygenated de-ionized water at 400°F (204°C), 1% hydrogen iodide at 62–450°F (17–232°C), and 10% hydrochloric acid at

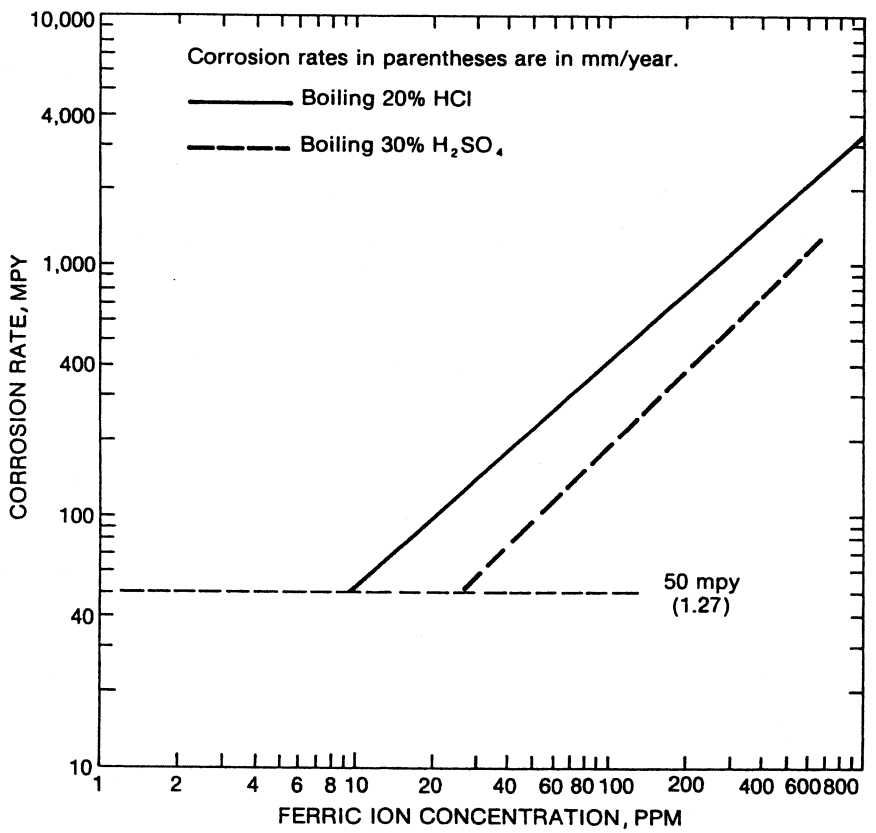



**Figure A.3** Effect of ferric ions on corrosion rate of alloy B-2 (from Ref. 4).

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400°F (204°C). In some environments, such as concentrated ammonia at 77–140°F (25–60°C), cracking has been observed if the alloy was aged at 1382°F (750°C) for 24 hours before the test. Precipitation of an ordered intermetallic phase $Ni_4Mo$ has been attributed as the cause of the increased embrittlement.

Table A.8 shows the compatibility of alloy B-2 with selected corrodents. Reference 3 contains a more extensive listing. Table A.9 lists the mechanical and physical properties of alloy B-2.

**Table A.8** Compatibility of Alloy B-2 and Alloy C-276 with Selected Corrodents[a]

| | Maximum temp. (°F/°C) | |
|---|---|---|
| Chemical | Alloy B-2 | C-276 |
| Acetaldehyde | 80/27 | 140/60 |
| Acetamide | | 60/16 |
| Acetic acid, 10% | 300/149 | 300/149 |
| Acetic acid, 50% | 300/149 | 300/149 |
| Acetic acid, 80% | 300/149 | 300/149 |
| Acetic acid, glacial | 560/293 | 560/293 |
| Acetic anhydride | 280/138 | 280/138 |
| Acetone | 200/93 | 200/93 |
| Acetyl chloride | 80/27 | |
| Acrylic acid | 210/99 | |
| Acrylonitile | 210/99 | 210/99 |
| Adipic acid | | 210/99 |
| Allyl alcohol | | 570/299 |
| Allyl chloride | 200/93 | |
| Alum | 150/66 | 150/66 |
| Aluminum acetate | 60/16 | 60/16 |
| Aluminum chloride, aqueous | 300/149 | 210/99 |
| Aluminum chloride, dry | 210/99 | 210/99 |
| Aluminum fluoride | 80/27 | 80/27 |
| Aluminum sulfate | 210/99 | 210/99 |
| Ammonia gas | 200/93 | 200/93 |
| Ammonium bifluoride | | 380/193 |
| Ammonium carbonate | 300/149 | 300/149 |
| Ammonium chloride, 10% | 210/99 | 210/99 |
| Ammonium chloride, 50% | 210/99 | 210/99 |
| Ammonium chloride, sat. | 570/299 | 570/299 |
| Ammonium fluoride, 10% | 210/99 | 210/99 |
| Ammonium fluoride, 25% | | 210/99 |
| Ammonium hydroxide, 25% | 210/99 | 570/299 |
| Ammonium hydroxide, sat. | 210/99 | 570/299 |
| Ammonium persulfate | x | |
| Ammonium sulfate, 10–40% | 80/27 | 200/93 |
| Ammonium sulfite | | 100/38 |
| Amyl acetate | 340/171 | 340/171 |
| Amyl alcohol | | 180/82 |
| Amyl chloride | 210/99 | 90/32 |

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**Table A.8** Compatibility of Alloy B-2 and Alloy C-276 with Selected Corrodents[a] (Continued)

| | Maximum temp. (°F/°C) | |
|---|---|---|
| Chemical | Alloy B-2 | C-276 |
| Aniline | 570/299 | 570/299 |
| Antimony trichloride | 210/99 | 210/99 |
| Aqua regia, 3:1 | x | x |
| Barium carbonate | 570/299 | 570/299 |
| Barium chloride | 570/299 | 210/99 |
| Barium hydroxide | 270/132 | 270/132 |
| Barium sulfate | 80/27 | |
| Benzaldehyde | 210/99 | 210/99 |
| Benzene | 210/99 | 210/99 |
| Benzene sulfonic acid, 10% | 210/99 | 210/99 |
| Benzoic acid | 210/99 | |
| Benzyl alcohol | 210/99 | 210/99 |
| Benzyl chloride | 210/99 | |
| Borax | 120/49 | 120/49 |
| Boric acid | 570/299 | 570/299 |
| Bromine gas, dry | 60/16 | 60/16 |
| Bromine gas, moist | | 60/16 |
| Bromine liquid | | 180/82 |
| Butadiene | 300/149 | 300/149 |
| Butyl acetate | 200/93 | 200/93 |
| Butyl alcohol | 210/99 | 200/93 |
| *n*-Butylamine | 210/99 | 210/99 |
| Butyric acid | 280/138 | 280/138 |
| Calcium bisulfite | | 80/27 |
| Calcium carbonate | 210/99 | 210/99 |
| Calcium chlorate | | 210/99 |
| Calcium chloride | 350/177 | 350/177 |
| Calcium hydroxide, 10% | 210/99 | 170/177 |
| Calcium hydroxide, sat. | 210/99 | |
| Calcium hypochlorite | x | |
| Calcium nitrate | 210/99 | 210/99 |
| Calcium oxide | | 90/32 |
| Calcium sulfate, 10% | 320/160 | 320/160 |
| Caprylic acid | 300/149 | 300/149 |
| Carbon bisulfide | 180/82 | 210/99 |
| Carbon dioxide, dry | 570/299 | 570/299 |
| Carbon dioxide, wet | 570/299 | 200/93 |
| Carbon disulfide | 180/82 | 300/149 |
| Carbon monoxide | 570/299 | 570/299 |
| Carbon tetrachloride | 300/149 | 300/149 |
| Carbonic acid | 80/27 | 80/27 |
| Cellosolve | 210/99 | 210/99 |
| Chloracetic acid, 50% water | | 210/99 |
| Chloracetic acid | 370/188 | 300/149 |
| Chlorine gas, dry | 200/93 | 570/299 |

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**Table A.8** Compatibility of Alloy B-2 and Alloy C-276 with Selected Corrodents[a] (Continued)

| | Maximum temp. (°F/°C) | |
|---|---|---|
| Chemical | Alloy B–2 | C-276 |
| Chlorine gas, wet | x | 220/104 |
| Chlorine, liquid | | 110/43 |
| Chlorobenzene | 350/177 | 350/177 |
| Chloroform | 210/99 | 210/99 |
| Chlorosulfonic acid | 230/110 | 230/110 |
| Chromic acid, 10% | 130/54 | 210/99 |
| Chromic acid, 50% | x | 210/99 |
| Chromyl chloride | 210/99 | 210/99 |
| Citric acid, 15% | 210/99 | 210/99 |
| Citric acid, conc. | 210/99 | 210/99 |
| Copper acetate | 100/38 | 100/38 |
| Copper carbonate | 90/32 | 90/32 |
| Copper chloride | 200/93 | 200/93 |
| Copper cyanide | 150/66 | 150/66 |
| Copper sulfate | 210/99 | 210/99 |
| Cresol | 210/99 | 210/99 |
| Cupric chloride, 5% | 60/16 | 210/99 |
| Cupric chloride, 50% | 210/99 | 210/99 |
| Cyclohexane | 210/99 | 210/99 |
| Cyclohexanol | 80/27 | 80/27 |
| Dichloroethane | 230/110 | 230/110 |
| Ethylene glycol | 570/299 | 570/299 |
| Ferric chloride | 90/32 | 90/32 |
| Ferric chloride, 50% in water | x | |
| Ferric nitrate, 10–50% | x | |
| Ferrous chloride | 280/138 | 280/138 |
| Fluorine gas, dry | 80/27 | 150/66 |
| Fluorine gas, moist | | 570/299 |
| Hydrobromic acid, dilute | 210/99 | |
| Hydrobromic acid, 20% | 210/99 | 90/32 |
| Hydrobromic acid, 50% | 260/127 | 90/32 |
| Hydrochloric acid, 20% | 140/60 | 150/66 |
| Hydrochloric acid, 38% | 140/60 | 90/32 |
| Hydrofluoric acid, 30% | 140/60 | 210/99 |
| Hydrofluoric acid, 70% | 110/43 | 200/93 |
| Hydrofluoric acid, 100% | 80/27 | 210/99 |
| Hypochlorous acid | 90/32 | 80/27 |
| Iodine solution, 10% | | 180/82 |
| Ketones, general | 180/82 | 100/38 |
| Lactic acid, 25% | 250/121 | 210/99 |
| Lactic acid, conc. | 250/121 | 210/99 |
| Magnesium chloride | 300/149 | 300/149 |
| Malic acid | 210/99 | 210/99 |
| Manganese chloride, 40% | 210/99 | 210/99 |

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**Table A.8** Compatibility of Alloy B-2 and Alloy C-276 with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. (°F/°C) | |
|---|---|---|
| | Alloy B–2 | C-276 |
| Methyl chloride | 210/99 | 90/32 |
| Methyl ethyl ketone | 210/99 | 210/99 |
| Methyl isobutyl ketone | 200/93 | 200/93 |
| Muriatic acid | 90/32 | 90/32 |
| Nitric acid, 5% | x | 210/99 |
| Nitric acid, 20% | x | 160/71 |
| Nitric acid, 70% | x | 200/93 |
| Nitric acid, anhydrous | x | 80/27 |
| Nitrous acid, conc. | x | x |
| Oleum, to 25% | 110/43 | 140/60 |
| Perchloric acid, 70% | | 220/104 |
| Phenol | 570/299 | 570/299 |
| Phosphoric acid, 50–80% | 210/99 | 210/99 |
| Picric acid | 220/104 | 300/149 |
| Potassium bromide, 30% | 90/32 | 90/32 |
| Salicylic acid | 80/27 | 250/121 |
| Silver bromide, 10% | 90/32 | 90/32 |
| Sodium carbonate | 570/299 | 210/99 |
| Sodium chloride, to 30% | 210/99 | 210/99 |
| Sodium hydroxide, 10%[b] | 240/116 | 230/110 |
| Sodium hydroxide, 50% | 250/121 | 210/99 |
| Sodium hydroxide, conc. | 200/93 | 120/49 |
| Sodium hypochlorite, 20% | x | x |
| Sodium hypochlorite, conc. | x | x |
| Sodium sulfide, to 50% | 210/99 | 210/99 |
| Stannic chloride, to 50% | 210/99 | 210/99 |
| Stannous chloride[c] | 570/299 | 210/99 |
| Sulfuric acid, 10% | 210/99 | 200/93 |
| Sulfuric acid, 50% | 230/110 | 230/110 |
| Sulfuric acid, 70% | 290/143 | 290/143 |
| Sulfuric acid, 90% | 190/88 | 190/88 |
| Sulfuric acid, 98% | 280/138 | 210/99 |
| Sulfuric acid, 100% | 290/143 | 190/88 |
| Sulfuric acid, fuming | 210/99 | 90/32 |
| Sulfurous acid | 210/99 | 370/188 |
| Toluene | 210/99 | 210/99 |
| Trichloroacetic acid | 210/99 | 210/99 |
| White liquor | 100/38 | 100/38 |
| Zinc chloride | 60/16 | 250/121 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable. When compatible, corrosion rate is <20 mpy.
[b]Alloy B-2 is subject to stress cracking.
[c]Alloy B-2 is subject to pitting.
*Source:* Ref. 3.

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**Table A.9** Mechanical and Physical Properties of Alloy B-2

| | |
|---|---|
| Modulus of elasticity $\times 10^6$, psi | 31.4 |
| Tensile strength $\times 10^3$, psi | 110 |
| Yield strength 0.2% offset $\times 10^3$, psi | 60 |
| Elongation in 2 in., % | 60 |
| Hardness, Brinell | 210 |
| Density, lb/in.$^3$ | 0.333 |
| Specific gravity | 9.22 |
| Specific heat, at 212°F, Btu/lb °F | 0.093 |
| Thermal conductivity, Btu/ft$^2$/in. h °F | |
| at 32°F | 77 |
| at 212°F | 85 |
| at 392°F | 93 |
| at 572°F | 102 |
| at 752°F | 111 |
| at 932°F | 120 |
| at 1112°F | 130 |
| Coefficient of thermal expansion, in./in. °F $\times 10^{-6}$ | |
| at 68–200°F | 5.7 |
| at 68–600°F | 6.2 |
| at 68–1000°F | 6.5 |

## ALLOY C-276

Hastelloy alloy C-276 is a low-carbon (0.01% maximum), low-silicon (0.08% maximum) version of Hastelloy alloy C. The chemical composition is given in Table A.10. Alloy C-276 was developed to overcome the corrosion problems associated with the welding of alloy C. When used in the as-welded condition, alloy C was often susceptible to serious intergranular corrosion attack in many oxidizing and chloride-containing environments. The low carbon and silicon content of alloy C-276 prevents continuous grain boundary precipitates in the weld heat-affected zone. Thus alloy C-276 can be used in most applications in the as-welded condition without suffering severe intergranular attack.

Alloy C-276 is extremely versatile because it possesses good resistance to both oxidizing and reducing media, including conditions with ion contamination. In dealing

**Table A.10** Chemical Composition of Alloy C-276 (N10276)

| Chemical | Weight percent |
|---|---|
| Carbon | 0.01 max. |
| Manganese | 0.5 |
| Silicon | 0.08 max. |
| Chromium | 15.5 |
| Nickel | 57 |
| Molybdenum | 16 |
| Tungsten | 3.5 |
| Iron | 5.5 |

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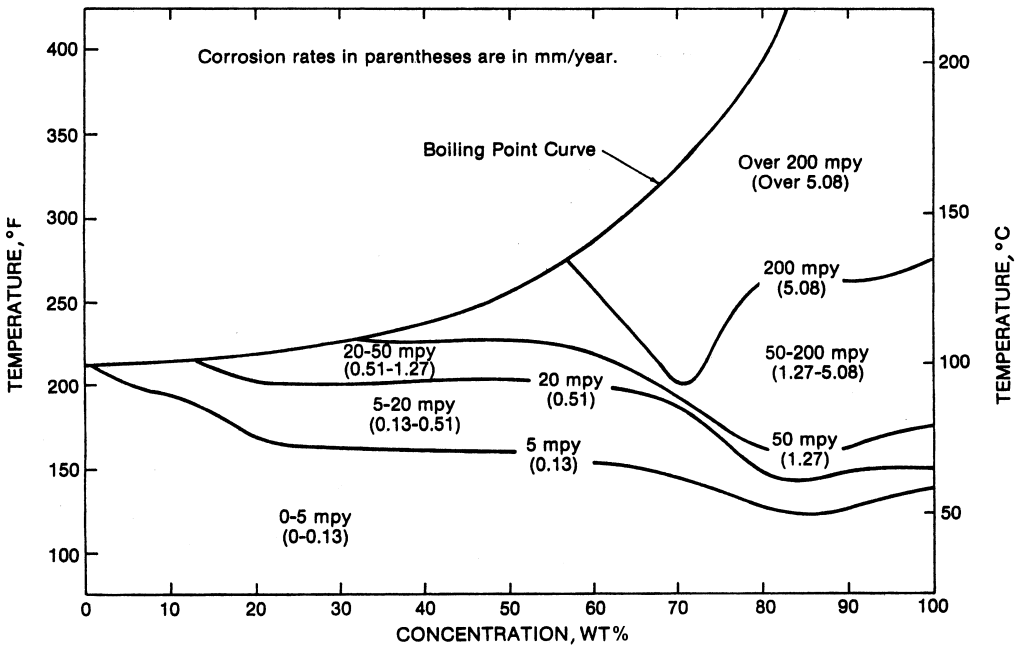



**Figure A.4** Isocorrosion diagram for Hastelloy C-276 in sulfuric acid (from Ref. 3).

with acid chloride salts, the pitting and crevice corrosion resistance of the alloy make it an excellent choice.

Alloy C-276 has exceptional resistance to many process materials, including highly oxidizing, neutral, and acid chlorides; solvents; chlorine; formic and acetic acids; and acetic anhydride. It also resists highly corrosive agents such as wet chlorine gas, hypochlorite, and chlorine solutions.

Exceptional corrosion resistance is exhibited in the presence of phosphoric acid at all temperatures below the boiling point of phosphoric acid, when concentrations are less than 65% weight. Corrosion rates of less than 5 mpy were recorded. At concentrations above 65% by weight and up to 85%, alloy C-276 displays similar corrosion rates, except at temperatures between 240°F (116°C) and the boiling point, where corrosion rates may be erratic and may reach 25 mpy.

Isocorrosion diagrams for alloy C-276 have been developed for a number of inorganic acids, for example, sulfuric (see Fig. A.4). Rather than having one or two acid systems in which the corrosion resistance is exceptional, as with alloy B-2, alloy C-276 is a good compromise material for a number of systems. For example, in sulfuric acid coolers handling 98% acid from the absorption tower, alloy C-276 is not the optimal alloy for the process-side corrosion, but it is excellent for the water-side corrosion and allows the use of brackish water or seawater. Concentrated sulfuric acid is used to dry chlorine gas. The dissolved chlorine will accelerate the corrosion of alloy B-2, but alloy C-276 has performed quite satisfactorily in a number of chlorine-drying applications.

Alloy C-276 has been indicated as a satisfactory material for scrubber construction, where problems of localized attack have occurred with other alloys because of pH,

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**Table A.11** Mechanical and Physical Properties of Alloy C-276

| | |
|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 29.8 |
| Tensile strength $\times 10^3$ (psi) | 100 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | 41 |
| Elongation in 2 in. (%) | 40 |
| Brinell hardness | 190 |
| Density (lb/in.$^3$) | 0.321 |
| Specific gravity | 8.89 |
| Specific heat (Btu/lb °F) | 0.102 |
| Thermal conductivity (Btu/ft$^2$/hr °F/in.) | |
| at –270°F | 50 |
| at 0°F | 65 |
| at 100°F | 71 |
| at 200°F | 77 |
| at 400°F | 90 |
| at 600°F | 104 |
| at 800°F | 117 |
| at 1000°F | 132 |
| at 1200°F | 145 |
| Coefficient of thermal expansion $\times 10^{-6}$ (in./in. °F) | |
| at 75–200°F | 6.2 |
| at 75–400°F | 6.7 |
| at 75–600°F | 7.1 |
| at 75–800°F | 7.3 |
| at 75–1000°F | 7.4 |
| at 75–1200°F | 7.8 |
| at 75–1400°F | 8.3 |
| at 75–1600°F | 8.8 |

temperature, or chloride content. Refer to Table A.8 for the compatibility of alloy C-276 with selected corrodents. The mechanical and physical properties are shown in Table A.11.

See Refs. 3 and 4.

## ALLOY C-22 (N06022)

Hastelloy alloy C-22 is a versatile nickel-chromium-molybdenum alloy with better overall corrosion resistance than other nickel-chromium-molybdenum alloys, including alloys C-276, C-4, and 625. The chemical composition is as follows:

Alloy C-22 resists the formation of grain boundary precipitates in the weld heat-affected zone. Consequently, it is suitable for most chemical process applications in the as-welded condition.

Although alloy C-276 is a versatile alloy, its main limitations are in oxidizing environments containing low amounts of halides and in environments containing nitric acid. In addition, the thermal stability of the alloy is not sufficient to enable it to be used as a casting.

Alloy C-22 was invented to improve the resistance to oxidizing environments, such as nitric acid, and also to improve the thermal stability sufficiently to enable it to be used

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| Chemical | Weight percent |
|---|---|
| Carbon | 0.015 max. |
| Manganese | 0.50 max. |
| Phosphorous | 0.025 max. |
| Sulfur | 0.010 max. |
| Chromium | 20.0–22.5 |
| Molybdenum | 12.5–14.5 |
| Cobalt | 2.5 max. |
| Tungsten | 2.5–3.5 |
| Iron | 2.0–6.0 |
| Silicon | 0.08 max. |
| Vanadium | 0.35 max. |
| Nickel | Balance |

for casting. The higher chromium level in this alloy not only makes it superior in oxidizing environments containing nitric acid, but also improves the pitting resistance over that of alloy C-276.

Alloy C-22 has outstanding resistance to pitting, crevice corrosion, and stress corrosion cracking. It has excellent resistance to oxidizing aqueous media, including acids with oxidizing agents, wet chlorine, and mixtures containing nitric or oxidizing acids with chloride ions. The alloy also has outstanding resistance to both reducing and oxidizing media and, because of its versatility, can be used where "upset" conditions are likely to occur or in multi purpose plants.

Alloy C-22 has exceptional resistance to a wide variety of chemical process environments, including strong oxidizers such as ferric and cupric chlorides, hot contaminated media (organic and inorganic), chlorine, formic, and acetic acids, acetic anhydride, seawater, and brine solutions. The compatibility of alloy C-22 with selected corrodents can be found in Table A.12.

The areas of application of alloy C-22 are the same as many of those for alloy C-276. It is being used in pulp and paper bleaching systems, pollution control systems, and various areas in the chemical process industry.

The mechanical and physical properties of alloy C-22 are shown in Table A.13.

## ALLOYS G (N06007), G-3 (N06985), AND G-30 (N06030)

Alloy G is a high-nickel austenitic stainless steel having the following chemical composition:

| Chemical | Weight percent |
|---|---|
| Chromium | 22 |
| Nickel | 45 |
| Iron | 20 |
| Molybdenum | 6.5 |
| Copper | 2.0 |
| Carbon | 0.05 max. |
| Niobium | 2.0 |

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**Table A.12** Compatibility of Alloy C-22 with Selected Corrodents

| Corrodent | Weight percent | Temperature (°F/°C) | Average corrosion rate (mpy) |
|---|---|---|---|
| Acetic acid | 99 | Boiling | Nil |
| Ferric chloride | 10 | Boiling | 1.0 |
| Formic acid | 88 | Boiling | 0.9 |
| Hydrochloric acid | 1 | Boiling | 2.5 |
| Hydrochloric acid | 1.5 | Boiling | 11 |
| Hydrochloric acid | 2 | 194/90 | Nil |
| Hydrochloric acid | 2 | Boiling | 61 |
| Hydrochloric acid | 2.5 | 194/90 | 0.3 |
| Hydrochloric acid | 2.5 | Boiling | 84 |
| Hydrochloric acid | 10 | Boiling | 400 |
| Hydrofluoric acid | 2 | 158/70 | 9.4 |
| Hydrofluoric acid | 5 | 158/70 | 19 |
| Phosphoric acid, reagent grade | 55 | Boiling | 12 |
| Phosphoric acid, reagent grade | 85 | Boiling | 94 |
| Nitric acid | 10 | Boiling | 0.8 |
| Nitric acid | 65 | Boiling | 5.3 |
| Nitric acid + 1% HCl | 5 | Boiling | 0.5 |
| Nitric acid + 2.5% HCl | 5 | Boiling | 1.6 |
| Sulfuric acid | 10 | Boiling | 11 |
| Sulfuric acid | 20 | 150/66 | 0.2 |
| Sulfuric acid | 20 | 174/79 | 1.2 |
| Sulfuric acid | 20 | Boiling | 33 |
| Sulfuric acid | 30 | 150/66 | 0.6 |
| Sulfuric acid | 30 | 174/79 | 3.3 |
| Sulfuric acid | 30 | Boiling | 64 |
| Sulfuric acid | 40 | 100/38 | 0.1 |
| Sulfuric acid | 40 | 150/66 | 0.5 |
| Sulfuric acid | 40 | 174/79 | 6.4 |
| Sulfuric acid | 50 | 100/38 | 0.2 |
| Sulfuric acid | 50 | 150/66 | 1.0 |
| Sulfuric acid | 50 | 174/79 | 16 |
| Sulfuric acid | 60 | 100/38 | 0.1 |
| Sulfuric acid | 70 | 100/38 | Nil |
| Sulfuric acid | 80 | 100/38 | Nil |

Alloy G is intended for use in the as-welded condition, even in the circumstance of multipass welding. The niobium addition provides better resistance than titanium additions in highly oxidizing environments. Because of the nickel base, the alloy is resistant to chloride-induced stress corrosion cracking. The 2% copper addition improves the corrosion resistance of the alloy in reducing acids, such as sulfuric and phosphoric. Alloy G will also resist combinations of sulfuric acid and halides.

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**Table A.13** Mechanical and Physical Properties of Alloy C-22 (N06022)

| | |
|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 29.9 |
| Tensile strength $\times 10^3$ (psi) | 115 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | 60 |
| Elongation (%) | 55 |
| Rockwell hardness | B-87 |
| Density (lb/in.$^3$) | 0.314 |
| Specific gravity | 8.69 |
| Thermal conductivity (Btu/ft$^2$ hr °F) | |
| at 70°F (20°C) | 5.8 |
| at 1500°F (816°C) | 12.3 |

Alloy G resists pitting, crevice corrosion, and intergranular corrosion. Uses include heat exchangers, pollution control equipment, and various applications in the manufacture of phosphoric and sulfuric acids.

Alloy G-3 was developed with a lower carbon content than alloy G to prevent precipitation at the welds. Its chemical composition is as follows:

| Chemical | Weight percent |
|---|---|
| Chromium | 22–23.5 |
| Molybdenum | 6.0–8.0 |
| Tungsten | 1.5 max. |
| Iron | 18–21 |
| Copper | 1.5–2.5 |
| Carbon | 0.015 max. |
| Niobium | 0.8 |
| Nickel | 44 |
| Silicon | 1.0 max. |

Although niobium stabilized alloy G from the formation of chromium-rich carbides in the heat-affected zones of the welds, secondary carbide precipitation still occurred when the primary niobium carbides dissolved at high temperatures, and the increased carbon in the matrix increases the tendency of the alloy to precipitate intermetallic phases. Alloy G-3 has a lower carbon content (0.015% maximum versus 0.05% maximum for alloy G) and a lower niobium content (0.8% maximum versus 2% for alloy G). The alloy also possesses a slightly higher molybdenum content (7% versus 5% for alloy G).

The corrosion resistance of alloy G-3 is about the same as that of alloy G; however, the thermal stability is much better. Refer to Table A.14 for the compatibility of alloys G and G-3 with selected corrodents.

Alloy G-30 has a higher chromium content than alloy G, which gives it a higher resistance to oxidizing environments compared with other alloys in this series. It has the following composition:

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| Chemical | Weight percent |
|---|---|
| Chromium | 28.0–31.5 |
| Molybdenum | 4.0–6.0 |
| Tungsten | 1.5–4.0 |
| Iron | 13.0–17.0 |
| Copper | 1.0–2.4 |
| Niobium | 0.30–1.50 |
| Nickel + Cobalt | Balance |

Alloy G-30 possesses excellent corrosion resistance in the as-welded condition. In acid mixtures such as nitric plus hydrofluoric and sulfuric plus nitric, alloy G-30 has the highest resistance of this class of alloys.

Applications include pipe and tubing in phosphoric acid manufacture, sulfuric acid manufacture, and fertilizer and pesticide manufacture. The alloy is also used in the evaporaters of commercial wet-process phosphoric manufacturing systems. This process contains complex mixtures of phosphoric, sulfuric, and hydrofluoric acids and various oxides. Under these conditions the corrosion rate for alloy G-30 was 6 mpy as compared with16 mpy for alloy G-3 and alloy 625.

The mechanical and physical properties of alloys G and G-3 can be found in Table A.15.

**Table A.14** Compatibility of Alloy G and Alloy G-3 with Selected Corrodents

| Chemical | Temperature (°F/°C) | Chemical | Temperature (°F/°C) |
|---|---|---|---|
| Ammonium chloride, 28% | 180/82 | Nitric acid, 50% | 180/82 |
| Calcium carbonate | 120/49 | Nitric acid, 70% | 180/82 |
| Calcium chloride, 3–20% | 220/104 | Nitrous oxide | 560/293 |
| Chlorine gas, wet | 80/27 | Oleum | 240/116 |
| Chlorobenzene, 3–60% | 100/38 | Phosphoric acid, 50–80% | 210/99 |
| Fluorosilicic acid, 3–12% | 180/82 | Potassium chloride, 10% | 230/110 |
| Hydrofluoric acid | x | Sodium chlorate | 80/27 |
| Hydrofluosilicic acid, 10–50% | 160/71 | Sodium chloride | 210/99 |
| Kraft liquor | 80/27 | Sodium hydroxide, conc. | x |
| Lime slurry | 140/60 | Sodium hypochlorite, conc. | 90/32 |
| Lithium chloride, 30% | 260/127 | Sodium sulfide, 3–20% | 120/49 |
| Magnesium hydroxide | 210/99 | Sodium dioxide, wet | 130/54 |
| Magnesium sulfate | 210/99 | Sulfuric acid, 10% | 250/121 |
| Mercury | 250/121 | Sulfuric acid, 30% | 210/99 |
| Nitric acid, 10% | 250/121 | Sulfuric acid, 70% | x |
| Nitric acid, 20% | 250/121 | Sulfuric acid, 98% | 270/131 |
| Nitric acid, 40% | 250/121 | | |

The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. When compatible, the corrosion rate is less that 20 mpy.

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**Table A.15** Mechanical and Physical Properties of Alloy G and Alloy G-3

| Property | G | G-3 |
|---|---|---|
| Modulus of elasticity $\times 10^6$, psi | 27.8 | 27.8 |
| Tensile strength $\times 10^3$, psi | 90 | 90 |
| Yield strength 0.2% offset $\times 10^3$, psi | 35 | 35 |
| Elongation in 2 in., % | 35 | 45 |
| Hardness, Brinell | 169 | 885(Rb) |
| Density, lb/in.$^3$ | 0.30 | 0.30 |
| Specific gravity | 8.31 | 8.31 |
| Specific heat, J/kg K | 456 | 464 |
| Thermal conductivity, W/mK | 10.1 | 10.0 |
| Coefficient of thermal expansion, in./in. °F $\times 10^{-6}$ | | |
| at 70–200°F | 7.5 | 7.5 |
| at 70–400°F | 7.7 | 7.7 |
| at 70–600°F | 7.9 | 7.9 |
| at 70–800°F | 8.3 | 8.3 |
| at 70–1000°F | 8.7 | 8.7 |
| at 70–1200°F | 9.1 | 9.1 |

## ALLOY 600 (N06600)

Alloy 600, also known as Inconel, is a nickel base alloy with about 16% chromium and 7% iron that is used primarily to resist corrosive atmospheres at elevated temperatures. The chemical composition will be found in Table A.16.

Alloy 600 has excellent mechanical properties and a combination of high strength and good workability. It performs well in temperatures from cryogenic to 1200°F (649°C) and is readily fabricated and welded.

Although alloy 600 is resistant to oxidation, the presence of sulfur in the environment can significantly increase the rate of attack. The mode of attack is generally intergranular, and therefore the attack proceeds more rapidly and the maximum use temperature is restricted to about 600°F (315°C).

Inconel has excellent resistance to dry halogens at elevated temperatures and has been used successfully for chlorination equipment at temperatures up to 1000°F

**Table A.16** Chemical Composition of Alloy 600 (N06600)

| Chemical | Weight percent |
|---|---|
| Nickel | 72.0 min. |
| Chromium | 14.0–17.0 |
| Iron | 6.0–10.0 |
| Carbon | 0.15 max. |
| Copper | 0.50 max. |
| Manganese | 1.0 max. |
| Sulfur | 0.015 max. |
| Silicon | 0.5 max. |

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(538°C). Where arrangements can be made for cooling the metal surface, the alloy can be used at even higher gas temperatures.

Resistance to stress corrosion cracking is imparted to alloy 600 by virtue of its nickel base. The alloy therefore finds considerable use in handling water environments where stainless steels fail by cracking. Because of its resistance to corrosion in high-purity water, it has a number of uses in nuclear reactors, including steam generator tubing and primary water piping. The lack of molybdenum in the alloy precludes its use in applications where pitting is the primary mode of failure.

In certain high-temperature caustic applications where sulfur is present, alloy 600 is substituted for alloy 201 because of its improved resistance. Inconel is, however, subject to stress corrosion cracking in high-temperature, high-concentration alkalies. For that reason the alloy should be stress relieved prior to use and the operating stresses kept to a minimum. Alloy-600 is almost entirely resistant to attack by solutions of ammonia over the complete range of temperatures and concentrations.

The alloy exhibits greater resistance to sulfuric acid under oxidizing conditions than either nickel 200 or alloy 400. The addition of oxidizing salts to sulfuric acid tends to passivate alloy 600, which makes it suitable for use with acid mine waters or brass pickling solutions, where alloy 400 cannot be used. Table A.17 provides the compatibility of alloy 600 with selected corrodents. Reference 3 provides a more comprehensive listing.

The mechanical and physical properties of alloy 600 can be found in Table A.18.

**Table A.17** Compatibility of Alloy 600 and Alloy 625 with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum Temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | 140 | 60 | Ammonium fluoride 10% | 90 | 32 |
| Acetic acid 10% | 80 | 27 | Ammonium fluoride 25% | 90 | 32 |
| Acetic acid 50% | x | x | Ammonium hydroxide 25% | 80 | 27 |
| Acetic acid 80% | x | x | Ammonium hydroxide, sat. | 90 | 32 |
| Acetic acid, glacial | 220 | 104 | Ammonium nitrate | x | x |
| Acetic anhydride | 200 | 93 | Ammonium persulfate | 80 | 27 |
| Acetone | 190 | 88 | Ammonium phosphate 10% | 210 | 99 |
| Acetyl chloride | 80 | 27 | Ammonium sulfate 10-40% | 210 | 99 |
| Acrylonitrile | 210 | 99 | Ammonium sulfide | | |
| Adipic acid | 210 | 99 | Ammonium sulfite | 90 | 32 |
| AlIyl alcohol | 200 | 93 | Amyl acetate | 300 | 149 |
| Allyl chloride | 150 | 66 | Amyl chloride | x | x |
| Alum | 200 | 93 | Aniline | 210 | 99 |
| Aluminum acetate | 80 | 27 | Antimony trichloride | 90 | 32 |
| Aluminum chloride, aqueous | x | x | Aqua regia 3:1 | x | x |
| Aluminum chloride, dry | x | x | Barium carbonate | 80 | 27 |
| Aluminum fluoride | 80 | 27 | Barium chloride | 570 | 299 |
| Aluminum hydroxide | 80 | 27 | Barium hydroxide | 90 | 32 |
| Aluminum sulfate | x | x | Barium sulfate | 210 | 99 |
| Ammonium carbonate | 190 | 88 | Benzaldehyde | 210 | 99 |
| Ammonium chloride 10%[b] | 230 | 110 | Benzene | 210 | 99 |
| Ammonium chloride 50% | 170 | 77 | Benzoic acid 10% | 90 | 32 |
| Ammonium chloride, sat. | 200 | 93 | Benzyl alcohol | 210 | 99 |

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**Table A.17** Compatibility of Alloy 600 and Alloy 625 with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum Temp. °F | °C |
|---|---|---|---|---|---|
| Benzyl chloride | 210 | 99 | Ethylene glycol | 210 | 99 |
| Borax | 90 | 52 | Ferric chloride | x | x |
| Boric acid | 80 | 27 | Ferric chloride 50% in water | x | x |
| Bromine gas, dry | 60 | 16 | Ferric nitrate 10–50% | x | x |
| Bromine gas, moist | x | x | Ferrous chloride | x | x |
| Butadiene | 80 | 27 | Fluorine gas, dry | 570 | 299 |
| Butyl acetate | 80 | 27 | Fluorine gas, moist | 60 | 16 |
| Butyl alcohol | 80 | 27 | Hydrobromic acid, dilute | 90 | 32 |
| *n*-Butylamine | | | Hydrobromic acid 20% | 80 | 27 |
| Butyl phthalate | 210 | 99 | Hydrobromic acid 50% | x | x |
| Butyric acid | x | x | Hydrochloric acid 20% | 80 | 27 |
| Calcium bisulfite | x | x | Hydrochloric acid 38% | x | x |
| Calcium carbonate | 90 | 32 | Hydrofluoric acid 30% | x | x |
| Calcium chlorate | 80 | 27 | Hydrofluoric acid 70% | x | x |
| Calcium chloride | 80 | 27 | Hydrofluoric acid 100% | 120 | 49 |
| Calcium hydroxide 10% | 210 | 99 | Lactic acid 25% | 210 | 99 |
| Calcium hydroxide, sat. | 90 | 32 | Lactic acid, concentrated | 90 | 32 |
| Calcium hypochlorite | x | x | Magnesium chloride 50% | 130 | 54 |
| Calcium sulfate[c] | 210 | 99 | Malic acid | 210 | 99 |
| Caprylic acid | 230 | 110 | Manganese chloride 37% | x | x |
| Carbon bisulfide | 80 | 27 | Methyl chloride | 210 | 99 |
| Carbon dioxide, dry | 210 | 99 | Methyl ethyl ketone | 210 | 99 |
| Carbon dioxide, wet | 200 | 93 | Methyl isobutyl ketone | 200 | 93 |
| Carbon disulfide | 80 | 27 | Muriatic acid | x | x |
| Carbon monoxide | 570 | 299 | Nitric acid 5% | 90 | 32 |
| Carbon tetrachloride | 210 | 99 | Nitric acid 20% | 80 | 27 |
| Carbonic acid | 210 | 99 | Nitric acid 70% | x | x |
| Cellosolve | 210 | 99 | Nitric acid. anhydrous | x | x |
| Chloracetic acid | x | x | Nitrous acid, concentrated | x | x |
| Chlorine gas, dry | 90 | 32 | Oleum | x | x |
| Chlorine gas, wet | x | x | Phenol | 570 | 299 |
| Chlorobenzene | 210 | 99 | Phosphoric acid 50–80% | 190 | 88 |
| Chloroform | 210 | 99 | Picric acid | x | x |
| Chromic acid 10% | 130 | 54 | Potassium bromide 30% | 210 | 99 |
| Chromic acid 50% | 90 | 32 | Salicylic acid | 80 | 27 |
| Chromyl chloride | 210 | 99 | Sodium carbonate to 30% | 210 | 99 |
| Citric acid 15% | 210 | 99 | Sodium chloride to 30% | 210 | 99 |
| Citric acid, concentrated | 210 | 99 | Sodium hydroxide 10% | 300 | 149 |
| Copper acetate | 100 | 38 | Sodium hydroxide 50%[b] | 300 | 149 |
| Copper carbonate | 80 | 27 | Sodium hydroxide, concentrated | 80 | 27 |
| Copper chloride | x | x | Sodium hypochlorite 20% | x | x |
| Copper cyanide | 80 | 27 | Sodium hypochlorite. concentrated | x | x |
| Copper sulfate | 80 | 27 | Sodium sulfide to 50% | 210 | 99 |
| Cresol | 100 | 38 | Stannic chloride | x | x |
| Cupric chloride 5% | x | x | Stannous chloride, dry | 570 | 299 |
| Cupric chloride 50% | x | x | Sulfuric acid 10% | x | x |
| Cyclohexanol | 80 | 27 | Sulfuric acid 50% | x | x |
| Dichloroethane (ethylene dichloride) | 200 | 93 | Sulfuric acid 70% | x | x |

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**Table A.17** Compatibility of Alloy 600 and Alloy 625 with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum Temp. °F | °C |
|---|---|---|---|---|---|
| Sulfuric acid 90% | x | x | Sulfurous acid | 90 | 32 |
| Sulfuric acid 98% | x | x | Toluene | 210 | 99 |
| Sulfuric acid 100% | x | x | Trichloroacetic acid | 80 | 27 |
| Sulfuric acid, fuming | x | x | Zinc chloride, dry | 80 | 27 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable, when compatible corrosion rate is <20 mpy.
[b]Material is subject to stress cracking.
[c]Material subject to pitting.
*Source:* PA Schweitzer. *Corrosion Resistance Tables,* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

**Table A.18** Mechanical and Physical Properties of Alloy 600

| | |
|---|---|
| Modulus of elasticity $\times 10^6$(psi) | 30–31 |
| Tensile strength $\times 10^3$ (psi) | 80 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | 30–35 |
| Elongation in 2 in. (%) | 40 |
| Rockwell hardness | B-120–170 |
| Density (lb/in.$^3$) | 0.306 |
| Specific gravity | 8.42 |
| Specific heat (Btu/lb °F) | 0.106 |
| Thermal conductivity (Btu/h/ft$^2$/°F/in.) | |
| at 70°F | 103 |
| at 200°F | 109 |
| at 400°F | 121 |
| at 600°F | 133 |
| at 800°F | 145 |
| at 1000°F | 158 |
| at 1200°F | 172 |
| Coefficient of thermal expansion $\times 10^6$ (in./in./°F) | |
| at 70–200°F | 7.4 |
| at 70–400°F | 7.7 |
| at 70–600°F | 7.9 |
| at 70–800°F | 8.1 |
| at 70–1000°F | 8.4 |
| at 70–1200°F | 8.6 |

## ALLOY 625 (N06625)

Alloy 625, also known as Inconel alloy 625, is used both for its high strength and for its aqueous corrosion resistance. The strength of alloy 625 is primarily a solid-solution effect from molybdenum and niobium. Alloy 625 has excellent weldability. The chemical composition is shown in Table A.19.

Because of its combination of chromium, molybdenum, carbon, and niobium + tantalum, the alloy retains its strength and oxidation resistance at elevated temperatures.

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**Table A.19** Chemical Composition of Alloy 625 (N06625)

| Chemical | Weight percent |
|---|---|
| Chromium | 20.0–23.0 |
| Molybdenum | 8.0–10.0 |
| Cobalt | 1.00 max. |
| Columbium + tantalum | 3.15–4.15 |
| Aluminum | 0.40 max. |
| Titanium | 0.40 max. |
| Carbon | 0.10 max. |
| Iron | 5.00 max. |
| Manganese | 0.50 max. |
| Silicon | 0.50 max. |
| Phosphorus | 0.015 max. |
| Sulfur | 0.015 max. |
| Nickel | Balance |

This alloy finds application where strength and corrosion resistance are required. It exhibits exceptional fatigue strength and superior strength and toughness at temperatures ranging from cryogenic to 2000°F (1093°C). The niobium and tantalum stabilization makes the alloy suitable for corrosion service in the as-welded condition. It has excellent resistance to chloride stress corrosion cracking.

Field operating experience has shown that alloy 625 exhibits excellent resistance to phosphoric acid solutions, including commercial grades that contain fluorides, sulfates, and chlorides that are used in the production of superphosphoric acid (72% $P_2O_5$).

Refer to Table A.17 for the compatibility of alloy 625 with selected corrodents.

Elevated-temperature applications include ducting systems, thrust reverser assemblies, and afterburners. Use of this alloy has been considered in the high-temperature, gas-cooled reactor; however, after long aging in the temperature range of 1100–1400°F (590–760°C), the room temperature ductility is significantly reduced.

Alloy 625 has been used in preheaters for sulfur dioxide scrubbing systems in coal-fired power plants and bottoms of electrostatic precipitaters that are flushed with seawater.

Table A.20 lists the mechanical and physical properties of alloy 625.

## ALLOY 686 (N06686)

Inconel alloy 686 is an austenitic nickel-chromium-molybdenum-tungsten alloy. The chemical composition can be found in Table A.21.

This highly alloyed material has good mechanical strength. It is most often used in the annealed condition. Since alloy 686 is a solid-solution alloy, it cannot be strengthened by heat treatment, but strain hardening by cold work will greatly increase the strength of the alloy. Exposure to high temperatures for long periods of time can have an embrittling effect on the alloy.

The alloy's composition provides resistance to general corrosion, stress corrosion cracking, pitting, and crevice corrosion in a broad range of aggressive environments. The

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**Table A.20** Mechanical and Physical Properties of Alloy 625

| | |
|---|---|
| Modulus of elasticity $\times 10^6$(psi) | 30.1 |
| Tensile strength $\times 10^3$ (psi) | 100–120 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | 60 |
| Elongation in 2 in. (%) | 30 |
| Brinell hardness | 192 |
| Density ((lb/in.$^3$) | 0.305 |
| Specific gravity | 8.44 |
| Specific heat (Btu/lb °F) | 0.098 |
| Thermal conductivity (Btu-in./ft$^2$ h °F) | |
| at –250°F | 50 |
| at –100°F | 58 |
| at 0°F | 64 |
| at 70°F | 68 |
| at 100°F | 70 |
| at 200°F | 75 |
| at 400°F | 87 |
| at 600°F | 98 |
| at 1000°F | 121 |
| at 1400°F | 144 |
| Coefficient of thermal expansion $\times 10^6$ in./in. °F | |
| at 70–200°F | 7.1 |
| at 70–400°F | 7.3 |
| at 70–600°F | 7.4 |
| at 70–800°F | 7.6 |
| at 70–1000°F | 7.8 |
| at 70–1200°F | 8.2 |
| at 70–1400°F | 8.5 |
| at 70–1600°F | 8.8 |

**Table A.21** Chemical Composition of Alloy 686 (N06686)

| Chemical | Weight percent |
|---|---|
| Chromium | 19.0–23.0 |
| Molybdenum | 15.0–17.0 |
| Tungsten | 3.0–4.0 |
| Titanium | 0.02–0.25 |
| Iron | 5.0 max. |
| Carbon | 0.01 max. |
| Manganese | 0.75 max. |
| Sulfur | 0.02 max. |
| Silicon | 0.08 max. |
| Phosphorus | 0.04 max. |
| Nickel | Balance |

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high nickel and molybdenum contents provide good corrosion resistance in reducing environments, while the high chromium level imparts resistance to oxidizing media. The molybdenum and tungsten also aid resistance to localized corrosion, such as pitting, while the low carbon content and other composition controls help minimize grain boundary precipitation to maintain resistance to corrosion in heat-affected zones of welded joints.

The ability of alloy 686 to resist pitting is evident from its pitting resistance equivalent, which is 51.

Alloy 686 has excellent resistance to mixed acids as well as reducing and oxidizing acids and to mixed acids containing high concentrations of halides. Good resistance has been shown to mixed acid media having pH levels of 1 or less and chloride levels in excess of 100,000 ppm.

The mechanical and physical properties are shown in Table A.22.

## ALUMINUM AND ALUMINUM ALLOYS

Aluminum is one of the most prevalent metallic elements in the solid portion of the earth's crust, comprising approximately 8%. It is always present in a combined form, usually a hydrated oxide, of which bauxite is the primary ore. Metallic aluminum is very active thermodynamically and seeks to return to the natural oxidized state through the process of corrosion.

Aluminum alloys possess a high resistance to corrosion by most atmospheres and waters, many chemicals, and other materials. Their salts are nontoxic, allowing applications with beverages, foods, and pharmaceuticals; are white or colorless, permitting applications with chemicals and other materials without discoloration, and are not damaging to the ecology. Other desirable properties of aluminum and its alloys include high electrical conductivity, high thermal conductivity, high reflectivity, and noncatalytic action. They are also nonmagnetic.

### Classifications and Designations

Wrought aluminum and aluminum alloys are classified based on their major alloying element via a four-digit numbering system as shown in Table A.23. These alloy numbers and their respective tempers are covered by the American National Standards Institute (ANSI) standard H35.1. In the 1XXX group the second digit indicates the purity of the aluminum used to

**Table A.22** Mechanical and Physical Properties of Alloy 686 (N06686) at 70°F/20°C

| | |
|---|---|
| Modulus of elasticity $\times 10^6$(psi) | 30 |
| Tensile strength $\times 10^3$ (psi) | 104 |
| Yield strength 0.2% $\times 10^3$ (psi) | 52.8 |
| Elongation in 2 in. (%) | 71 |
| Density (lb/in.$^3$) | 0.315 |
| Specific heat (Btu/lb °F) | 0.089 |
| Coefficient of thermal expansion $\times 10^{-6}$ (in./in.°F) | 6.67 |
| Impact strength (ft-lb) | 299 |

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**Table A.23** Wrought Aluminum and Aluminum Alloy Designation

| Senes designation | Alloying materials |
|---|---|
| 1XXX | 99.9% min. Al |
| 2XXX | Al-Cu, Al-Cu-Mg, Al-Cu-Mg-Li, Al-Cu-Mg-Si |
| 3XXX | Al-Mn, Al-Mn-Mg |
| 4XXX | Al-Si |
| 5XXX | Al-Mg, Al-Mg-Mn |
| 6XXX | Al-Mg-Si, Al-Mg-Si-Mn, Al-Mg-Si, Cu |
| 7XXX | Al-Zn, Al-Zn-Mg, Al-Zn-Mg-Mn, Al-Zn-Mg-Cu |

**Table A.24** Major Alloying Ingredients

| Series designation | Major alloying ingredient |
|---|---|
| 1XXX | Aluminum $\geq$ 99.0% |
| 2XXX | Copper |
| 3XXX | Manganese |
| 4XXX | Silicon |
| 5XXX | Magnesium |
| 6XXX | Magnesium and silicon |
| 7XXX | Zinc |
| 8XXX | Other elements |
| 9XXX | Unused series |

manufacture this particular grade. The zero in the 10XX group indicates that the aluminum is essentially of commercial purity, while a second digit of 1 through 9 indicates special control of one or more individual impurity elements. In the 2XXX through 7XXX alloy groups the second digit indicates an alloy modification. If the second digit is zero, the alloy is the original alloy; numbers 1 through 9 are assigned consecutively as the original alloy becomes modified. The last two digits serve only to identify the different alloys in the group and have no numerical significance. The classification shown in Table A.23 is based on the major alloying ingredients as shown in Table A.24.

The Unified Numbering System (UNS), used for other metals, is also used for aluminum. A comparison for selected aluminum alloys between the Aluminum Association designation and the UNS designation is shown in Table A.25.

## Chemical Composition

The word aluminum can be misleading since it is used for both the pure metal and for the alloys. Practically all commercial products are composed of aluminum alloys.

For aluminum to be considered "unalloyed" it must have a minimum content of 99.0% aluminum. Most unalloyed specifications range from 99.00% to 99.75% minimum aluminum.

To assist in the smelting process, elements such as bismuth and titanium are added, while chromium, manganese, and zirconium are added for grain control during solidification of large ingots. Elements such as copper, magnesium, manganese, nickel, and zinc

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**Table A.25** Aluminum Association Designation System and UNS Equivalencies for Aluminum Alloys

| Aluminum Association designation | UNS designation |
|---|---|
| 1050 | A91050 |
| 1080 | A91080 |
| 1100 | A91100 |
| 1200 | A91200 |
| 2014 | A92014 |
| 2024 | A92024 |
| 3003 | A93003 |
| 3004 | A93004 |
| 4043 | A94043 |
| 4047 | A94047 |
| 5005 | A95005 |
| 5052 | A95052 |
| 5464 | A95464 |
| 6061 | A96061 |
| 6063 | A96063 |
| 6463 | A96463 |
| 7005 | A97005 |
| 7050 | A97050 |
| 7075 | A97075 |

are added to impart properties such as strength, formability, and stability at elevated temperature and other extreme conditions. Some unintentional impurities are present, coming from trace elements contained in the ore, from pickup from ceramic furnace linings, or from the use of scrap metal in recycling.

There are three types of composition listings in use. First there is the nominal, or target, composition of the alloy. This is used in discussing the generic types of alloys and their uses. Second are the alloy limits registered with the Aluminum Association, which are the specification limits against which alloys are produced. In these limits intentional alloying elements are defined as an allowable range. The usual impurity elements are listed as the maximum amount allowed. Rare trace elements are grouped into an "each other" category. A trace element cannot exceed a specified "each" amount, and the total of all trace elements cannot exceed the slightly higher "total" amount. The third listing consists of the elements actually present as found in an analyzed sample. Examples of all three types of these compositions for unalloyed aluminum (1160), a heat-treatable alloy (2024), and a non-heat-treatable alloy (3004) are shown in Table A.26.

When the melt is analyzed, the intentional elements must be within the prescribed range, but not necessarily near the midpoint if the range is wide. For example, as shown in Table A.26, copper in alloy 2024 can be skewed to a high content (sample 2) to improve strength or a low content to improve toughness (sample 3). The producer will target for the nominal composition when the allowable range is only about half a percentage point or less.

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**Table A.26** Comparison of Composition Listings of Aluminum and Aluminum Alloys

| Alloy | Si | Fe | Cu | Mn | Mg | Cr | Ni | Zn | Ti | Others Each | Others Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nominal (target) chemical composition of wrought alloys (%)[a] | | | | | | | | | | | |
| 1160 | (99.6% min. Al; all other elements 0.040%) | | | | | | | | | | |
| 2024 | — | — | 4.4 | 0.6 | 1.5 | — | — | — | — | | |
| 3004 | — | — | 1.2 | 1.0 | — | — | — | — | — | | |
| Registered chemical composition limits of wrought alloys (%)[b] | | | | | | | | | | | |
| 1160 | 0.25 | 0.35 | 0.05 | 0.03 | 0.03 | — | — | 0.05 | 0.03 | 0.03 | |
| 2024 | 0.50 | 0.40 | 3.8–4.9 | 0.30–0.9 | 1.2–1.8 | 0.10 | — | 0.25 | 0.05 | 0.05 | 0.15 |
| 3004 | 0.30 | 0.70 | 0.25 | 1.0–1.5 | 0.8–1.3 | — | — | 0.25 | 0.05 | 0.05 | 0.15 |
| Analysis of aluminum samples alloying elements present (%)[c] | | | | | | | | | | | |
| 1160 sample 1 | 0.080 | 0.100 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.000 | 0.020 | | |
| 2024 sample 2 | 0.25 | 0.32 | 4.77 | 0.61 | 1.77 | 0.00 | 0.00 | 0.025 | 0.03 | | |
| 2024 sample 3 | 0.10 | 0.12 | 4.40 | 0.55 | 1.45 | 0.00 | 0.00 | 0.00 | 0.02 | | |
| 3004 sample 4 | 0.030 | 0.42 | 0.00 | 1.25 | 1.10 | 0.00 | 0.00 | 0.00 | 0.03 | | |

[a]Aluminum and normal impurities constitute remainder.
[b]Alloying elements shown as a required range; impurity elements are the maximum tolerable. Aluminum and trace impurities constitute remainder.
[c]Remainder is aluminum.

Specified impurity elements must be at or below the maximum limit. Individual nonspecified impurities should be less than the "0.05% each" level, with the total less than 0.15%. It should be recognized that, as shown in Table A.26, some impurity elements will be present, but usually well below the allowed limit. Every sample will not contain all of the impurity elements, but some amounts of iron and silicon are usually present except in ultrarefined pure aluminum. Certain alloys are produced in several levels of purity, with the less pure levels being less expensive and the higher purity levels improving some property. For example, when the iron and silicon levels are both less than 0.10%, toughness is improved.

It is important to know that other metallic elements are present and necessary for desired properties. Many elements combine with one another and with aluminum to produce intermetallic compounds that are either soluble or insoluble in the aluminum matrix. The presence of second-phase particles is normal, and they can be seen and identified by metallographic examination.

The nominal chemical composition of representative aluminum wrought alloys are given in Table A.27.

There are two types of wrought alloys: non–heat-treatable of the 1XXX, 3XXX, 4XXX, and 5XXX series, and heat-treatable of the 2XXX, 6XXX, and 7XXX series.

A high resistance to general corrosion is exhibited by all of the non–heat-treatable alloys. Because of this, selection is usually based on other factors. Alloys of the 1XXX series have relatively low strength. Alloys of the 3XXX series have the same desirable properties as those of the 1XXX series but with higher strength.

Magnesium added to some alloys in the series provides additional strength, but the amount is low enough that the alloys still behave more like those with manganese alone than like the stronger Al-Mg alloys of the 5XXX series. Alloys of the 4XXX series are low-strength alloys used for brazing and welding products and for cladding in architectural products.

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**Table A.27** Nominal Chemical Compositions of Representative Aluminum Wrought Alloys

| | Percent of alloying elements | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Alloy | Si | Cu | Mn | Mg | Cr | Zn | Ti | V | Zr |
| *Non–heat-treatable alloys* | | | | | | | | | |
| 1060 | 99.60% min. Al | | | | | | | | |
| 1100 | 99.00% min. Al | | | | | | | | |
| 1350 | 99.50% min. Al | | | | | | | | |
| 3003 | | 0.12 | 1.2 | | | | | | |
| 3004 | | | 1.2 | 1.0 | | | | | |
| 5052 | | | | 2.5 | 0.25 | | | | |
| 5454 | | | 0.8 | 2.7 | 0.12 | | | | |
| 5456 | | | 0.8 | 5.1 | 0.12 | | | | |
| 5083 | | | 0.7 | 4.4 | 0.15 | | | | |
| 5086 | | | 0.45 | 4.0 | 0.15 | | | | |
| 7072[a] | | | | | | 1.0 | | | |
| *Heat-treatable alloys* | | | | | | | | | |
| 2014 | 0.8 | 4.4 | 0.8 | 0.50 | | | | | |
| 2219 | | 6.3 | 0.30 | | | | 0.06 | 0.10 | 0.18 |
| 2024 | | 4.4 | 0.6 | 1.5 | | | | | |
| 6061 | 0.6 | 0.28 | | 1.0 | 0.20 | | | | |
| 6063 | 0.4 | | | 0.7 | | | | | |
| 7005 | | | 0.45 | 1.4 | 0.13 | 4.5 | 0.04 | | 0.14 |
| 7050 | | 2.3 | | 2.2 | | 6.2 | | | |
| 7075 | | 1.6 | | 2.5 | 0.23 | 5.6 | | | |

[a]Cladding for Alclad products.

The strongest non–heat-treatable alloys are those of the 5XXX series, and in most products they are more economical than alloys of the IXXX and 3XXX series in terms of strength per unit cost.

Alloys of the 5XXX series have the same high resistance to general corrosion as the other non–heat-treatable alloys in most environments. In addition, they exhibit a better resistance in slightly alkaline solutions than any other aluminum alloy. These alloys are widely used because of their high as-welded strength when welded with a compatible 5XXX series filler wire.

Of the heat-treatable alloys those of the 6XXX series exhibit a high resistance to general corrosion, equal to or approaching that of the non–heat-treatable alloys. A high resistance to corrosion is also exhibited by alloys of the 7XXX series that do not contain copper as an alloying ingredient. All other heat-treatable alloys have a lower resistance to general corrosion. Table A.28 shows the mechanical and physical properties of aluminum.

## Corrosion of Aluminum

The resistance of aluminum to corrosion is dependent on the passivity of a protective oxide film. The thermodynamic conditions under which this film forms in aqueous solutions are expressed by the potential-pH diagram according to Pourbaix (refer to Fig. A.5).

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**Table A.28** Mechanical and Physical Properties or Aluminum Alloys

| | Aluminum alloy | | | |
|---|---|---|---|---|
| Property | 3003-3 | 5052-0 | 606 l-T6 | 6063-T6 |
| Modulus of elasticity $\times 10^6$, psi | 10 | 10.2 | 10 | 10 |
| Tensile strength $\times 10^3$ psi | 17 | 41 | 45 | 35 |
| Yield strength 0.2% offset $\times 10^3$, psi | 8 | 36 | 40 | 31 |
| Elongation in 2 in., % | 40 | 25 | 12 | 12 |
| Density, lb/in.$^3$ | 0.099 | 0.097 | | 0.098 |
| Specific gravity | 2.73 | 2.68 | | 2.70 |
| Specific heat, Btu/h °F | 0.23 | 0.23 | | |
| Thermal conductivity, Btu/h/ft$^2$/°F/in. | 1070 | 960 | 900 | 1090 |
| Coefficient of thermal expansion, in./°F/in. $\times 10^{-6}$ | | | | |
| at 58–68 °F | 12 | | 12.1 | 12.1 |
| at 68–212 °F | 12.9 | 13.2 | 13.0 | 13.0 |
| at 68–392 °F | 13.5 | | 13.5 | 13.6 |
| at 68–572 °F | 13.9 | | 14.1 | 14.2 |

Note from the diagram that aluminum is passive only in the pH range of 4 to 9. The limits of passivity depend on the form of oxide present, the temperature, and the low dissolution of aluminum that must be assumed for inertness. (Theoretically, this value cannot be zero for any metal.) At a pH of about 5 the various forms of aluminum oxide all exhibit a minimum solubility.

When the protective oxide film is formed in water and atmospheres at ambient temperatures, it is only a few nanometers thick and structureless. Thicker films are formed at higher temperatures. These may consist of a thin structureless barrier layer next to the aluminum and a thicker crystalline layer next to the barrier layer. Highly protective films of boehmite (aluminum oxide hydroxide, A100H) are formed in water near its boiling point, particularly if it is made slightly alkaline. In water or steam at still higher temperatures, thicker, more protective films are formed.

A protective film in water or steam ceases to develop starting at a temperature of about 445°F/230°C, and the reaction progresses rapidly until eventually all the aluminum exposed to this medium is converted to oxide. Special alloys containing iron and nickel retard this reaction. These alloys have an allowable operating temperature of 680°F/360°C without excessive attack.

As shown in Fig. A.5, aluminum corrodes under both acidic and alkaline conditions. In the first case trivalent $Al^{3+}$ ions are formed and in the latter case $Al_2O_3$ ions are formed. There are a few exceptions, either when the oxide film is not soluble in an acidic or alkaline solution, or when it is maintained by the oxidizing nature of the solution. Exceptions include acetic acid, ammonium hydroxide above 30% concentration by weight, nitric acid above 80% concentration by weight, and sulfuric acid in the concentration range of 98% to 100%.

It is possible for aluminum to corrode as a result of defects in its protective oxide film. As purity is increased, resistance to corrosion improves, but the oxide film on even the purest aluminum still contains a few defects where minute corrosion can develop. The presence of second phases in the less pure aluminums of the 1XXX series and in aluminum alloys becomes the more important factor. These phases are present as an

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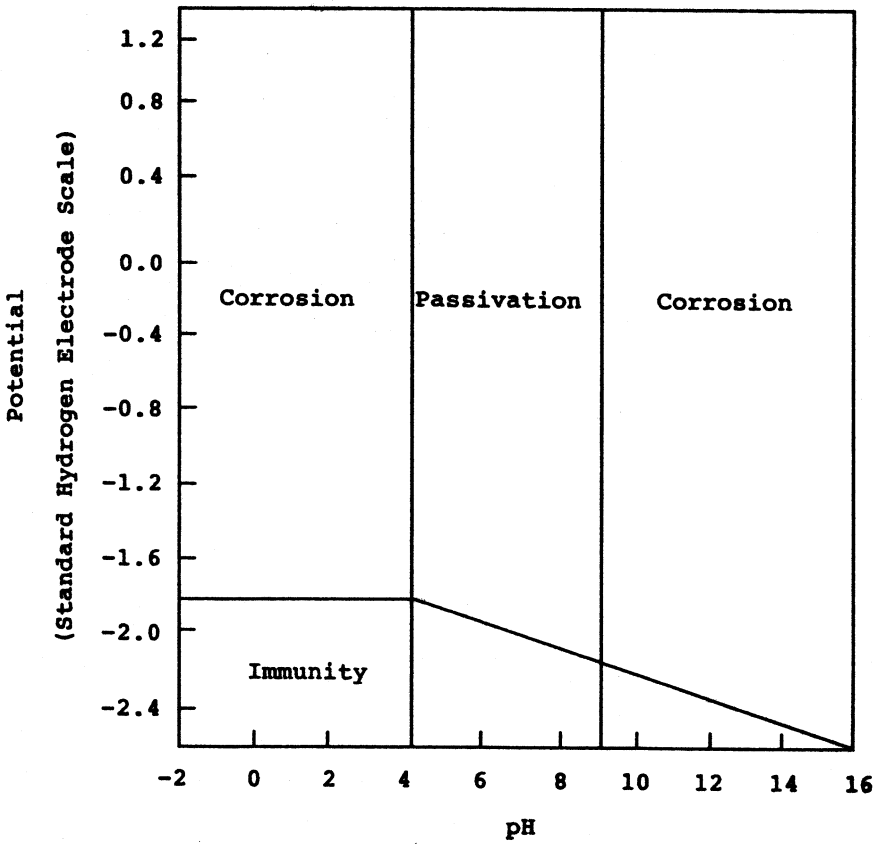



**Figure A.5** Potential-pH diagram according to Pourbaix for aluminum at 77°F (25°C) with an oxide film of hydrargillite (from Ref. 5).

insoluble constituent of intermetallic compounds produced primarily from iron, silicon, and other impurities plus a smaller precipitate of compounds produced primarily from soluble alloying elements. While most of the phases are cathodic to aluminum, a few are anodic. In either case, they produce galvanic cells because of the potential difference between them and the aluminum matrix.

## Pitting Corrosion

As with other passive metals, any corrosion of aluminum in its passive range may be of the pitting type. This type of corrosion is produced primarily by halide ions, notably chloride, which is the one most frequently encountered in service.

Pitting of aluminum is reduced as the acidity or alkalinity is increased beyond the passive range of aluminum, at which point the corrosion attack becomes more nearly uniform.

Pits that are almost invisible to the naked eye will develop in polluted outdoor atmospheres. Their growth is relatively rapid during the first few years of exposure, but it eventually stops and seldom exceeds 200 $\mu$m. These pits have no effect on the mechanical strength of the structure, but the bright appearance of the surface is gradually replaced

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by a gray patina of corrosion products. If soot is present, it will become absorbed by the corrosion products and the patina will become dark. Exterior areas exposed to rain will generally age uniformly, but areas sheltered from the washing action of the rain will corrode and produce an uneven gray discoloration. By regularly washing these sections, this condition can be prevented.

## Galvanic Relations

The galvanic series of aluminum alloys and other metals representative of their electrochemical behavior in seawater and in most natural waters and atmospheres is shown in Table A.29. The effect of alloying elements in determining the position of aluminum alloys in the series is shown in Fig. A.6. These elements, primarily copper and zinc, affect electrode potential only when they are in solid solution.

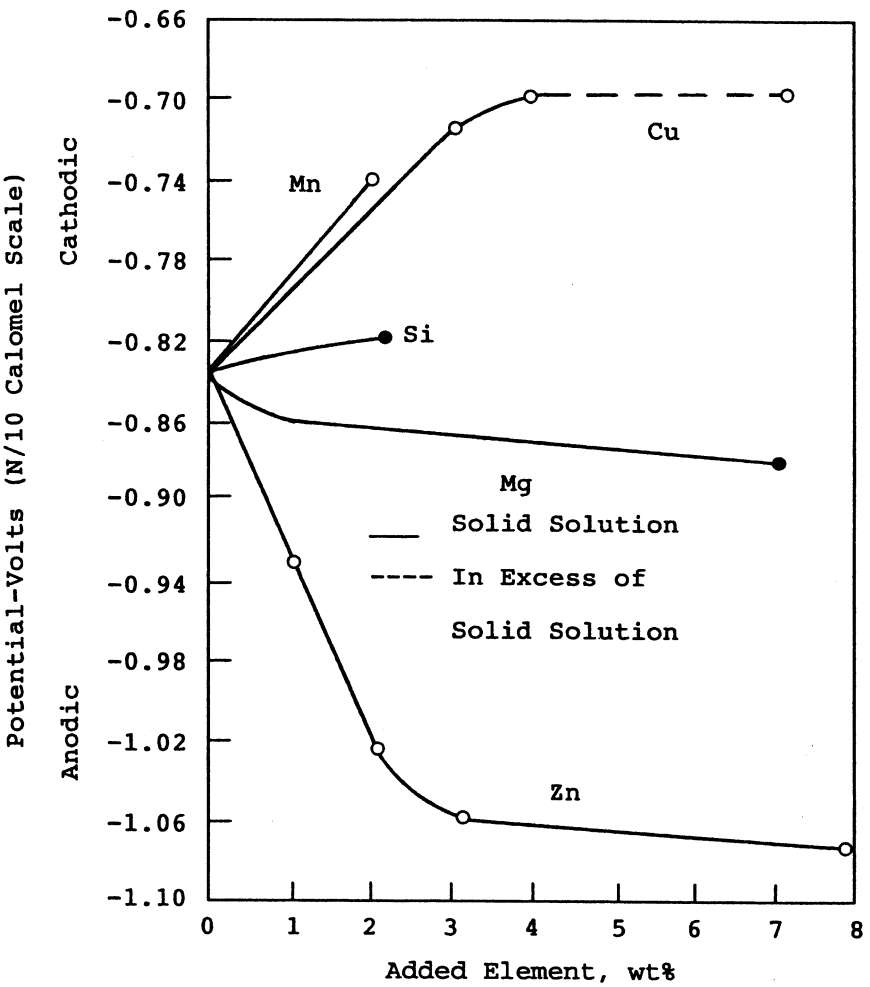



**Figure A.6** Effect of alloying elements on the electrode potential of aluminum.

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**Table A.29** Electrode Potentials of Representative Aluminum Alloys and Other Metals[a]

| Aluminum alloy or other metal[b] | Potential (V) |
|---|---|
| Chromium | +0.18 to –0.40 |
| Nickel | –0.07 |
| Silver | –0.08 |
| Stainless steel (300 series) | –0.09 |
| Copper | –0.20 |
| Tin | –0.49 |
| Lead | –0.55 |
| Mild carbon steel | –0.58 |
| 2219-T3, T4 | –0.64[c] |
| 2024-T3, T4 | –0.69[c] |
| 295.O-T4 (SC or PM) | –0.70 |
| 295.O-T6 (SC or PM) | –0.71 |
| 2014-T6, 355.O-T4 (SC or PM) | –0.78 |
| 355.O-T6 (SC or PM) | –0.79 |
| 221 9-T6, 6061-T4 | –0.80 |
| 2024-T6 | –0.81 |
| 2219-T8, 2024-T8, 356.O-T6 (SC or PM) | –0.82 |
| 443.O-F (PM), cadmium | |
| 1100, 3003, 6061-T6, 6063-T6, 7075-T6[c] | –0.83 |
| 443.O-F (SC) | |
| 1060, 1350, 3004, 7050-T73[c], 7075-T73[c] | –0.84 |
| 5052, 5086 | –0.85 |
| 5454 | –0.86 |
| 5456, 5083 | –0.87 |
| 7072 | –0.96 |
| Zinc | –1.10 |
| Magnesium | –1.73 |

[a]Measured in an aqueous solution of 53 g of NaCI and 3 g of $H_2O_2$ per liter at 25°C; 0.1 N calomel reference electrode.
[b]The potential of an aluminum alloy is the same in all tempers where ever the temper is not designated.
[c]The potential varies ±0.01 to 0.02 V with quenching rate.

As can be seen in Table A.29, aluminum or its alloy becomes the anode in galvanic cells with most metals and corrodes sacrificially to protect them. Only magnesium and zinc are more anodic and corrode to protect aluminum. Neither aluminum nor cadmium corrodes sacrificially in a galvanic cell because the two have nearly the same electrode potential. The degree to which aluminum is polarized in a galvanic cell will determine the degree to which aluminum corrodes when coupled to a more cathodic metal. Contact with copper and its alloys should be avoided because of the low degree of polarization of these metals. Aluminum may be used in contact with stainless steel and chromium in atmospheric and other mild environments with only a slight increase of corrosion. In these environments the two metals polarize highly; therefore, the additional corrosion current impressed onto the aluminum with them in the galvanic cell is small.

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When in contact with other metals, the ratio of exposed aluminum to the more cathodic metal should be kept as high as possible. This reduces the current density on the aluminum. In order to minimize corrosion, paints and other coatings may be applied to both the aluminum and the cathodic metal, or to the cathodic metal alone, but never applied to only the aluminum since it is very difficult to apply and maintain the coatings free of defects.

Cathodic metals in nonhalide salt solutions usually corrode aluminum to a lesser degree than in solutions of halide salts. This is because the aluminum is less likely to be polarized to its pitting potential. Galvanic corrosion is reduced in any solution when the cathodic reactant is removed. Therefore, the corrosion rate of aluminum coupled with copper in seawater is reduced greatly when the seawater is de-aerated.

### Reduction of Ions of Other Metals by Aluminum

The metals most commonly encountered are copper, cobalt, lead, mercury, nickel, and tin. The corrosive action is twofold since a chemical equivalent of aluminum is oxidized for each equivalent of ion reduced, but galvanic cells are set up because the metal reduced from the ions plates onto the aluminum. Acidic solutions with reducible metallic ions are of most concern. In alkaline solutions they are less of a concern because of their greatly reduced solubilities.

Rainwater entering aluminum gutters from roofs with copper flashing is a common source of copper ions. A threshold concentration of 0.02 ppm of copper is generally accepted for the reduction of copper ions. If more than 0.25% copper is present as an alloying ingredient, the corrosion resistance of the aluminum alloy is reduced because the alloys reduce the copper ions in any corrosion product from them.

Whenever stress is present, mercury, whether reduced from its ions or introduced directly in the metallic form, can be severely damaging to aluminum. This results from the amalgamation of mercury with aluminum, which, once started, progresses for long periods since the aluminum in the amalgam oxidizes immediately in the presence of water, continuously regenerating the mercury. Any concentration in a solution of more than a few parts per billion is susceptible to attack. Under no circumstances should metallic mercury be allowed to come into contact with aluminum.

### Stress Corrosion Cracking

Stress corrosion cracking (SCC) is experienced only in aluminum alloys having appreciable amounts of copper, magnesium, silicon, and zinc as alloying elements. The cracking is normally intergranular and may be produced whenever alloying ingredients precipitate along grain boundaries, depleting the regions adjacent to them of these ingredients. Metallurgical treatment of these alloys can improve or prevent stress corrosion cracking in aluminum alloys. The process of stress corrosion cracking can be retarded greatly, if not completely eliminated, by cathodic protection.

Stress corrosion cracking of an aluminum alloy in a susceptible temper is determined by the magnitude and duration of a tensile stress acting on its surface. Resistance to SCC is highest for stressing parallel to the longitudinal direction of grains and lowest for stressing across the minimum thickness of grains. Therefore, in wrought alloys having an elongated grain structure, and in products thick enough for stressing in all directions, resistance to SCC in the short transverse direction may be the controlling factor in applying these alloys.

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For SCC to take place, water or water vapor must be present; otherwise cracking will not occur. The presence of halides will accelerate cracking further.

Sufficient amounts of alloying elements are present in wrought alloys of the 2XXX, 5XXX, 6XXX, and 7XXX series to make them subject to SCC. Special treatment can cause SCC in 6XXX series, but cracking has never been experienced in commercial alloys. Tempers have been developed to provide a very high resistance to stress corrosion cracking in the other three alloy series.

### Exfoliation Corrosion

Exfoliation corrosion is a leafing or delamination of the product. Wrought aluminum products, in certain tempers, are subject to this type of corrosion. Alloys of the 2XXX, 5XXX, and 7XXX series are the most prone to this type of corrosion. Both exfoliation corrosion and stress corrosion cracking in alloys of this series are associated with decomposition of solid solution selectively along boundaries. Consequently, metallurgical treatment that improves resistance to SCC also improves resistance to exfoliation corrosion; however, resistance to the latter is usually achieved first.

Exfoliation corrosion is infrequent and less severe in wrought alloys of the non–heat-treatable type.

### Weathering

Aluminum alloys, except those containing copper as a major alloying element, have a high resistance to weathering in most atmospheres. After an initial period of exposure, the depth of attack decreases to a low rate. The loss in strength decreases in the same manner after the initial period, but not to as low a rate.

This "self-limiting" characteristic of corrosive attack during weathering also occurs with aluminum alloys in many other environments.

### Waters

Wrought alloys of the 1XXX, 3XXX, and 5XXX series exhibit excellent resistance to highpurity water. When first exposed a slight reaction takes place, producing a protective oxide film on the alloys within a few days, after which pickup of aluminum by water becomes negligible. The presence of carbon dioxide or oxygen dissolved in the water does not appreciably affect the corrosion resistance of these alloys; neither is the corrosion resistance affected by the chemicals added to the water to minimize the corrosion of steel because of the presence of these gases.

These same alloys are also resistant to many natural waters, their resistance being greater in neutral or slightly alkaline waters and less in acidic waters.

Resistance to corrosion by seawater is also high. General corrosion is minimal. Corrosion of these alloys in seawater is primarily of the pitting type. The rates of pitting usually range from 3 to 6 $\mu$m/year during the first year and from 0.8 to 1.5 $\mu$m/year averaged over a 10-year period. The lower rate for the longer period indicates the tendency of older pits to become inactive.

Alloys of the 5XXX series have the highest resistance to seawater and are widely used for marine applications.

### General Corrosion Resistance

All of the non–heat-treatable alloys have a high degree of corrosion resistance. These alloys, which do not contain copper as a major alloying ingredient, have a high resistance

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to corrosion by many chemicals. They are compatible with dry salts of most inorganic chemicals and, within their passive range of pH 4–9 in aqueous solutions, with most halide salts, under conditions at which most alloys are polarized to their pitting potentials. In most other solutions where conditions are less likely to occur that will polarize the alloys to these potentials, pitting is not a problem.

Aluminum alloys are not compatible with most inorganic acids, bases, and salts with pH outside the passive range of 4–9.

Aluminum alloys are resistant to a wide variety of organic compounds, including most aldehydes, esters, ethers, hydrocarbons, ketones, mercaptans, other sulfur-containing compounds, and nitro compounds. They are also resistant to most organic acids, alcohols, and phenols, except when these compounds are nearly dry and near their boiling points. Carbon tetrachloride also exhibits this behavior.

Aluminum alloys are most resistant to organic compounds halogenated with chlorine, bromine, and iodine. They are also resistant to highly polymerized compounds.

It should be noted that the compatibility of aluminum alloys with mixtures of organic compounds cannot always be predicted from their compatibility with each of the compounds. For example, some aluminum alloys are corroded severely in mixtures of carbon tetrachloride and methyl alcohol, even though they are resistant to each compound alone. Caution should be exercised in using data for pure organic compounds to predict performance of the alloys with commercial grades that may contain contaminents. Ions of halides and reducible metals, commonly copper and chloride, frequently have been found to be the cause of excessive corrosion of aluminum alloys in commercial grades of organic chemicals that would not have been predicted from their resistance to pure compounds.

Regardless of environment, pure aluminum has the greatest corrosion resistance, followed by the non–heat-treatable alloys and finally the heat treatable alloys. The two most frequently used alloys are 3003 and 3004. The 3XXX series of alloys are not susceptible to the more drastic forms of localized corrosion. The principal type of corrosion encountered is pitting corrosion. With a low copper content of <0.05% the 3003 and 3004 alloys are almost as resistant as pure aluminum.

Large quantities of aluminum are used for household cooking utensils and for the commercial handling and processing of foods. Aluminum and aluminum alloys such as foil, foil laminated to plastics, and cans are used for the packaging of foods and beverages. For most applications, lacquers and plastically laminated coatings are applied to the alloys because of the long periods of exposure, where only the smallest amount of corrosion can be tolerated.

Refer to Table A.30 for the compatibility of aluminum with selected corrodents. Reference 3 provides a more detailed listing.

See also Refs. 5–7.

## ALUMINUM BRONZE

See "Copper-Aluminum Alloys."

## AMBIENT TEMPERATURE

Ambient temperature is the temperature of the surrounding medium coming into contact with a material or apparatus. It is not necessarily room temperature.

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**Table A.30** Compatibility of Aluminum Alloys with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | 360 | 182 | Benzene | 210 | 99 |
| Acetamide | 340 | 171 | Benzene sulfonic acid 10% | x | x |
| Acetic acid 10% | 110 | 43 | Benzoic acid 10% | 400 | 204 |
| Acetic acid 50% | 130 | 54 | Benzyl alcohol | 110 | 43 |
| Acetic acid 80% | 90 | 32 | Benzyl chloride | x | x |
| Acetic acid, glacial | 210 | 99 | Borax | x | x |
| Acetic anhydride | 350 | 177 | Boric acid | 100 | 38 |
| Acetone | 500 | 260 | Bromine gas, dry | 60 | 16 |
| Acetyl chloride | x | x | Bromine gas. moist | x | x |
| Acrylonitrile | 210 | 99 | Bromine liquid | 210 | 99 |
| Adipic acid | 210 | 99 | Butadiene | 110 | 43 |
| Allyl alcohol | 150 | 66 | Butyl acetate | 110 | 43 |
| Allyl chloride | x | x | Butyl alcohol | 210 | 99 |
| Alum | 110 | 43 | *n*-Butylamine | 90 | 32 |
| Aluminum acetate | 60 | 16 | Butyl phthalate | x | x |
| Aluminum chloride, aqueous | x | x | Butyric acid | 180 | 82 |
| Aluminum chloride, dry | 60 | 16 | Calcium bisulfite | x | x |
| Aluminum fluoride | 120 | 49 | Calcium carbonate | x | x |
| Aluminum hydroxide | 80 | 27 | Calcium chlorate | 140 | 60 |
| Aluminum nitrate | 110 | 43 | Calcium chloride 20% | 100 | 38 |
| Aluminum sulfate | x | x | Calcium hydroxide 10% | x | x |
| Ammonia gas | x | x | Calcium hydroxide, sat. | x | x |
| Ammonium carbonate | 350 | 177 | Calcium hypochlorite | x | x |
| Ammonium chloride 10% | x | x | Calcium nitrate | 170 | 77 |
| Ammonium chloride 50% | x | x | Calcium oxide | 90 | 32 |
| Ammonium chloride, sat. | x | x | Calcium sulfate[b] | 210 | 99 |
| Ammonium fluoride 10% | x | x | Caprylic acid | 300 | 149 |
| Ammonium fluoride 25% | x | x | Carbon bisulfide | 210 | 99 |
| Ammonium hydroxide 25% | 350 | 177 | Carbon dioxide, dry | 570 | 299 |
| Ammonium hydroxide, sat. | 350 | 177 | Carbon dioxide, wet | 170 | 77 |
| Ammonium nitrate | 350 | 177 | Carbon disulfide | 210 | 99 |
| Ammonium persulfate | 350 | 177 | Carbon monoxide | 570 | 299 |
| Ammonium phosphate | x | x | Carbon tetrachloride | x | x |
| Ammonium sulfate 10–40% | x | x | Carbonic acid | 80 | 27 |
| Ammonium sulfide | 170 | 77 | Cellosolve | 210 | 99 |
| Ammonium sulfite | x | x | Chloracetic acid, 50% water | x | x |
| Amyl acetate | 350 | 177 | Chloracetic acid | x | x |
| Amyl alcohol | 170 | 77 | Chlorine gas, dry | 210 | 99 |
| Amyl chloride | 90 | 32 | Chlorine gas, wet | x | x |
| Aniline[b] | 350 | 177 | Chlorobenzene | 150 | 66 |
| Antimony trichloride | x | x | Chloroform, dry | 170 | 77 |
| Aqua regia 3:1 | x | x | Chlorosulfonic acid, dry | 170 | 77 |
| Barium carbonate | x | x | Chromic acid 10% | 200 | 93 |
| Barium chloride 30% | 180 | 82 | Chromic acid 50% | 100 | 38 |
| Barium hydroxide | x | x | Chromyl chloride | 210 | 99 |
| Barium sulfate | 210 | 99 | Citric acid 15% | 210 | 99 |
| Barium sulfide | x | x | Citric acid, concentrated | 70 | 21 |
| Benzaldehyde | 120 | 49 | Copper acetate | x | x |

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**Table A.30** Compatibility of Aluminum Alloys with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Copper carbonate | x | x | Nitric acid 20% | x | x |
| Copper chloride | x | x | Nitric acid 70% | x | x |
| Copper cyanide | x | x | Nitric acid, anhydrous | 90 | 32 |
| Copper sulfate | x | x | Nitrous acid, concentrated | x | x |
| Cresol | 150 | 66 | Oleum | 100 | 38 |
| Cupric chloride 5% | x | x | Perchloric acid 10% | x | x |
| Cyclohexane | 180 | 81 | Perchloric acid 70% | x | x |
| Cyclohexanol | x | x | Phenol | 210 | 99 |
| Dichloroethane (ethylene dichloride) | 110 | 43 | Phosphoric acid 50–80% | x | x |
| Ethylene glycol | 100 | 38 | Picric acid | 210 | 99 |
| Ferric chloride | x | x | Potassium bromide 30%[b] | 80 | 27 |
| Ferric chloride 50% in water | x | x | Salicylic acid | 130 | 54 |
| Ferric nitrate 10–50% | x | x | Silver bromide 10% | x | x |
| Ferrous chloride | x | x | Sodium carbonate | x | x |
| Fluorine gas, dry | 470 | 243 | Sodium chloride | x | x |
| Fluorine gas, moist | x | x | Sodium hydroxide 10% | x | x |
| Hydrobromic acid, dilute | x | x | Sodium hydroxide 50% | x | x |
| Hydrobromic acid 20% | x | x | Sodium hydroxide, concentrated | x | x |
| Hydrobromic acid 50% | x | x | Sodium hypochlorite 20% | 80 | 27 |
| Hydrochloric acid 20% | x | x | Sodium hypochlorite, concentrated | x | x |
| Hydrochloric acid 38% | x | x | Sodium sulfide to 50% | x | x |
| Hydrocyanic acid 10% | 100 | 38 | Stannic chloride | x | x |
| Hydrofluoric acid 30% | x | x | Stannous chloride, dry | x | x |
| Hydrofluoric acid 70% | x | x | Sulfuric acid 10% | x | x |
| Hydrofluoric acid 100% | x | x | Sulfuric acid 50% | x | x |
| Hypochlorous acid | x | x | Sulfuric acid 70% | x | x |
| Iodine solution 10% | x | x | Sulfuric acid 90% | x | x |
| Ketones, general | 100 | 38 | Sulfuric acid 98% | x | x |
| Lactic acid 25% | 80 | 27 | Sulfuric acid 100% | x | x |
| Lactic acid, concentrated[c] | 100 | 38 | Sulfuric acid, fuming | 90 | 32 |
| Magnesium chloride | x | x | Sulfurous acid | 370 | 188 |
| Malic acid | 210 | 99 | Thionyl chloride | x | x |
| Methyl chloride | x | x | Toluene | 210 | 99 |
| Methyl ethyl ketone | 150 | 66 | Trichloroacetic acid | x | x |
| Methyl isobutyl ketone | 150 | 66 | White liquor | 100 | 38 |
| Muriatic acid | x | x | Zinc chloride | x | x |
| Nitric acid 5% | x | x | | | |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. When compatible, corrosion rate is <20 mpy.
[b]Material subject to pitting.
[c]Material subject to intergranular corrosion.
*Source:* PA Schweitzer. *Corrosion Resistance Tables*. 4th ed. Vols. 1–3 New York: Marcel Dekker, 1995.

## ANAEROBIC CORROSION

Anaerobic corrosion is usually caused by the sulfide metabolic reaction products (biogenic sulfides) of sulfate-reducing bacteria. It occurs where there is an abundance of sulfate and the reaction of the metal substrate is between pH 5.5 and 8.5.

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Corroded steel is characterized by a coating of strongly reduced black-sulfide-containing corrosion products. Cast iron migrates from the metal, leaving a soft residue of largely carbon.

## ANNEALING

Annealing is a heating and cooling operation of a metal or alloy that usually implies relatively slow cooling. The purpose of such a heat treatment may be (a) to induce softness; (b) to remove stress; (c) to alter ductility, toughness, electrical, magnetic, or other physical properties; (d) to refine the crystalline structure; (e) to remove gases; or (f) to produce a definite microstructure. The temperature of the operation and the rate of cooling depend upon the material being heat treated and the purpose of the treatment. Certain specific heat treatments coming under the comprehensive term annealing are as follows.

### Process Annealing

Heating iron-based alloys to a temperature below or close to the lower limit of the critical temperature, generally 1000 to 1300°F (540 to 750°C).

### Normalizing

Heating iron-based alloys to approximately 100°F (50°C) above the critical temperature range, followed by cooling to below that range in still air at ordinary temperatures.

### Patenting

Heating iron-based alloys above the critical temperature range followed by cooling below that range in air, molten lead, or a mixture of nitrates and nitrites maintained at a temperature usually between 800 and 1050°F (425 to 555°C), depending on the carbon content of the steel and the properties required in the finished product. This treatment is applied in the wire industry to medium or high carbon steel as a treatment to precede further wire drawing.

### Spheradizing

Any process of heating and cooling steel that produces a rounded or globular form of carbide. The following spheradizing methods are used: (a) prolonged heating at a temperature just below the lower critical temperature, usually followed by relatively slow cooling; (b) for small objects of high carbon steels, the spheradizing result is achieved more rapidly by prolonged heating to temperatures alternately within and slightly below the critical temperature range; (c) tool steel is generally spheradized by heating to a temperature of 1380 to 1480°F (750 to 805°C) for carbon steels and higher for many alloy tool steels, holding at heat from 1 to 4 h and cooling slowly in the furnace.

### Tempering (Drawing)

Reheating carbon steel to a temperature below the lower critical temperature followed by any desired rate of cooling. Although the terms tempering and drawing are practically synonymous as used in commercial practice, the term tempering is preferred.

The term annealing is also applied to the heat treatment of polymer alloys to effect similar benefits.

See Ref. 8.

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## ANODE

An anode is an electrode of an electrolytic cell where oxidation is the principal reaction. It is also the electrode where corrosion usually occurs and from where metal ions enter into solution.

A sacrificial anode is a chemically active metal that when electrically connected will provide energy needed to cathodically protect a less anodic metal. Zinc, aluminum, and magnesium are commonly used as sacrificial anodes. See "Cathodic Protection."

## ANODIC PROTECTION

Anodic protection is a technique used to reduce the corrosion rate of a metal by polarizing it into its passive region. For its corrosion resistance the anodic metal is dependent upon an insoluble film that can be reinforced and maintained by the anodic effect of an impressed anodic polarization.

A typical example of anodic protection is found in steel storage tanks used to store sulfuric acid. Anodic protection systems require careful supervision, because if the proper potentials are not maintained continuously, corrosion by electrolysis may take place.

See Refs. 9 and 10.

## ANODIC UNDERMINING

Anodic undermining is a form of corrosion that takes place underneath an organic coating. A typical example is the dissolution of the tin coating between the organic coating and the steel substrate in a food container. A cathodic reaction develops that may involve a component in the foodstuff, or a defect in the tin coating that may expose iron, which then serves as a cathode. Under these circumstances the tin is selectively dissolved and the coating separates from the metal and loses its protective character.

## ANODIZING

Anodizing is one commercial method whereby a conversion coating is formed by electrolytic methods. By means of anodic oxidation a thin, dense, and durable oxide film is formed on a metal surface. The predominant application is for the protection of aluminum.

Two types of oxide films have been produced on aluminum by anodic oxidation. They are porous and nonporous films. The porous oxide films are widely used for corrosion protection. They consist of a duplex layered structure having an outer porous layer and an inner nonporous layer (barrier type).

The porous structure has a strong adsorbing ability permitting the surface of an anodic film to be dyed, but it may be contaminated. Since this property of a porous layer causes the formation of corrosion cells, a process to seal the pore is a very important posttreatment.

Sealing is accomplished using hot water or steam. This process seals the pores of the aluminum by formation of boehmite ($Al_2O_3$-$H_2O$) or bayerite ($Al_2O_3$-$3H_2O$). In practice sealing is conducted after dyeing, since the sealed film will not absorb dye.

An anodized coating has desirable protective, decorative, or functional properties. Titanium, stainless steel, and zirconium are also subject to anodizing.

See Ref. 9.

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## ARAMID FIBERS

Aramid fibers are high-strength fibers used as reinforcing in FRP structures. See "Thermoset Reinforcing Materials."

## ATMOSPHERIC CORRODENTS

See "Atmospheric Corrosion."

## ATMOSPHERIC CORROSION

Atmospheric corrosion, though not a separate form of corrosion, has received considerable attention because of the staggering associated costs that result. With the large number of outdoor structures such as buildings, fences, bridges, towers, automobiles, ships, and innumerable other applications exposed to the atmospheric environment, it is no wonder that so much attention has been given to the subject.

Atmospheric corrosion is a complicated electrochemical process taking place in corrosion cells consisting of base metal, metallic corrosion products, surface electrolyte, and the atmosphere. Many variables influence the corrosion characteristics of an atmosphere. Relative humidity, temperature, sulfur dioxide content, hydrogen sulfide content, chloride content, amount of rainfall, dust, and even position of the exposed metal exhibit marked influences on corrosion behavior. Geographical location is also another factor.

Because this is an electrochemical process, an electrolyte must be present on the surface of the metal for corrosion to occur. In the absence of moisture, which is the common electrolyte associated with atmospheric corrosion, metals corrode at a negligible rate. For example, carbon steel parts left in a desert remain bright and tarnish free over long periods. Also in climates where the air temperature is below the freezing point of water or of aqueous condensation on the metal surface, rusting is negligible because ice is a poor conductor and does not function effectively as an electrolyte.

Atmospheric corrosion depends not only on the moisture content present but also on the dust content and the presence of other impurities in the air, all of which have an effect on the condensation of moisture on the metal surface and the resulting corrosiveness. Air temperature can also be a factor.

### Atmospheric Types

Since corrosion rates are affected by local conditions, atmospheres are generally divided into rural, industrial, and marine.

Additional subdivisions such as urban, arctic, and tropical (wet or dry) can also be included. But the three major categories are of main concern.

For all practical purposes, the more rural the area, with little or no heavy manufacturing operations, or with very dry climatic conditions, the less will be the problems of atmospheric corrosion.

In an industrial atmosphere, all types of contamination by sulfur in the form of sulfur dioxide or hydrogen sulfide are usually the most important. The burning of fossil fuels generates large amounts of sulfur dioxide, which is converted to sulfuric and sulfurous acids in the presence of moisture. Theoretically the combustion of these fossil fuels and hazardous waste products should produce only carbon dioxide, water vapor, and

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inert gas as combustion products. This is seldom the case, however. Depending upon the impurities contained in the fossil fuel, the chemical composition of the hazardous waste materials incinerated, and the combustion conditions encountered, a multitude of other compounds may be formed.

In addition to the most common contaminants, previously mentioned pollutants such as hydrogen chloride, chlorine, hydrogen fluoride, and hydrogen bromide are produced as combustion products from the burning of chemical wastes. When organophosphorous compounds are incinerated, corrosive phosphorous compounds are produced. Chlorides arc also a product of municipal incinerators.

Road traffic and energy production lead to the formation of $NO_x$, which may be oxidized to $HNO_3$. This reaction has a very low rate; therefore, in the vicinity of the emission source the contents of $HNO_3$ and nitrates are very low. The antipollution regulations that have been enacted do not prevent the escape into the atmosphere of quantities of these materials sufficient to prevent corrosion problems. The corrosivity of an industrial atmosphere diminishes with increasing distance from the city.

Marine environments are subject to chloride attack resulting from the deposition of fine droplets of crystals formed by evaporation of spray that has been carried by the wind from the sea. The quantity of chloride deposition from marine environments is directly proportional to the distance from the shore. The closer to the shore, the greater the deposition and corrosive effect. The atmospheric test station at Kure Beach, NC, shows that steels exposed 80 feet from the ocean corrode ten to fifteen times faster than steels exposed 800 feet from the ocean.

In addition to these general air contaminants, there may also be specific pollutants found in a localized area. These may be emitted from a manufacturing operation on a continuous or spasmodic basis and can result in a much more serious corrosion problem than that caused by the presence of general atmospheric pollutants.

Because of these varying conditions, a material that is resistant to atmospheric corrosion in one area may not be satisfactory in another. For example, galvanized iron is perfectly suitable for application in rural atmospheres, but it is not suitable when exposed to industrial atmospheres.

## Factors Affecting Atmospheric Corrosion

As previously described, atmospheric corrosion is an electrochemical process and as such depends upon the presence of an electrolyte. The usual electrolyte associated with atmospheric corrosion is water resulting from rain, dew, fog, melting snow, and/or high humidity. Since an electrolyte is not always present, atmospheric corrosion is considered a discontinuous process. Corrosion takes place only during the "time of wetness."

### *Time of Wetness*

This term refers to the length of time during which the metal surface is covered by a film of water that renders significant atmospheric corrosion possible. The "time of wetness" is dependent upon local climatic conditions such as the frequency of rain, fog, and dew; the temperature of the metal surface; the temperature of the air; the relative humidity of the atmosphere; the wind speed; and the hours of sunshine.

The "time of wetness" can be determined by either meteorological measurements of temperature and relative humidity or by electrochemical cells. The "time of wetness"

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determined by meteorological measurements may not necessarily be the same as the actual "time of wetness," because wetness is influenced by the type of metal, pollution of the atmosphere, presence of corrosion products, and degree of coverage against rain. However, the results from these measurements usually show a good correlation with corrosion data from field tests under ordinary outdoor conditions.

### *Adsorption Layers*

The adsorption of water on the metal surface may be the result of the relative humidity of the atmosphere, of the chemical and physical properties of the corrosion products, of the properties of the materials deposited from the air, or of a combination of all three. Industrial atmospheres contain suspended particles of carbon, carbon compounds, metal oxides, sulfuric acid, sodium chloride, and ammonium sulfate. When these substances combine with moisture or when because of their hygroscopic nature they form an electrolyte on the surface, corrosion is initiated.

When hygroscopic salts which are deposited or formed by corrosion absorb moisture from the atmosphere, the metal surface may become wetted. Such absorption occurs above a certain relative humidity, called the critical relative humidity, which corresponds to the vapor pressure above a saturated solution of the salt present. The amount of water on the surface has a direct effect on the corrosion rate. The more water present, the greater the corrosion rate.

### *Phase Layers*

Phase layers are the result of the formation of dew by condensation on a cold metallic surface, or of precipitation in the form of rain or fog, and wet or melting snow. The rate of corrosion will be dependent upon the concentration and nature of the corrodents in the electrolyte, which will vary depending upon the deposition rates, frequency of wetting, drying conditions, and degree of rain protection provided.

If the surface is wetted after a long dry spell during which there has been a large accumulation of surface contamination, the corrosion rate will be greater than for a smaller amount accumulated during a shorter dry period. Corrosion will also be affected by the quantity of electrolyte present.

Dew is an important source of atmospheric corrosion—more so than rain—and particularly under sheltered conditions. Dew forms when the temperature of the metal surface falls below the dew point of the atmosphere. This can occur outdoors during the night when the surface temperature of the metal is lowered as a result of radiant heat transfer between the metal and the sky. It is also quite common for dew to form during the early morning hours when the air temperature rises faster than the metal temperature. Dew may also form when metal products are brought into warm storage after cold shipment.

Under sheltered conditions dew is an important cause of corrosion. The high corrosivity of dew is a result of several factors. Relatively speaking, the concentration of contaminants in dew is higher than in rainwater, which leads to lower pH values. Heavily industrialized areas have reported pH values of dew in the range of 3 and lower.

The washing effect, which occurs with rain, is usually slight or negligible. With little or no runoff, the pollutants remain in the electrolyte and continue their corrosive action. As the dew dries, these contaminants remain on the surface to repeat their corrosive activity with subsequent dew formations.

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Depending upon the conditions, rain can either increase or decrease the effects of atmospheric corrosion. Corrosive action is caused by rain when a phase layer of moisture is formed on the metal surface. This activity is increased when the rain washes corrosive promoters such as $H^+$ and $SO_4^{2-}$ from the air (acid rain). Rain has the ability to decrease corrosive action on the surface of the metal as a result of washing away the pollutants that have been deposited during the preceding dry spell.

Whether the rain will increase or decrease the corrosive action is dependent upon the ratio of deposition between the dry and wet contaminants. When the dry period deposition of pollutants is greater than the wet period deposition of sulfur compounds, the washing effect of the rain will dominate and the corrosive action will be decreased.

In areas where the air is not as heavily polluted, the corrosive action of the rain will assume much greater importance because it will increase the corrosion rate.

High concentrations of sulfate and nitrate, and high acidity, will be found in areas having an appreciable amount of air pollution. The pH of fog water has been found to be in the range of 2.2 to 4.0 in highly contaminated areas. This leads to increased corrosivity.

### *Dust*

On a weight basis, in many locations, dust is the primary air contaminant. When in contact with metallic surfaces and combined with moisture, this dust can promote corrosion by forming galvanic or differential aeration cells that, because of their hygroscopic nature, form an electrolyte on the surface. This is particularly true if the dust consists of water-soluble particles, or particles on which sulfuric acid is absorbed. Dust-free air therefore is less likely to cause corrosion.

### *Temperature*

During long-term exposure in a temperate climatic zone, temperature appears to have little or no effect on the corrosion rate. The overall effect of temperature on the corrosion rate is complex. As the temperature increases, the rate of corrosive attack is increased as the result of an increase in the rate of electrochemical and chemical reactions as well as the diffusion rate. Consequently, under constant humidity conditions, a temperature increase will promote corrosion.

By the same token, an increase in temperature can cause a decrease in the corrosion rate by causing a more rapid evaporation of the surface moisture film created by rain or dew. This reduces the time of wetness, which in turn reduces the corrosion rate. In addition, as the temperature increases, the solubility of oxygen and other corrosive gases in the electrolyte film is decreased.

When the air temperature falls below 32°F (0°C) the electrolyte film may freeze. When freezing occurs, there is a pronounced decrease in the corrosion rate, which is illustrated by the low corrosion in subarctic or arctic regions.

In general, temperature is a factor influencing corrosion rates, but it is of importance only under extreme conditions.

## Specific Atmospheric Corrodents

The electrolyte film on the surface will contain various materials deposited from the atmosphere or originating from the corroding metal. The composition of the electrolyte is often the factor that determines the rate of corrosion.

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The primary contaminants in the air that lead to atmospheric corrosion are $SO_x$, $NO_x$, chlorides, and oxygen.

### $SO_X$

Sulfur dioxide, which results from the burning of fossil fuels (such as coal and oil) and the combustion products from the incineration of organic and hazardous wastes, is the most important corrosive contaminant found in industrial atmospheres. Most of the sulfur derived from the burning of fossil fuels is emitted in the form of gaseous $SO_2$. Once in the atmosphere, their physical and chemical state undergoes change. The sulfur dioxide is oxidized on moist particles or in droplets of water to sulfuric acid:

$$SO_2 + H_2O + \frac{1}{2}O_2 \rightarrow H_2SO_4$$

The sulfuric acid can he partially neutralized, particularly with ammonia resulting from the biological decomposition of organic matter. This neutralization forms particles containing $(NH_4)_2SO_4$ and forms of acid ammonium sulfate such as $NH_4HSO_4$ and $(NH_4)_3H(SO_4)_2$. Atmospheric corrosion results from the deposition of these various materials on metallic surfaces. Deposition of these sulfur compounds is accomplished by:

1. Dry deposition
   a. Absorption of sulfur dioxide gas on metal surfaces
   b. Impaction of sulfate particles
2. Wet deposition
   a. Removal of gas from the atmosphere by precipitation in the form of rain or fog.

The primary cause of atmospheric corrosion is the dry deposition of sulfur dioxide on metallic surfaces. This type of corrosion is usually confined to areas having a high population, many structures, and severe pollution. Therefore, the atmospheric corrosion caused by sulfur pollutants is usually restricted to the source.

### $NO_X$

These emissions originate from combustion processes other than those emitting $SO_x$. Road traffic and energy production are the primary sources. Most of the nitrogen oxides are emitted as NO in combustion processes. In the atmosphere, oxidation to $NO_2$ takes place successfully according to:

$$2\ NO + O_2 \rightarrow 2\ NO_2$$

As the pollutant moves further from the source it is further oxidized by the influence of ozone:

$$NO + O_3 \rightarrow NO_2 + O_2$$

Near the emission source nitrogen dioxide is considered to be the primary pollutant. The $NO_2$/NO ratio in the atmosphere varies with time and distance from the source. Allowed enough time, the $NO_x$ may be further oxidized according to the reaction:

$$2\ NO + H_2O + \frac{3}{2}O_2 \rightarrow 2\ HNO_3$$

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Since this reaction has a very slow rate, the amounts of $HNO_3$ and nitrates in the vicinity of the source are very low.

### *Chlorides*

In marine environments chloride deposition is in the form of droplets or crystals formed by evaporation of spray that has been carried by the wind from the sea. As distance from the shore increases, this deposition decreases as the droplets and crystals are filtered off when the wind passes through vegetation, or when the particles are settled by gravity.

Gaseous HCl is a combustion product derived from the burning of coal and municipal incinerators. This gaseous HCl is very soluble in water and forms hydrochloric acid, which is extremely corrosive.

### *Oxygen*

Oxygen is a natural constituent of air and is readily absorbed from the air into the water film on the metal surface, which may be considered saturated, thus promoting any oxidation reactions.

### *Hydrogen Sulfide*

Trace amounts of hydrogen sulfide are present in some contaminated atmospheres. This can cause the tarnishing of silver and copper by the formation of tarnish films.

## Effects on Metals Used for Outdoor Applications

Carbon steel is the most widely used metal for outdoor applications, although large quantities of zinc, aluminum, copper, and nickel-hearing alloys are also used. Metals customarily used for outdoor installations will be discussed.

### *Carbon Steel*

Except in a dry, clean atmosphere, carbon steel does not have the ability to form a protective coating, as some other metals do. In such an atmosphere a thick oxide film will form that prevents further oxidation. Solid particles on the surface are responsible for the start of corrosion. The settled airborne dust promotes corrosion by absorbing $SO_2$ and water vapor from the air. Even greater corrosive effects result when particles of hygroscopic salts, such as sulfates or chlorides, settle on the surface and form a corrosive electrolyte.

To protect the surface of unalloyed carbon steel, an additional surface protection must be applied. This protection usually takes the form of an antirust paint or other type of paint formulated for resistance against a specific type of contaminant known to be present in the area. On occasion, plastic or metallic coatings are used.

### *Weathering Steels*

These are steels to which small amounts of copper, chromium, nickel, phosphorus, silicon, manganese, or various combinations thereof have been added. This results in a low-alloy carbon steel that has improved corrosion resistance in rural areas, or in areas exhibiting relatively low pollution levels. Factors that affect the corrosion resistance of these steels are climatic conditions, pollution levels, degree of sheltering from the atmosphere, and specific composition of the steel. Exposure to most atmospheres results in a corrosion rate that becomes stabilized in 3 to 5 years. Over this period of time a protective film, or

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patina, dark brown to violet in color, forms. This patina is a tightly adhering rust formation on the surface of the steel that cannot be wiped off. Since the formation of this film is dependent upon the pollution in the air, in rural areas where there may be little or no pollution a longer period of time may be required to form this film. In areas that have a high pollution level of $SO_2$, loose rust particles are formed with a much higher corrosion rate. This film of loose particles offers little or no protection against continued corrosion.

When chlorides are present, such as in a marine environment, the protective film will not be formed. Under these conditions corrosion rates of the weathering steels are equivalent to those of unalloyed carbon steel.

In order to form the patina, periodic flushing followed by a dry period is required. If the steel is installed in such a manner as to be sheltered from the rain, the dark patina will not be formed. Instead, a rust lighter in color forms, which provides the same resistance. The corrosion rate of the weathering steels will be the same as the corrosion rate of unalloyed steel when it is continuously exposed to wetness, such as in water or soil.

Since the patina formed has a pleasant aesthetic appearance, the weathering steels can be used without the application of any protective coating of antirust paint, zinc, or aluminum. This is particularly true in urban and rural areas.

In order to receive the maximum benefit from weathering steels, consideration must be given to the design. The design should eliminate all possible areas where water, dirt, and corrosion products can accumulate. When pockets are present, the time of wetness increases, which leads to the development of corrosive conditions. The design should make maximum use of exposure to the weather. Sheltering from rain should be avoided.

While the protective film is forming, rusting will proceed at a relatively high rate, during which time rusty water is produced. This rusty water may stain masonry, pavements and the like. Consequently, steps should be taken to prevent detrimental staining effects, such as coloring the masonry brown, so that any staining will not be obvious.

### *Zinc*

Galvanized steel (zinc-coated steel) is used primarily in rural or urban atmospheres for protection from atmospheric corrosion. Galvanizing will also resist corrosion in marine atmospheres, provided saltwater spray does not come into direct contact. In areas where $SO_2$ is present in any appreciable quantity, galvanized surfaces will be attacked.

### *Aluminum*

Except for those aluminum alloys that contain copper as a major alloying ingredient, aluminum alloys have a high resistance to weathering in most atmospheres. When exposed to air, the surface of the aluminum becomes covered with an amorphous oxide film that provides protection against atmospheric corrosion, particularly $SO_2$.

The shiny metal appearance of aluminum gradually disappears and becomes rough when exposed to $SO_2$. A gray patina of corrosion products forms on the surface. If aesthetics are a consideration, the original surface luster can be retained by anodizing. This anodic oxidation strengthens the oxide coating and improves its protective properties.

It is important that the design utilizing aluminum should eliminate rain-sheltered pockets on which dust and other pollutants may collect. The formation of the protective film will be disturbed and corrosion accelerated by the presence of these pollutants.

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### *Copper*

When exposed to the atmosphere over long periods of time, copper will form a coloration on the surface known as patina, which in reality is a corrosion product that acts as a protective film against further corrosion. The length of time required to form the patina depends upon the atmospheres, because the color is due to the formation of copper hydroxide compounds. Initially the patina has a dark color; gradually it turns green. In urban or industrial atmospheres the compound is a mixture of copper/hydroxide/chloride. It takes approximately 7 years for these compounds to form. When exposed to clean or rural atmospheres tens or hundreds of years may be required to form the patina.

The corrosion resistance of copper is the result of the formation of this patina or protective film. Copper roofs are still in existence on many castles and monumental buildings that are centuries old.

### *Nickel 200*

When exposed to the atmosphere a thin corrosion film (usually a sulfate) forms, dulling the surface. The rate of corrosion is extremely slow but increases as the $SO_2$ content of the atmosphere increases. When exposed to marine or rural atmospheres the corrosion rate is very low.

### *Monel Alloy 400*

The corrosion of monel is negligible in all types of atmospheres. When exposed to rain a thin gray-green patina forms. In sulfurous atmospheres, a smooth brown adherent film forms.

### *Inconel Alloy 600*

In rural atmospheres Inconel alloy 600 will remain bright for many years. When exposed to sulfur-bearing atmospheres a slight tarnish is apt to develop. It is desirable to expose this alloy to atmospheres where the beneficial effects of rain in washing the surface and sun and wind in drying can be utilized. It is not recommended to design on the basis of sheltered exposure.

See Refs. 6, 11–15.

## AUSTENITE

Austenite is a form of carbon steel with a face-centered cubic crystal structure. This form of carbon steel cannot exist below 1333°F (710°C). During heat treatment the holding temperature and time is specified so that the alloy becomes fully austenitic. For common carbon steels the holding temperature is typically specified at 1650°F (900°C). This will make the alloy fully austenitic.

Since austenite has a higher solubility for carbon than the lower-temperature forms of carbon steel, heating the steel to an austenizing temperature causes any carbides that may have formed at the lower temperature to dissolve. Alloys that can form austenite at high temperatures, but transform to other crystal forms at lower temperatures, are capable of being hardened by heat treatment. Martensitic steels are an example.

The austenitic microstructure can be made to be stable at low temperatures by alloying with nickel or manganese. See "Austenitic Stainless Steels."

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## AUSTENITIC DUCTILE CAST IRONS

These cast irons are similar to the austenitic gray cast irons except that they have been treated with magnesium to produce a nodular graphite structure, thereby producing a ductile material. Several different grades are produced, with grade D-2 being the most commonly used grade.

These alloys find use in mildly oxidizing acids, alkalies, salts, seawater, water, foods, plastics, and synthetic fiber manufacturing.

See Refs. 16 and 17.

## AUSTENITIC GRAY CAST IRONS

The austenitic gray cast irons are gray irons that have been alloyed with nickel and sometimes copper to produce an austenitic matrix similar to that of the 300 series stainless

## AUSTENITIC STAINLESS STEELS

The austenitic stainless steels are the most widely used family of stainless alloys. They find application in settings ranging from mildly corrosive atmospheres to extremely corrosive environments. This group of alloys are nonmagnetic and are the most important for process industry applications. These stainless steels have a face-centered austenite structure from far below zero up to near melting temperatures as a result of the alloy additions of nickel and manganese. They are not hardenable by heat treatment but can be strain hardened by cold work, which also includes a small amount of ferromagnetism.

To form the austenitic structure it is necessary to add about 8% nickel to the 18% chromium plateau to cause the transition from ferritic to austenitic. Compared with the ferritic structure, the austenitic structure is very tough, formable, and weldable. The nickel addition also improves the corrosion resistance to mild corrodents. This includes resistance to most foods, a wide range of organic chemicals, mild inorganic chemicals, and most natural environments.

To further improve the corrosion resistance, molybdenum is added. This provides excellent corrosion resistance in oxidizing environments, particularly in aqueous solutions. The molybdenum aids in strengthening the passive film which forms on the surface of the stainless steel along with chromium and nickel. The types of stainless steels comprising this group are as follows:

| | | |
|---|---|---|
| 201 | 304 | 316L |
| 202 | 304L | 317 |
| 22-13-5 | 305 | 317L |
| 216L | 308 | 321 |
| 301 | 309 | 329 |
| 302 | 310 | 347 |
| 303 | 316 | 348 |

Austenitic alloys also make use of the concept of stabilization. Stainless steel types 321 and 347 are stabilized with titanium and niobium, respectively. Another approach is taken to avoid the effects of chromium carbide precipitation. Since the amount of chro-

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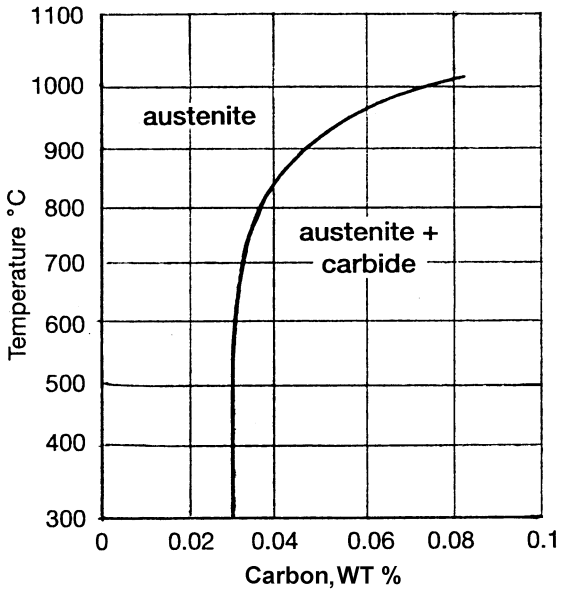



**Figure A.7** Solubility of carbon in austenite.

mium that will precipitate is proportional to the amount of carbon present, lowering the carbon content will prevent sensitization.

From an examination of Fig. A.7 it can be seen that by maintaining the carbon content below about 0.035%, versus the usual 0.08% maximum, the harmful effects of chromium carbide precipitation can be avoided. This fact along with improvements in melting technology has resulted in the development of the low-carbon version of many of these alloys.

Various other elements are added to enhance specific properties. The 200 and 300 series of stainless steels both start with the same high-temperature austenite phase that exists in carbon steel, but as mentioned previously retain this structure to below zero. The 200 series of alloys rely mostly on manganese and nitrogen, while the 300 series utilize nickel. Both series of stainless steels have useful levels of ductility and strength. Grades 201 and 301, which are on the lean side of the retention elements, will transform to martensite when formed, but cool to austenite. This results in high-strength parts made by stretching a low-strength starting material. Table A.31 gives the chemical composition of the most commonly used austenitic stainless steels.

As previously mentioned, the corrosion resistance of the austenitic stainless steels is the result of the formation of a passive oxide film on the surface of the metal. Consequently, they perform best under oxidizing conditions, since reducing conditions and chloride ions destroy the film, causing rapid attack. Chloride ions combined with high tensile stresses cause stress corrosion cracking.

## Type 201 (S20100)

This is one of the alloys based on the substitution of manganese for nickel because of the shortage of nickel during and shortly after World War II. It was developed as a substitute

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**Table A.31** Chemical Composition of Austenitic Stainless Steels

| AISI Type | C max. | Mn max. | Si | Cr | Ni | Others[a] |
|---|---|---|---|---|---|---|
| 210 | 0.15 | 7.5[b] | 1.00 | 16.00–8.00 | 3.50–5.50 | 0.25 max. N |
| 202 | 0.15 | 10.00[c] | 1.00 | 17.00–19.00 | 4.00–6.00 | 0.25 max. N |
| 205 | 0.25 | 10.50[d] | 0.50 | 16.50–18.00 | 1.00–1.75 | 0.32–0.4 max. N |
| 301 | 0.15 | 2.00 | 1.00 | 16.00–18.00 | 6.00–8.00 | |
| 302B | 0.15 | 2.00 | 3.00[d] | 17.00–19.00 | 8.00–10.00 | |
| 303 | 0.15 | 2.00 | 1.00 | 17.00–19.00 | 8.00–10.00 | 0.15 min. S |
| 303 (Se) | 0.15 | 2.00 | 1.00 | 17.00–19.00 | 8.00–10.00 | 0.15 min. Se |
| 304 | 0.08 | 2.00 | 1.00 | 18.00–20.00 | 8.00–12.00 | |
| 304L | 0.03 | 2.00 | 1.00 | 18.00–20.00 | 8.00–12.00 | |
| 304N | 0.08 | 2.00 | 1.00 | 18.00–20.00 | 8.00–10.50 | 0.1–0.16 N |
| 305 | 0.12 | 2.00 | 1.00 | 17.00–19.00 | 10.00–13.00 | |
| 308 | 0.08 | 2.00 | 1.00 | 19.00–21.00 | 10.00–12.00 | |
| 309 | 0.20 | 2.00 | 1.00 | 22.00–24.00 | 12.00–15.00 | |
| 309S | 0.08 | 2.00 | 1.00 | 22.00–24.00 | 12.00–15.00 | |
| 310 | 0.25 | 2.00 | 1.50 | 24.00–26.00 | 19.00–22.00 | |
| 310S | 0.08 | 2.00 | 1.50 | 24.00–26.00 | 19.00–22.00 | |
| 314 | 0.25 | 2.00 | 3.00[e] | 23.00–26.00 | 19.00–22.00 | |
| 316 | 0.08 | 2.00 | 1.00 | 16.00–18.00 | 10.00–14.00 | 2.00–3.00 Mo |
| 316F | 0.08 | 2.00 | 1.00 | 16.00–18.00 | 10.00–14.00 | 1.75–2.50 Mo |
| 316L | 0.03 | 2.00 | 1.00 | 16.00–18.00 | 10.00–14.00 | 2.00–3.00 Mo |
| 316N | 0.08 | 2.00 | 1.00 | 16.00–18.00 | 10.00–14.00 | 2.00–3.00 Mo |
| 317 | 0.08 | 2.00 | 1.00 | 18.00–20.00 | 11.00–15.00 | 3.00–4.00 Mo |
| 317L | 0.03 | 2.00 | 1.00 | 18.00–20.00 | 11.00–15.00 | 3.00–4.00 Mo |
| 321 | 0.08 | 2.00 | 1.00 | 17.00–19.00 | 9.00–12.00 | 5 × min. Cb-Ta |
| 330 | 0.08 | 2.00 | 1.50 | 17.00–20.00 | 34.00–39.00 | 0.10 Ta |
| 347 | 0.08 | 2.00 | 1.00 | 17.00–19.00 | 9.00–13.00 | 10 × min. Cb–Ta |
| 348 | 0.08 | 2.00 | 1.00 | 17.00–19.00 | 9.00–13.00 | 10 × min. Cb–Ta, 2.0 Mo, 3.0 Cu |

[a]Other elements in addition to those shown are as follows:
Phosphorus is 0.03% max. in type 205; 0.06% max. in type 202 and 205; 0.045% max. in types 301, 302, 302B, 304, 304L, 304N, 305, 308, 309, 310, 310S, 314, 316, 316N, 316L, 317, 317L, 321, 330, 347, and 348; 0.2% max. in types 303, 303 (Se), and 316D. Sulfur is 0.30% max. in types 201, 202, 205, 301, 302, 302B, 304, 304L, 304N, 305, 308, 309, 309S, 310, 310X, 314, 316, 316L, 316N, 317, 317L, 321, 330, 347, and 348; 0.15% min. in type 303; and 0.10% min. in type 316D.
b = Mn range 4.40–7.50%
c = Mn range 7.50–10.00%
d = Mn range 14.00–15.50%
e = Si range 2.00–3.00%
f = Si range 1.500–3.00

for type 304 stainless steel. By adding about 4% manganese and 0.2% nitrogen, the nickel content could be lowered to about 5%. The chemical composition is shown in Table A.31. Although the strength of this alloy is higher than that of type 304, its corrosion resistance is inferior. It does have a corrosion resistance comparable to type 301.

This alloy can be cold worked to high strength levels. It is nonmagnetic as annealed and becomes somewhat magnetic after cold work. Table A.32 shows the mechanical and physical properties of type 201 and 202 stainless steel.

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**Table A.32** Mechanical and Physical Properties of Types 201 and 202 Stainless Steel

| Property | Type 201 | Type 202 |
|---|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 28.6 | 28.6 |
| Tensile strength $\times 10^3$ (psi) | 95 | 90 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | 45 | 45 |
| Elongation in 2 in. (%) | 40 | 40 |
| Rockwell hardness | B-90 | B-90 |
| Density (lb/in.$^3$) | 0.28 | 0.28 |
| Specific gravity | 7.7 | 7.7 |
| Specific heat at 32–212°F (Btu/lb °F) | 0.12 | 0.12 |
| Thermal conductivity at 212°F (Btu/hr ft$^2$ °F) | 9.4 | 9.4 |
| Izod impact (ft-lb) | 115 | |

## Type 22-13-5 (S20910)

This is a nitrogen-strengthened stainless alloy having the following composition:

| | |
|---|---|
| Carbon | 0.06% |
| Manganese | 4.00–6.00% |
| Phosphorous | 0.040% |
| Sulfur | 0.030% |
| Silicon | 1.00% |
| Chromium | 20.50–23.50% |
| Nickel | 11.50–13.50% |
| Molybdenum | 1.50–3.00% |
| Niobium | 0.10–0.30% |
| Vanadium | 0.10–0.30% |
| Nitrogen | 0.20–0.40% |
| Iron | Balance |

It is superior in corrosion resistance to type 316 stainless steel with twice the yield strength. It can be welded, machined, and cold worked using the same equipment and methods used for the conventional 300 series stainless steels. It remains nonmagnetic after cold work.

Type 22-13-5 stainless steel has very good corrosion resistance in many reducing and oxidizing acids, chlorides, and pitting environments. It has a pitting resistance equivalent number (PREN) of 45.5. In particular, the alloy provides an excellent level of resistance to pitting and crevice corrosion in seawater. Resistance to intergranular attack in boiling 65% nitric acid and in ferric sulfate–sulfuric acid, is excellent for both the annealed and sensitized conditions. Like other austenitic stainless steels, S20910 under certain conditions may suffer stress corrosion cracking in hot chloride environments. This alloy also exhibits good resistance to sulfide stress cracking at ambient temperatures.

This alloy is sometimes referred to as nitronic 50. Refer to Table A.33 for the mechanical and physical properties of S20910 stainless steel.

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**Table A.33** Mechanical and Physical Properties of S20910 Stainless Steel

| Property | |
|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 28 |
| Tensile strength $\times 10^3$ (psi) | 210 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | 65 |
| Elongation in 2 in. (%) | 45 |
| Rockwell hardness | B-96 |
| Density (lb/in.$^3$) | 0.285 |
| Specific gravity | 7.88 |
| Specific heat at 32–212°F (Btu/lb °F) | 0.12 |
| Thermal conductivity at 300 °F (Btu/hr ft$^2$ °F) | 108 |
| Thermal expansion coefficient at 32–212°F $\times 10^{-6}$ (in./in. °F) | 9.0 |
| Izod impact (ft-lb) | 160 |

## Type 216L (S21603)

This is a low-carbon alloy in which a portion of the nickel has been replaced by molybdenum. It has the following composition:

| | |
|---|---|
| Carbon | 0.30% |
| Manganese | 7.50–9.00% |
| Chromium | 17.50–22.00% |
| Molybdenum | 2.00–3.00% |
| Silicon | 1.00% |
| Iron | Balance |

This alloy finds application in aircraft, hydraulic lines, heat exchanger tubes, pollution control equipment, and particle accelerator tubes.

## Type 301 (S30100)

This is a nitrogen-strengthened alloy that has the ability to work harden. As with the 200 series alloys, it forms martensite while deforming but retains the contained strain to higher levels. The chemical composition is shown in Table A.31. Types 301L and 301LN find application in passenger rail cars, buses, and light rail vehicles. The chemical compositions of type 301L (S30103) and type 301LN (S30153) are as follows:

| | Alloy (%) | |
|---|---|---|
| Alloying element | 301L | 301LN |
| Carbon | 0.030 max. | 0.030 max. |
| Chromium | 16.0–18.0 | 16.0–18.0 |
| Manganese | 2.0 max. | 2.0 max. |
| Nitrogen | 0.20 max | 0.07–0.20 |
| Nickel | 5.0–8.0 | 5.0–8.0 |
| Phosphorus | 0.045 max. | 0.045 max. |
| Sulfur | 0.030 max. | 0.030 max. |
| Silicon | 1.0 max. | 1.0 max. |

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**Table A.34** Mechanical and Physical Properties of Type 301 Stainless Steel

| Property | |
|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 28 |
| Tensile strength $\times 10^3$ (psi) | 110 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | 40 |
| Elongation in 2 in. (%) | 60 |
| Rockwell hardness | B-95 |
| Density (lb/in.$^3$) | 0.29 |
| Specific gravity | 8.02 |
| Specific heat at 32–212°F (Btu/lb °F) | 8.12 |
| Thermal conductivity at 212°F (Btu/hr ft$^2$ °F) | 93 |
| Thermal expansion coefficient at 32–212°F $\times 10^{-6}$ (in./in. °F) | 9.4 |
| Izod impact (ft-lb) | |

Refer to Table A.34 for the mechanical and physical properties.

## Type 302 (S30200)

Type 302 and type 302B are nonmagnetic, extremely tough and ductile, and two of the most widely used of the chromium-nickel stainless and heat-resisting steels. They are hardenable by heat treating. The chemical composition is shown in Table A.31 and the mechanical and physical properties are shown in Table A.35.

## Type 303 (S303000)

This is a free-machining version of type 304 stainless steel for automatic machining. It is corrosion resistant to atmospheric exposures, sterilizing solutions, most organic and many inorganic chemicals, most dyes, nitric acid, and foods. The chemical composition is given in Table A.31, and the mechanical and physical properties are listed in Table A.36.

## Type 304 (S30400)

Type 304 stainless steels are the most widely used of all stainless steels. Although they have a wide range of corrosion resistance, they are not the most corrosion resistant of

**Table A.35** Mechanical and Physical Properties of Types 302 and 302B Stainless Steel

| Property | Type 302 | Type 302B |
|---|---|---|
| Modulus of elasticity $\times 10^6$(psi) | 28 | 28 |
| Tensile strength $\times 10^3$ (psi) | 90 | 95 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | 40 | 40 |
| Elongation in 2 in. (%) | 50 | 55 |
| Rockwell hardness | B-85 | B-85 |
| Density (lb/in.$^3$) | 0.29 | 0.29 |
| Specific gravity | 8.02 | 8.02 |
| Specific heat at 32–212°F (Btu/lb °F) | 0.12 | 0.12 |
| Thermal conductivity at 212°F (Btu/hr ft$^2$ °F) | 9.3 | 9.3 |
| Thermal expansion coefficient at 32–212°F $\times 10^{-6}$ (in./in. °F) | 9.6 | 9.6 |
| Izod impact (ft-lb) | | |

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**Table A.36** Mechanical and Physical Properties of Types 303 and 303Se Stainless Steel

| Property | Type 303 | Type 303Se |
|---|---|---|
| Modulus of elasticity $\times 10^6$(psi) | 28 | 28 |
| Tensile strength $\times 10^3$ (psi) | 90 | 90 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | 35 | 35 |
| Elongation in 2 in. (%) | 50 | 50 |
| Rockwell hardness | | |
| Density (lb/in.$^3$) | 0.29 | 0.29 |
| Specific gravity | 8.027 | 8.027 |
| Specific heat at 32–212°F (Btu/lb °F) | 9.3 | 9.3 |
| Thermal conductivity at 212°F (Btu/hr ft$^2$ °F) | | |
| Thermal expansion coefficient at 32–212°F $\times 10^{-6}$ (in./in. °F) | | |
| Izod impact (ft-lb) | 120 | |

the austenitic stainlesses. The chemical composition of various 304 alloys are shown in Table A.31.

Type 304 stainless steel is subject to intergranular corrosion as a result of carbide precipitation. Welding can cause this phenomenon, but competent welders using good welding techniques can control the problem. Depending on the particular corrodent being handled, the effect of carbide precipitation may or may not present a problem. If the corrodent will attack through intergranular corrosion, another alloy should be used.

If the carbon content of the alloy is not allowed to exceed 0.030%, carbide precipitation can be controlled. Type 304L is such an alloy. This alloy can be used for welded sections with no danger of carbide precipitation.

Type 304N has nitrogen added to the alloy, which improves its resistance to pitting and crevice corrosion.

Types 304 and 304L stainless steel exhibit good overall corrosion resistance. They are used extensively in the handling of nitric acid. Refer to Table A.37 for the compatibility of the alloys with selected corrodents and to Table A.38 for the mechanical and physical properties.

### Type 305 (S30500)

Type 305 stainless steel is used extensively for cold heading, severe deep drawing, and spinning operations. The chemical composition is shown in Table A.31. Type 305 stainless steel has the equivalent corrosion resistance of type 304 stainless steel. Refer to Table A.39 for the mechanical and physical properties.

**Table A.37** Compatibility of Types 304, 304L, and 347 Stainless Steel with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetaldehyde | 200 | 93 | Acetic acid, glacial | 210 | 99 |
| Acetamide | 100 | 38 | Acetic anhydride | 220 | 104 |
| Acetic acid 10% | 200 | 93 | Acetone | 190 | 88 |
| Acetic acid 50% | 170 | 77 | Acetyl chloride | 100 | 38 |
| Acetic acid 80% | 170 | 77 | Acrylic acid | 130 | 54 |

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**Table A.37** Compatibility of Types 304, 304L, and 347 Stainless Steel with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acrylonitrile | 210 | 99 | Bromine gas, moist | x | x |
| Adipic acid | 210 | 99 | Bromine liquid | x | x |
| Allyl alcohol | 220 | 104 | Butadiene | 180 | 82 |
| Allyl chloride | 120 | 49 | Butyl acetate | 80 | 27 |
| Alum | x | x | Butyl alcohol | 200 | 93 |
| Aluminum acetate | 210 | 99 | Butyl phthalate | 210 | 99 |
| Aluminum chloride, aqueous | x | x | Butyric acid | 180 | 82 |
| Aluminum chloride, dry | 150 | 66 | Calcium bisulfite[d] | 300 | 149 |
| Aluminum fluoride | x | x | Calcium carbonate | 210 | 99 |
| Aluminum hydroxide | 80 | 27 | Calcium chlorate 10% | 210 | 99 |
| Aluminum nitrate | 80 | 27 | Calcium chloride[b,c] | 80 | 27 |
| Aluminum sulfate[b] | 210 | 99 | Calcium hydroxide 10% | 210 | 99 |
| Ammonia gas | 90 | 32 | Calcium hydroxide, sat. | 200 | 93 |
| Ammonium carbonate | 200 | 93 | Calcium hypochlorite | x | x |
| Ammonium chloride 10% | 230 | 110 | Calcium nitrate | 90 | 32 |
| Ammonium chloride 50% | x | x | Calcium oxide | 90 | 32 |
| Ammonium chloride, sat. | x | x | Calcium sulfate | 210 | 99 |
| Ammonium fluoride 10% | x | x | Caprylic acid[a] | 210 | 99 |
| Ammonium fluoride 25% | x | x | Carbon bisulfide | 210 | 99 |
| Ammonium hydroxide 25% | 230 | 110 | Carbon dioxide, dry | 210 | 99 |
| Ammonium hydroxide, sat. | 210 | 99 | Carbon dioxide, wet | 200 | 93 |
| Ammonium nitrate[c] | 210 | 99 | Carbon disulfide | 210 | 99 |
| Ammonium persulfate | x | x | Carbon monoxide | 570 | 299 |
| Ammonium phosphate 40% | 130 | 54 | Carbon tetrachloride | 210 | 99 |
| Ammonium sulfate 10–40% | x | x | Carbonic acid | 210 | 99 |
| Ammonium sulfide | 210 | 99 | Cellosolve | 210 | 99 |
| Ammonium sulfite | 210 | 99 | Chloracetic acid, 50% water | x | x |
| Amyl acetate | 300 | 149 | Chloracetic acid | x | x |
| Amyl alcohol | 80 | 27 | Chlorine gas, dry | x | x |
| Amyl chloride | 150 | 66 | Chlorine gas, wet | x | x |
| Aniline | 500 | 260 | Chlorine, liquid[b] | 110 | 43 |
| Antimony trichloride | x | x | Chlorobenzene | 210 | 99 |
| Aqua regia 3:1 | x | x | Chloroform[c] | 210 | 99 |
| Barium carbonate | 80 | 27 | Chlorosulfonic acid | x | x |
| Barium chloride | x | x | Chromic acid 10% | 200 | 93 |
| Barium hydroxide | 230 | 110 | Chromic acid 50% | 90 | 32 |
| Barium sulfate | 210 | 99 | Chromyl chloride | 210 | 99 |
| Barium sulfide | 210 | 99 | Citric acid 15% | 210 | 99 |
| Benzaldehyde | 210 | 99 | Citric acid, concentrated | 80 | 27 |
| Benzene | 230 | 110 | Copper acetate | 210 | 99 |
| Benzene sulfonic acid 10% | 210 | 99 | Copper carbonate 10% | 80 | 27 |
| Benzoic acid | 400 | 204 | Copper chloride | x | x |
| Benzyl alcohol | 90 | 32 | Copper cyanide | 210 | 99 |
| Benzyl chloride | 210 | 99 | Copper sulfate[d] | 210 | 99 |
| Borax | 150 | 66 | Cresol | 160 | 71 |
| Boric acid[b] | 400 | 204 | Cupric chloride 5% | x | x |
| Bromine gas, dry | x | x | Cupric chloride 50% | x | x |

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**Table A.37** Compatibility of Types 304, 304L, and 347 Stainless Steel with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Cyclohexane | 100 | 38 | Nitric acid, anhydrous | 80 | 27 |
| Cyclohexanol | 80 | 27 | Nitrous acid, concentrated | 80 | 27 |
| Dichloroethane (ethylene dichloride) | 210 | 99 | Oleum | 100 | 38 |
| Ethylene glycol | 210 | 99 | Perchloric acid 10% | x | x |
| Ferric chloride | x | x | Perchloric acid 70% | x | x |
| Ferric chloride 50% in water | x | x | Phenol[b] | 560 | 293 |
| Ferric nitrate 10–50% | 210 | 99 | Phosphoric acid 50-80%[d] | 120 | 49 |
| Ferrous chloride | x | x | Picric acid[b] | 300 | 149 |
| Fluorine gas, dry | 470 | 243 | Potassium bromide 30% | 210 | 99 |
| Fluorine gas, moist | x | x | Salicylic acid | 210 | 99 |
| Hydrobromic acid, dilute | x | x | Silver bromide 10% | x | x |
| Hydrobromic acid 20% | x | x | Sodium carbonate 30% | 210 | 99 |
| Hydrobromic acid 50% | x | x | Sodium chloride to 30%[b] | 210 | 99 |
| Hydrochloric acid 20% | x | x | Sodium hydroxide 10% | 210 | 99 |
| Hydrochloric acid 38% | x | x | Sodium hydroxide 50% | 210 | 99 |
| Hydrocyanic acid 10% | 210 | 99 | Sodium hydroxide, concentrated | 90 | 32 |
| Hydrofluoric acid 30% | x | x | Sodium hypochlorite 20% | x | x |
| Hydrofluoric acid 70% | x | x | Sodium hypochlorite, concentrated | x | x |
| Hydrofluoric acid 100% | x | x | Sodium sulfide to 50%[b] | 210 | 99 |
| Hypochlorous acid | x | x | Stannic chloride | x | x |
| Iodine solution 10% | x | x | Stannous chloride | x | x |
| Ketones, general | 200 | 93 | Sulfuric acid 10% | x | x |
| Lactic acid 25%[b,d] | 120 | 49 | Sulfuric acid 50% | x | x |
| Lactic acid, concentrated[b,d] | 80 | 27 | Sulfuric acid 70% | x | x |
| Magnesium chloride | x | x | Sulfuric acid 90%[d] | 80 | 27 |
| Malic acid 50% | 120 | 49 | Sulfuric acid 98%[d] | 80 | 27 |
| Manganese chloride | x | x | Sulfuric acid 100%[d] | 80 | 27 |
| Methyl chloride[b] | 210 | 99 | Sulfuric acid, fuming | 90 | 32 |
| Methyl ethyl ketone | 200 | 93 | Sulfurous acid | x | x |
| Methyl isobutyl ketone | 200 | 93 | Thionyl chloride | x | x |
| Muriatic acid | x | x | Toluene | 210 | 99 |
| Nitric acid 5% | 210 | 99 | Trichloroacetic acid | x | x |
| Nitric acid 20% | 190 | 88 | White liquor | 100 | 38 |
| Nitric acid 70% | 170 | 77 | Zinc chloride | x | x |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. When compatible, the corrosion rate is <20 mpy.
[b]Subject to pitting.
[c]Subject to stress cracking.
[d]Subject to intergranular attack (type 304).
*Source:* PA Schweitzer. *Corrosion Resistance Tables*. 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

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**Table A.38** Mechanical and Physical Properties of Types 304 and 304L Stainless Steel

| | Type of alloy | |
|---|---|---|
| Property | 304 | 304L |
| Modulus of elasticity $\times 10^6$psi | 28.0 | 28.0 |
| Tensile strength $\times 10^3$ psi | 85 | 80 |
| Yield strength 0.2% offset $\times 10^3$ psi | 35 | 30 |
| Elongation in 2 in., % | 55 | 55 |
| Hardness, Rockwell | B-80 | B-80 |
| Density, lb/in.$^3$ | 0.29 | 0.29 |
| Specific gravity | 8.02 | 8.02 |
| Specific heat (32–212°F), Btu/lb °F | 0.12 | 0.12 |
| Thermal conductivity, Btu/h ft$^2$ °F at 212°F | 9.4 | 9.4 |
| Thermal expansion coefficient (32–212°F) $\times 10^{-6}$ in./in. °F | 9.6 | 9.6 |
| Izod impact, ft-lb | 110 | 110 |

**Table A.39** Mechanical and Physical Properties of Alloy Type 305 Stainless Steel

| Property | |
|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 28 |
| Tensile strength $\times 10^3$ (psi) | 85 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | 35 |
| Elongation in 2 in. (%) | 50 |
| Rockwell hardness | B-80 |
| Density (lb/in.$^3$) | 0.29 |
| Specific gravity | 8.027 |

**Table A.40** Mechanical and Physical Properties of Alloy Type 308 Stainless Steel

| Property | |
|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 28 |
| Tensile strength $\times 10^3$ (psi) | 115 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | 80 |
| Elongation in 2 in. (%) | 40 |
| Rockwell hardness | B-80 |

## Type 308 (S30800)

The chemical composition of type 308 stainless steel is given in table A.31. Note that this alloy has an increased chromium and nickel content over that of type 304 stainless steel. In the annealed condition, type 308 exhibits greater yield and tensile strength than annealed type 304. The corrosion resistance of type 308 is slightly better than that of 304 stainless. Refer to Table A.40 for the mechanical and physical properties.

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**Table A.41** Mechanical and Physical Properties of Types 309 and 309S Stainless Steel

| Property | Type 309 | Type 309S |
|---|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 29 | 29 |
| Tensile strength $\times 10^3$ (psi) | 90 | 90 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | 45 | 45 |
| Elongation in 2 in. (%) | 45 | 45 |
| Rockwell hardness | B-85 | B-85 |
| Density (lb/in.$^3$) | 0 | 0.29 |
| Specific gravity | 8.02 | 8.02 |
| Specific heat at 32–212°F (Btu/lb °F) | 0.12 | 0.12 |
| Thermal conductivity at 212°F (Btu/hr ft$^2$ °F) | 8 | 8 |
| Thermal expansion coefficient at 32–212°F $\times 10^{-6}$ (in./in. °F) | 8.3 | 8.3 |

## Type 309 (S30900)

Types 309 and 309S are superior heat-resisting stainless alloys. They are applicable for continuous exposure to 2000°F (1093°C) and for intermittent exposure to 1800°F (982°C). The chemical composition is shown in Table A.31.

Types 309 and 309S have slightly better corrosion resistance to the corrosive action of high-sulfur gases, provided they are oxidizing, but poor resistance to reducing gases like hydrogen sulfide. These alloys are excellent in resisting sulfite liquors, nitric acid, nitric-sulfuric acid mixtures, and acetic and lactic acids. Type 309S, with a maximum of 0.08% carbon, resists corrosion in welded parts. These alloys may be susceptible to chloride stress corrosion cracking. The mechanical and physical properties are shown in Table A.41.

## Type 310 (S31000)

This is an alloy for high temperatures. It is an improvement over types 309 and 309S. The 310 and 310S alloys have a maximum allowable temperature of 2100°F (1149°C) at continuous operation and 1900°F (1037°C) for intermittent service. Chemical compositions are shown in Table A.31.

These alloys have better general corrosion resistance than type 304 and type 309. They have excellent high-temperature oxidation resistance and good resistance to both carburizing and reducing environments. Chloride stress corrosion cracking may cause a problem under the right conditions. Type 310S, with 0.08% maximum carbon, offers improved resistance in welded components. Refer to Table A.42 for the mechanical and physical properties.

## Type 316 (S31600)

These chromium-nickel grades of stainless steel have molybdenum added in the range of 2–3%. The molybdenum substantially increases resistance to pitting and crevice corrosion in systems containing chlorides and improves overall resistance to most types of corrosion in chemical-reducing neutral solutions.

In general, these alloys are more corrosion resistant than type 304 stainless steels. With the exception of oxidizing acids, such as nitric, the type 316 alloys will provide satisfactory resistance to corrodents handled by type 304 with the added ability to handle some corrodents that type 304 alloy cannot handle.

Type 316L stainless steel is the low-carbon version of type 316 and offers the additional feature of preventing excessive intergranular precipitation of chromium carbides

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**Table A.42** Mechanical and Physical Properties of Type 310 and Type 310S Stainless Steel

| Property | Type 310 | Type 310S |
|---|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 29 | 29 |
| Tensile strength $\times 10^3$ (psi) | 95 | 95 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | 45 | 45 |
| Elongation in 2 in. (%) | 45 | 45 |
| Rockwell hardness | B-85 | B-85 |
| Density (lb/in.$^3$) | 0.28 | 0.28 |
| Specific gravity | 7.7 | 7.7 |
| Thermal conductivity (Btu/ft hr °F) | | |
| at 70°F | | 8.0 |
| at 1500°F | | 10.8 |

during welding and stress relieving. Table A.43 shows the compatibility of types 316 and 316L stainless steel with selected corrodents. The chemical composition of types 316 and 316L stainless steel are shown in Table A.31. The mechanical and physical properties of type 316 and 316L stainless steel are shown in Table A.44.

**Table A.43** Compatibility of Types 316, 316L Stainless Steels with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetaldehyde | 210 | 99 | Ammonium carbonate | 400 | 204 |
| Acetamide | 340 | 171 | Ammonium chloride 10% | 230 | 110 |
| Acetic acid 10% | 420 | 216 | Ammonium chloride 50% | x | x |
| Acetic acid 50% | 400 | 204 | Ammonium chloride, sat. | x | x |
| Acetic acid 80% | 230 | 110 | Ammonium fluoride 10% | 90 | 32 |
| Acetic acid, glacial | 400 | 204 | Ammonium fluoride 25% | x | x |
| Acetic anhydride | 380 | 193 | Ammonium hydroxide 25% | 230 | 110 |
| Acetone | 400 | 204 | Ammonium hydroxide, sat. | 210 | 99 |
| Acetyl chloride | 400 | 204 | Ammonium nitrate[b] | 300 | 149 |
| Acrylic acid | 120 | 49 | Ammonium persulfate 10% | 360 | 182 |
| Acrylonitrile | 210 | 99 | Ammonium phosphate 40% | 130 | 54 |
| Adipic acid | 210 | 99 | Ammonium sulfate 10–40% | 400 | 204 |
| Allyl alcohol | 400 | 204 | Ammonium sulfide | 390 | 171 |
| Allyl chloride | 100 | 38 | Ammonium sulfite | 210 | 99 |
| Alum | 200 | 93 | Amyl acetate | 300 | 149 |
| Aluminum acetate | 200 | 93 | Amyl alcohol | 400 | 204 |
| Aluminum chloride, aqueous | x | x | Amyl chloride | 150 | 56 |
| Aluminum chloride, dry | 150 | 66 | Aniline | 500 | 260 |
| Aluminum fluoride | 90 | 32 | Antimony trichloride | x | x |
| Aluminum hydroxide | 400 | 204 | Aqua regia 3:1 | x | x |
| Aluminum nitrate | 200 | 93 | Barium carbonate | 80 | 27 |
| Aluminum sulfate[b] | 210 | 99 | Barium chloride[c] | 210 | 99 |
| Ammonia gas | 90 | 32 | Barium hydroxide | 400 | 204 |
| Ammonium bifluoride 10% | 90 | 32 | Barium sulfate | 210 | 99 |

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**Table A.43** Compatibility of Types 316, 316L Stainless Steels with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Barium sulfide | 210 | 99 | Citric acid 15% | 200 | 93 |
| Benzaldehyde | 400 | 204 | Citric acid, concentrated[c] | 380 | 193 |
| Benzene | 400 | 204 | Copper acetate | 210 | 99 |
| Benzene sulfonic acid 10% | 210 | 99 | Copper carbonate 10% | 80 | 27 |
| Benzoic acid | 400 | 204 | Copper chloride | x | x |
| Benzyl alcohol | 400 | 204 | Copper cyanide | 210 | 99 |
| Benzyl chloride | 210 | 99 | Copper sulfate | 400 | 204 |
| Borax | 400 | 204 | Cresol | 100 | 38 |
| Boric acid | 400 | 204 | Cupric chloride 5% | x | x |
| Bromine gas, dry | x | x | Cupric chloride 50% | x | x |
| Bromine gas, moist | x | x | Cyclohexane | 400 | 204 |
| Bromine liquid | x | x | Cyclohexanol | 80 | 27 |
| Butadiene | 400 | 204 | Dichloroethane (ethylene dichloride) | 400 | 204 |
| Butyl acetate | 380 | 193 | Ethylene glycol | 340 | 171 |
| Butyl alcohol | 400 | 204 | Ferric chloride | x | x |
| *n*-Butylamine | 400 | 204 | Ferric chloride 50% in water | x | x |
| Butyl phthalate | 210 | 99 | Ferric nitrate 10–50% | 350 | 177 |
| Butyric acid | 400 | 204 | Ferrous chloride | x | x |
| Calcium bisulfide | 60 | 16 | Fluorine gas, dry | 420 | 216 |
| Calcium bisulfite | 350 | 177 | Fluorine gas, moist | x | x |
| Calcium carbonate | 205 | 96 | Hydrobromic acid, dilute | x | x |
| Calcium chloride[b] | 210 | 99 | Hydrobromic acid 20% | x | x |
| Calcium hydroxide 10% | 210 | 99 | Hydrobromic acid 50% | x | x |
| Calcium hypochlorite | 80 | 27 | Hydrochloric acid 20% | x | x |
| Calcium nitrate | 350 | 177 | Hydrochloric acid 38% | x | x |
| Calcium oxide | 80 | 27 | Hydrocyanic acid 10% | 210 | 99 |
| Calcium sulfate | 210 | 99 | Hydrofluoric acid 30% | x | x |
| Caprylic acid | 400 | 204 | Hydrofluoric acid 70% | x | x |
| Carbon bisulfide | 400 | 204 | Hydrofluoric acid 100% | 80 | 27 |
| Carbon dioxide, dry | 570 | 299 | Hypochlorous acid | x | x |
| Carbon dioxide, wet | 200 | 93 | Iodine solution 10% | x | x |
| Carbon disulfide | 400 | 204 | Ketones, general | 250 | 121 |
| Carbon monoxide | 570 | 299 | Lactic acid 25% | 210 | 99 |
| Carbon tetrachloride[b,c] | 400 | 204 | Lactic acid, concentrated[c,e] | 300 | 149 |
| Carbonic acid | 350 | 177 | Magnesium chloride 50%[b,c] | 210 | 99 |
| Cellosolve | 400 | 204 | Malic acid | 250 | 121 |
| Chloracetic acid, 50% water | x | x | Manganese chloride 30% | 210 | 99 |
| Chloracetic acid | x | x | Methyl chloride, dry | 350 | 177 |
| Chlorine gas, dry | 400 | 204 | Methyl ethyl ketone | 330 | 166 |
| Chlorine gas, wet | x | x | Methyl isobutyl ketone | 350 | 177 |
| Chlorine, liquid dry | 120 | 49 | Muriatic acid | x | x |
| Chlorobenzene, ELC only | 260 | 127 | Nitric acid 5%[e] | 210 | 99 |
| Chloroform[b] | 210 | 99 | Nitric acid 20%[e] | 270 | 132 |
| Chlorosulfonic acid | x | x | Nitric acid 70%[e] | 400 | 204 |
| Chromic acid 10%[d] | 400 | 204 | Nitric acid, anhydrous[e] | 110 | 43 |
| Chromic acid 50%[d] | 150 | 49 | Nitrous acid, concentrated | 80 | 27 |
| Chromyl chloride | 210 | 99 | Oleum | 80 | 27 |

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**Table A.43** Compatibility of Types 316, 316L Stainless Steels with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Perchloric acid 10% | x | x | Stannic chloride | x | x |
| Perchloric acid 70% | x | x | Stannous chloride 10% | 210 | 99 |
| Phenol | 570 | 299 | Sulfuric acid 10% | x | x |
| Phosphoric acid 50–80%[e] | 400 | 204 | Sulfuric acid 50% | x | x |
| Picric acid | 400 | 204 | Sulfuric acid 70% | x | x |
| Potassium bromide 30%[c] | 350 | 177 | Sulfuric acid 90%[c] | 80 | 27 |
| Salicylic acid | 350 | 177 | Sulfuric acid 98%[e] | 210 | 99 |
| Silver bromide 10% | x | x | Sulfuric acid 100%[c] | 210 | 99 |
| Sodium carbonate | 350 | 177 | Sulfuric acid, fuming | 210 | 99 |
| Sodium chloride to 30%[b] | 350 | 177 | Sulfurous acid[e] | 150 | 66 |
| Sodium hydroxide 10% | 350 | 177 | Thionyl chloride | x | x |
| Sodium hydroxide 50%[a] | 350 | 177 | Toulene | 350 | 177 |
| Sodium hydroxide, concentrated | 350 | 177 | Trichloroacetic acid | x | x |
| Sodium hypochlorite 20% | x | x | White liquor | 100 | 38 |
| Sodium hypochlorite, concentrated | x | x | Zinc chloride | 200 | 93 |
| Sodium sulfide to 50% | 190 | 88 | | | |

[a]The chemicals listed arc in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. When compatible, the corrosion rate is <20 mpy.
[b]Subject to stress cracking.
[c]Subject to pitting
[d]Subject to crevice attack.
[e]Subject to intergranular corrosion.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

**Table A.44** Mechanical and Physical Properties of Type 316 and 316L Stainless Steels

| Property | Alloy type 316 | 316L |
|---|---|---|
| Modulus of elasticity $\times 10^6$, psi | 28 | 28 |
| Tensile strength $\times 10^3$ psi | 75 | 70 |
| Yield strength 0.2% offset $\times 10^3$ psi | 30 | 25 |
| Elongation in 2 in., % | 50 | 50 |
| Hardness, Rockwell | B-80 | B-80 |
| Density, lb/in.$^3$ | 0.286 | 0.286 |
| Specific gravity | 7.95 | 7.95 |
| Specific heat (32–212°F Btu/lb °F) | 0.12 | 0.12 |
| Thermal conductivity. Btu/h ft$^2$ °F | | |
| at 70°F | 9.3 | 9.3 |
| at 1500°F | 12.4 | 12.4 |
| Thermal expansion coefficient (32–212°F) $\times 10^{-6}$ in./in. °F | 8.9 | 8.9 |
| Izod impact, ft-lb | 110 | 110 |

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Type 316H stainless steel has a higher carbon content for better high-temperature creep properties and to meet requirements of ASME Section VIII, Table UHA-21, Footnote 8. This alloy is used in temperatures over 1832°F (1000°C). It has the following chemical composition:

| | |
|---|---|
| Chromium | 16.0–18.0% |
| Nickel | 10.0–14.0% |
| Molybdenum | 2.0–3.0% |
| Carbon | 0.04–0.10% |
| Iron | Balance |

The corrosion resistance of type 316H stainless steel is the same as that of type 316 stainless except after long exposure to elevated temperatures, where intergranular corrosion may be more severe. It may also be susceptible to chloride stress cracking.

Type 316N is a high-nitrogen type 316 stainless steel. The chemical composition is shown in Table A.31. It has a higher strength than type 316 and greater ASME Section VIII allowables. Corrosion resistance is the same as for type 316, and it may be susceptible to chloride stress cracking.

Type 316LN stainless steel is a low-carbon, high-nitrogen type 316 stainless with the following composition:

| | |
|---|---|
| Chromium | 16.0–18.0% |
| Nickel | 10.0–15.0% |
| Molybdenum | 2.0–3.0% |
| Carbon | 0.035% |
| Nitrogen | 0.10–0.16% |
| Iron | Balance |

Type 316LN stainless has the same high-temperature strength and ASME allowables as type 316, but the weldability of type 316L. The corrosion resistance is the same as that of type 316 stainless, and there may be susceptibility to chloride stress corrosion cracking.

## Type 317 (S317000)

Type 317 stainless steel contains greater amounts of molybdenum, chromium, and nickel than type 316. The chemical composition is shown in Table A.31. As a result of the increased alloying elements, these alloys offer higher resistance to pitting and crevice corrosion than type 316 in various process environments encountered in the process industry. However, they may still be subject to chloride stress corrosion cracking.

Type 317L is a low-carbon version of the basic alloy that offers the additional advantage of preventing inter-granular precipitation of chromium carbide during welding and stress relieving. The chemical composition is shown in Table A.31.

Type 317L has improved pitting resistance over type 316L, but still may be subject to chloride stress corrosion cracking. The compatibility of type 317 and type 317L stainless steel with selected corrodents is shown in Table A.45. Refer to Table A.46 for the mechanical and physical properties of type 317 and 317L stainless steel.

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**Table A.45** Compatability of Types 317 and 317L Stainless Steel with Selected Corrodents[a]

| Chemical | Maximum temp. °F/°C | Chemical | Maximum temp. °F/°C |
|---|---|---|---|
| Acetaldehyde | 150/66 | Copper sulfate | 70/21 |
| Acetic acid 10% | 232/111 | Ferric chloride | 70/21 |
| Acetic acid 50% | 232/111 | Hydrochloric acid 20% | x |
| Acetic acid 80% | 240/116 | Hydrochloric acid 38% | x |
| Acetic acid, glacial | 240/116 | Hydrofluoric acid 30% | x |
| Acetic anhydride | 70/21 | Hydrofluoric acid 70% | x |
| Acetone | 70/21 | Hydrofluoric acid 100% | x |
| Aluminum chloride, aqueous | x | Iodine solution 10% | 70/21 |
| Aluminum chloride, dry | x | Lactic acid 25% | 70/21 |
| Aluminum sulfate 50–55% | 225/107 | Lactic acid, concentrated | 330/166 |
| Ammonium nitrate 66% | 70/21 | Magnesium chloride | 70/21 |
| Ammonium phospate | 80/27 | Nitric acid 5% | 70/21 |
| Ammonium sulfate 10–40% | 100/38 | Nitric acid 20% | 210/99 |
| Benzene | 100/38 | Nitric acid 70% | 210/99 |
| Boric acid | 210/99 | Phenol | 70/21 |
| Bromine gas, dry | x | Phosphoric acid 50–80% | 140/60 |
| Bromine gas, moist | x | Sodium carbonate | 210/99 |
| Bromine liquid | x | Sodium chloride | x |
| Butyl alcohol 5% | 195/91 | Sodium hydroxide 10% | 210/99 |
| Calcium chloride | 210/99 | Sodium hydroxide 50% | 70/21 |
| Calcium hypochlorite | 70/21 | Sodium hydrochlorite 20% | 70/21 |
| Carbon tetrachloride | 70/21 | Sodium hypochlorite, concentrated | 70/21 |
| Carbonic acid | 70/21 | Sodium sulfate to 50% | 210/99 |
| Chloracetic acid 78% | 122/50 | Sulfuric acid 10% | 120/49 |
| Chlorine, liquid | x | Sulfuric acid 50% | x |
| Chlorobenzene | 265/129 | Sulfuric acid 70% | x |
| Chromic acid 10% | x | Sulfuric acid 90% | x |
| Chromic acid 50% | x | Sulfuric acid 98% | x |
| Citric acid 15% | 210/99 | Sulfuric acid 100% | x |
| Citric acid, concentrated | 210/99 | Sulfurous acid | x |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatability is shown to the maximum allowable temperature for which data are available. Incompatability is shown by an x. When compatible the corrosion rate is < 20 mpy.

*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

Type 317LM stainless steel is a low-carbon, high-molybdenum form of type 317. It has better corrosion resistance than types 317L, 316L, and 304L and the best chloride resistance of the 300 series stainless steels. It may be susceptible to chloride stress corrosion cracking. The chemical composition of type 317LM is as follows:

| | |
|---|---|
| Chromium | 18.0–20.0% |
| Nickel | 13.0–17.0% |
| Molybdenum | 4.0–5.0% |
| Nitrogen | 0.1% max. |
| Carbon | 0.03% max. |
| Nickel | Balance |

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**Table A.46** Mechanical and Physical Properties of Type 317 and 317L Stainless Steels

| | Alloy type | |
|---|---|---|
| Property | 317 | 317L |
| Modulus of elasticity $\times 10^6$, psi | 28.0 | 28.0 |
| Tensile strength $\times 10^3$, psi | 75 | 75 |
| Yield strength 0.2% offset $\times 10^3$, psi | 30 | 30 |
| Elongation in 2 in., % | 35 | 35 |
| Hardness, Rockwell | B-85 | B-85 |
| Density, lb/in.$^3$ | 0.286 | 0.286 |
| Specific gravity | | |
| Specific heat (32-212°F) Btu/lb°F | 0.12 | 0.12 |
| Thermal conductivity, Btu/h ft$^2$ °F | | |
| at 70°F | 9.3 | 9.3 |
| at 1500°F | 12.4 | 12.4 |
| Thermal expansion coefficient (32–212°F) $\times 10^{-6}$, in./in. °F | 9.2 | 9.2 |
| Izod impact, ft-lb | 110 | 110 |

Type 317LMN is a low-carbon, high-molybdenum, high-nitrogen type 317 stainless steel with the following chemical composition:

| | |
|---|---|
| Chromium | 17.0–20.0% |
| Nickel | 13.0–17.0% |
| Molybdenum | 4.0–5.0% |
| Nitrogen | 0.1–0.2% |
| Carbon | 0.03% max. |
| Nickel | Balance |

The corrosion resistance of this alloy is the same as for type 317LM with the added advantage of preventing chromium carbide precipitation during welding or stress relieving.

## Type 321 (S32100)

By alloying austenitic stainless steels with a small amount of an element having a higher affinity for carbon than does chromium, carbon is restrained from diffusing to the grain boundaries, and any carbon that reaches the boundary reacts with the element instead of the chromium. These are known as stabilized grades. Type 321 is such an alloy which is stabilized by the addition of titanium. Its chemical composition is shown in Table A.31. The mechanical and physical properties are shown in Table A.47.

Type 321 stainless steel can be used wherever type 316 is suitable, with improved corrosion resistance, particularly in the presence of nitric acid. This alloy is particularly useful in high-temperature service in the carbide precipitation range and for parts heated intermittently between 800 and 1650°F (427–899°C). Even with the improved overall corrosion resistance it still may be susceptible to chloride stress corrosion cracking. Table A.48 provides the compatibility of type 321 with selected corrodents.

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**Table A.47** Mechanical and Physical Properties of Type 321 Stainless Steel

| Property | |
|---|---|
| Modulus of elasticity $\times 10^6$, psi | 29 |
| Tensile strength $\times 10^3$, psi | 75 |
| Yield strength 0.2% offset $\times 10^3$, psi | 30 |
| Elongation in 2 in., % | 35 |
| Hardness, Rockwell | B-85 |
| Density, lb/in.$^3$ | 0.286 |
| Specific gravity | 7.92 |
| Specific heat (32–212°F) Btu/lb°F | 0.12 |
| Thermal conductivity, Btu/h ft$^2$ °F | |
| at 70°F | 9.3 |
| at 1500°F | 12.8 |
| Thermal expansion coefficient (312–212°F) $\times 10^{-6}$, in./in. °F | 9.3 |
| Izod impact, ft-lb | 110 |

**Table A.48** Compatability of Type 321 Stainless Steel with Selected Components[a]

| Chemical | Maximum temp. °F/°C | Chemical | Maximum temp. °F/°C |
|---|---|---|---|
| Acetic acid 10% | x | Copper sulfate | 70/21 |
| Acetic acid 50% | x | Ferric chloride | x |
| Acetic acid 80% | x | Hydrochloric acid 20% | x |
| Acetic acid, glacial | x | Hydrochloric acid 38% | x |
| Acetic anhydride | 70/21 | Hydrofluoric acid 30% | x |
| Alum | x | Hydrofluoric acid 70% | x |
| Aluminum chloride, aqueous | x | Hydrofluoric acid 100% | x |
| Aluminum chloride, dry | x | Iodine solution 10% | x |
| Aluminum sulfate | 70/21 | Lactic acid 25% | 70/21 |
| Ammonium phosphate | 70/21 | Lactic acid, concentrated | 70/21 |
| Ammonium sulfate 10–40% | 70/21 | Magnesium chloride | x |
| Benzene | 100/38 | Nitric acid 5% | 70/21 |
| Boric acid | 210/99 | Nitric acid 20% | 210/99 |
| Bromine gas, dry | x | Nitric acid 70% | 210/99 |
| Bromine gas, moist | x | Phenol | x |
| Bromine liquid | x | Phosphoric acid 50–80% | 70/21 |
| Calcium chloride | x | Sodium carbonate | 70/21 |
| Calcium hypochlorite | x | Sodium chloride | x |
| Carbon tetrachloride | x | Sodium hydroxide 10% | 70/21 |
| Carbonic acid | 70/21 | Sodium hydroxide 50% | 70/21 |
| Chloracetic acid | x | Sodium hydrochlorite 20% | x |
| Chlorine, liquid | x | Sodium hypochlorite, concentrated | x |
| Chromic acid 10% | x | Sodium sulfate to 50% | 70/21 |
| Chromic acid 50% | x | Sulfuric acid 98% | x |
| Citric acid 15% | 70/21 | Sulfuric acid 100% | x |
| Citric acid, concentrated | 70/21 | Sulfurous acid | x |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatability is shown to the maximum allowable temperature for which data are available. Incompatability is shown by an x. When compatible the corrosion rate is < 20 mpy.

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Type 321H is a high-carbon type 321 stainless steel with better high-temperature creep properties, and it meets the requirements of ASME Section VIII, Table UHA.21, Footnote 8.

The corrosion resistance of type 321H is the same as the corrosion resistance of type 321, and it may be susceptible to chloride stress corrosion cracking. It has the following chemical composition:

| | |
|---|---|
| Chromium | 17.0–20.0% |
| Nickel | 9.0–13.0% |
| Carbon | 0.04–0.10% |
| Titanium | 4× carbon min., 0.60% max. |
| Iron | Balance |

Type 321H stainless steel is used in applications where temperatures exceed 1000°F/538°C.

## Type 329 (S32900)

Type 329 stainless steel is listed under the austenitic stainless steels but in actuality is the basic material of duplex stainless steels. It has the following chemical composition:

| | |
|---|---|
| Chromium | 26.5% |
| Nickel | 4.5% |
| Molybdenum | 1.5% |
| Carbon | 0.05% |
| Iron | Balance |

The general corrosion resistance of type 329 stainless steel is slightly above that of type 316 stainless steel in most media. In addition, since the nickel content is low, it has good resistance to chloride stress corrosion cracking.

The mechanical and physical properties are shown in Table A.49.

## Type 347 (S34700)

Type 347 stainless steel is a niobium-stabilized alloy. Its chemical composition can be found in Table A.31. Being stabilized, it will resist carbide precipitation during welding and intermittent heating to 800–1650°F (427–899°C), and it has good high-temperature scale resistance. Basically, this alloy is equivalent to type 304 stainless steel with the added protection against carbide precipitation. Type 304L offers this protection but is limited to a maximum operating temperature of 800°F (427°C), while type 347 can be operated to 1000°F (538°C).

In general, the corrosion resistance of type 347 is equivalent to that of type 304 stainless steel, and it may be susceptible to chloride stress corrosion cracking. Table A.36 shows the compatibility of type 347 stainless with selected corrodents. Table A.50 shows the mechanical and physical properties of type 347 stainless steel.

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**Table A.49** Mechanical and Physical Properties of Types 329 and 330 Stainless Steel

| Property | Type 329 | Type 330 |
|---|---|---|
| Modulus of elasticity $\times 10^6$, psi | | 28.5 |
| Tensile strength $\times 10^3$, psi | 105 | 80 |
| Yield strength 0.2% offset $\times 10^3$, psi | 80 | 38 |
| Elongation in 2 in., % | 25 | 40 |
| Hardness, Rockwell | Brinell 230 | Rockwell B-80 |
| Density, lb/inc$^3$ | 0.280 | 0.289 |
| Specific gravity | 7.7 | 8.01 |
| Specific heat (32–212°F) Btu/lb°F | | 8.0 |
| Thermal conductivity at 70°F (Btu/h ft$^2$ °F) | | |
| Thermal expansion coefficient at 32–212°F) $\times 10^{-6}$, (in./in. °F) | | |
| Izod impact, (ft-lb) | 90 | |

**Table A.50** Mechanical and Physical Properties of Type 347 Stainless Steel

| Property | |
|---|---|
| Modulus of elasticity $\times 10^6$, psi | 29.0 |
| Tensile strength $\times 10^3$, psi | 75 |
| Yield strength 0.2% offset $\times 10^3$, psi | 30 |
| Elongation in 2 in., % | 35 |
| Hardness, Rockwell | B-85 |
| Density, lb/inc$^3$ | 0.285 |
| Specific gravity | 7.92 |
| Specific heat (32–212°F) Btu/lb°F | |
| Thermal conductivity, Btu/h ft$^2$ °F | |
| at 70–212°F | 9.3 |
| at 1500°F | 12.8 |
| Thermal expansion coefficient (32–212°F) $\times 10^{-6}$, (in./in. °F) | 9.3 |
| Izod impact, (ft-lb) | 110 |

Type 347H stainless steel is a high-carbon type 347 to provide better high-temperature creep properties and to meet requirements of ASME Section VIII, Table UHA21, Footnote 8. The chemical composition is as follows:

| | |
|---|---|
| Chromium | 17–20% |
| Nickel | 9–13% |
| Carbon | 0.04–0.10% |
| Niobium + Tantalum | 8× carbon min., 1.0% max. |
| Iron | Balance |

Type 347H has the same corrosion resistance as type 347 and may be susceptible to chloride stress corrosion cracking. It is used in applications where temperatures can exceed 1000°F/538°C. Refer to Table A.51 for the mechanical and physical properties.

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**Table A.51** Mechanical and Physical Properties of Type 347H Stainless Steel

| Property | |
|---|---|
| Modulus of elasticity $\times 10^6$, psi | 29 |
| Tensile strength $\times 10^3$, psi | 75 |
| Yield strength 0.2% offset $\times 10^3$, psi | 30 |
| Elongation in 2 in., % | 35 |
| Hardness, Rockwell | B-90 |
| Density, lb/in.$^3$ | 0.285 |
| Specific gravity | 7.88 |
| Thermal conductivity, Btu/h ft$^2$ °F | |
| at 70–212°F | 9.3 |
| at 1500°F | 12.8 |

## Type 348 (S34800)

Type 348 stainless steel is the same as type 347 except that the tantalum content is restricted to a maximum of 0.10%. The chemical composition is as follows:

| | |
|---|---|
| Chromium | 17.0–20.0% |
| Nickel | 9.0–13.0% |
| Carbon | 0.08% max. |
| Niobium + Tantalum | 10× Carbon min. 1.0% max. (0.01% max. Tantalum) |
| Iron | Balance |

In general, the corrosion resistance is the same as that of type 347 stainless, and it may be subject to chloride stress corrosion cracking. This alloy is used in nuclear applications where tantalum is undesirable because of high neutron cross-section. Table A.52 shows the mechanical and physical properties of type 348 stainless steel.

**Table A.52** Mechanical and Physical Properties of Type 348 Stainless Steel

| Property | |
|---|---|
| Modulus of elasticity $\times 10^6$, psi | 29.0 |
| Tensile strength $\times 10^3$, psi | 95 |
| Yield strength 0.2% offset $\times 10^3$, psi | 40 |
| Elongation in 2 in., % | 45 |
| Hardness, Rockwell | B-85 |
| Density, lb/in.$^3$ | 0.285 |
| Specific gravity | 7.88 |
| Thermal conductivity at 212°F (Btu/h ft$^2$ °F) | 9.3 |

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Type 348H stainless steel is a high carbon version of type 348 designed to provide better high-temperature creep properties and to meet the requirements of ASME Section VIII, Table UHA-21, Footnote 8. It finds application in nuclear environments, at temperatures over 1000°F (538°C).

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# B

## BACTERIAL CORROSION

When certain bacteria produce substances such as sulfuric acid, ammonia, etc. the resulting corrosion is known as bacterial corrosion. See also "Biological Corrosion."

## BARRIER COATINGS

Barrier coatings are used to keep moisture and/or corrosive materials away from a metallic (usually steel) substrate. These protective barriers may vary in thickness from a thin paint film of only a few mils to a mastic coating applied about 1/4 to 1/2 inch thick, to acid-proof brick linings several inches thick. Barrier coatings are effective because they keep moisture, oxygen, and corrosives away from the metallic substrate. The lower the moisture vapor transmission of the polymer, the more effective it is as a vehicle for protective coatings. Protective coatings vary greatly in composition, cost, and performance. Refer to "Liquid Applied Linings" and "Paint Coatings."

## BASE

A compound of a metal or metal-like group, with hydrogen and oxygen in the proportion to form an OH radical, which ionizes in aqueous solution to yield hydroxyl ions. A base is formed when a metallic oxide reacts with water.

## BAUMÉ SCALE

For liquids heavier than water, a Baumé hydrometer is used to determine specific gravity and concentration by weight. It is most often used in relation to acids.

This hydrometer was originally based on the density of a 10% sodium chloride solution, which was given the value of 10°, and the density of pure water, which was given the value of 0°. The interval between these two values was divided into ten equal parts. Other reference points have been taken, and as a result there are about thirty-six different scales in use, many of which are incorrect. In general, a Baumé hydrometer should have inscribed on it the temperature at which it was calibrated and the temperature of the water used in relating the density to a specific gravity. The relationship between the specific gravity and the Baumé scale is as follows:

$$\text{specific gravity} = \frac{m}{m - \text{Baumé}}$$



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where:

$m = 145$ at 60°/60°F (15.56°C) for the American scale
$m = 144$ for the old scale used in Holland
$m = 146.3$ at 15°C for the Gedach scale
$m = 144.3$ at 15°C for the Rational scale generally used in Germany.

Tables B.1, B.2, and B.3 show the conversion from degrees Baumé based on specific gravity and weight percent of hydrochloric acid, nitric acid, and sulfuric acid, respectively. Conversion of degrees Baumé based on weight percent of other solutions may be found in similar tables.

## BEARING CORROSION

During operation the lubricating oil or grease contained within the bearing may be subject to chemical deterioration and produce a corrosive material. When this corrodent attacks one of the metals in the bearing alloy, the action is referred to as bearing corrosion.

## BIOLOGICAL CORROSION

Corrosive conditions can be developed by living organisms as a result of their influence on anodic and cathodic reactions. This metabolic activity can directly or indirectly cause deterioration of a metal by the corrosion process. This activity can

1. Produce a corrosive environment
2. Create electrolytic concentration cells on the metal surface
3. Alter the resistance of surface films
4. Have an influence on the rate of anodic or cathodic reaction
5. Alter the environment composition

Because this form of corrosion gives the appearance of pitting, it is first necessary to diagnose the presence of bacteria. Once established, prevention can be accomplished by the use of biocides or by the selection of a more resistant material of construction. For some species of bacteria a change in pH will provide control. Refer to "Microbial Corrosion."

See Refs. 1 and 2.

**Table B.1** Baumé Scale Conversion for Hydrochloric Acid

Based on Baumé hydrometers graduated using the following formula, which must be printed on the scale:

$$\text{Baumé} = 145 - \frac{145}{\text{sp. gr.}}$$

| Be° | Sp. gr. | % HCl | Be° | Sp. gr. | % HCl | Be° | Sp. gr. | % HCl |
|---|---|---|---|---|---|---|---|---|
| 1.00 | 1.0069 | 1.40 | 4.00 | 1.0284 | 5.69 | 5.50 | 1.0394 | 7.89 |
| 2.00 | 1.0140 | 2.82 | 5.00 | 1.0357 | 7.15 | 5.75 | 1.0413 | 8.26 |
| 3.00 | 1.0211 | 4.25 | 5.25 | 1.0375 | 7.52 | 6.00 | 1.0432 | 8.64 |

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**Table B.1** Baumé Scale Conversion for Hydrochloric Acid (Continued)

| Be° | Sp. gr. | % HCl | Be° | Sp. gr. | % HCl | Be° | Sp. gr. | % HCl |
|---|---|---|---|---|---|---|---|---|
| 6.25 | 1.0450 | 9.02 | 16.2 | 1.1256 | 24.90 | 20.4 | 1.1637 | 32.19 |
| 6.50 | 1.0488 | 9.78 | 16.3 | 1.1265 | 24.06 | 20.5 | 1.1647 | 32.38 |
| 7.00 | 1.0507 | 10.17 | 16.4 | 1.1274 | 25.23 | 20.6 | 1.1656 | 32.56 |
| 7.25 | 1.0526 | 10.55 | 16.5 | 1.1283 | 25.39 | 20.7 | 1.1666 | 32.76 |
| 7.50 | 1.0545 | 10.94 | 16.6 | 1.1292 | 25.56 | 20.8 | 1.1675 | 32.93 |
| 7.75 | 1.0564 | 11.32 | 16.7 | 1.1301 | 25.72 | 20.9 | 1.1684 | 33.12 |
| 8.00 | 1.0584 | 11.71 | 16.8 | 1.1310 | 25.89 | 21.0 | 1.1694 | 33.31 |
| 8.25 | 1.0603 | 12.09 | 16.9 | 1.1319 | 26.05 | 21.1 | 1.1703 | 33.50 |
| 8.50 | 1.0623 | 12.48 | 17.0 | 1.1326 | 26.22 | 21.2 | 1.1713 | 33.69 |
| 8.75 | 1.0624 | 12.87 | 17.1 | 1.1336 | 26.39 | 21.3 | 1.1722 | 33.88 |
| 9.00 | 1.0662 | 13.26 | 17.2 | 1.1345 | 26.56 | 21.4 | 1.1732 | 34.07 |
| 9.25 | 1.0681 | 13.65 | 17.3 | 1.1354 | 26.73 | 21.5 | 1.1741 | 34.26 |
| 9.50 | 1.0701 | 14.04 | 17.4 | 1.1363 | 26.90 | 21.6 | 1.1751 | 34.45 |
| 9.75 | 1.0721 | 14.43 | 17.5 | 1.1372 | 27.07 | 21.7 | 1.1760 | 34.64 |
| 10.00 | 1.0741 | 14.83 | 17.6 | 1.1381 | 27.24 | 21.8 | 1.1770 | 34.83 |
| 10.25 | 1.0761 | 15.22 | 17.7 | 1.1390 | 27.41 | 21.9 | 1.1779 | 35.02 |
| 10.50 | 1.0781 | 15.62 | 17.8 | 1.1399 | 27.58 | 22.0 | 1.1789 | 35.21 |
| 10.75 | 1.0801 | 16.01 | 17.9 | 1.1408 | 27.75 | 22.1 | 1.1798 | 35.40 |
| 11.00 | 1.0821 | 16.41 | 18.0 | 1.1417 | 27.92 | 22.2 | 1.1808 | 35.69 |
| 11.25 | 1.0841 | 16.81 | 18.1 | 1.1426 | 28.09 | 22.3 | 1.1817 | 35.78 |
| 11.50 | 1.0861 | 17.21 | 18.2 | 1.1435 | 28.26 | 22.4 | 1.1827 | 35.97 |
| 11.75 | 1.0881 | 17.61 | 18.3 | 1.1444 | 28.44 | 22.5 | 1.1836 | 36.16 |
| 12.00 | 1.0902 | 18.01 | 18.4 | 1.1453 | 28.61 | 22.6 | 1.1846 | 36.35 |
| 12.25 | 1.0922 | 18.41 | 18.5 | 1.1462 | 28.78 | 22.7 | 1.1856 | 36.54 |
| 12.50 | 1.0943 | 18.82 | 18.6 | 1.1471 | 28.95 | 22.8 | 1.1866 | 36.73 |
| 12.75 | 1.0964 | 19.22 | 18.7 | 1.1480 | 29.13 | 22.9 | 1.1875 | 36.93 |
| 13.00 | 1.0985 | 19.63 | 18.8 | 1.1489 | 29.30 | 23.0 | 1.1885 | 37.14 |
| 13.25 | 1.1006 | 20.04 | 18.9 | 1.1498 | 29.48 | 23.1 | 1.1895 | 37.36 |
| 13.50 | 1.1027 | 20.45 | 19.0 | 1.1508 | 29.65 | 23.2 | 1.1904 | 37.58 |
| 13.75 | 1.1048 | 20.86 | 19.1 | 1.1517 | 29.83 | 23.3 | 1.1914 | 37.80 |
| 14.00 | 1.1069 | 21.27 | 19.2 | 1.1526 | 30.00 | 23.4 | 1.1924 | 38.03 |
| 14.25 | 1.1090 | 21.68 | 19.3 | 1.1535 | 30.18 | 23.5 | 1.1934 | 38.26 |
| 14.50 | 1.1111 | 22.09 | 19.4 | 1.1544 | 30.35 | 23.6 | 1.1944 | 38.49 |
| 14.75 | 1.1132 | 22.50 | 19.5 | 1.1554 | 30.53 | 23.7 | 1.1953 | 38.72 |
| 15.00 | 1.1154 | 22.92 | 19.6 | 1.1563 | 30.71 | 23.8 | 1.1963 | 38.93 |
| 15.25 | 1.1176 | 23.33 | 19.7 | 1.1572 | 30.80 | 23.9 | 1.1973 | 39.18 |
| 15.50 | 1.1197 | 23.75 | 19.8 | 1.1581 | 31.08 | 24.0 | 1.1983 | 39.41 |
| 15.75 | 1.1219 | 24.16 | 19.9 | 1.1690 | 31.27 | 24.1 | 1.1993 | 34.64 |
| 16.00 | 1.1240 | 24.57 | 20.0 | 1.1600 | 31.45 | 24.2 | 1.2903 | 39.96 |
| 15.50 | 1.1197 | 23.75 | 20.1 | 1.1609 | 31.64 | 24.3 | 1.2013 | 40.09 |
| 15.75 | 1.1219 | 24.16 | 20.2 | 1.1619 | 31.82 | 24.4 | 1.2023 | 40.32 |
| 16.00 | 1.1240 | 24.57 | 20.3 | 1.1628 | 32.01 | 24.5 | 1.2033 | 40.55 |
| 16.1 | 1.1248 | 24.73 | | | | | | |

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**Table B.2** Baumé Scale Conversion for Nitric Acid

Based on Baumé hydrometers graduated using the following formula, which must always be printed on the scale:

$$\text{Baumé} = 145 - \frac{145}{\text{sp. gr.}}$$

| Be° | Sp. gr. | % $HNO_3$ | Be° | Sp. gr. | % $HNO_3$ | Be° | Sp. gr. | % $HNO_3$ |
|---|---|---|---|---|---|---|---|---|
| 10.00 | 1.0741 | 12.86 | 21.25 | 1.1718 | 28.02 | 32.50 | 1.2889 | 45.68 |
| 10.25 | 1.0761 | 13.18 | 21.50 | 1.1741 | 28.36 | 32.75 | 1.2918 | 46.14 |
| 10.50 | 1.0781 | 13.49 | 21.75 | 1.1765 | 28.72 | 33.00 | 1.2946 | 46.58 |
| 10.75 | 1.0801 | 13.81 | 22.00 | 1.1789 | 29.07 | 33.25 | 1.2975 | 47.04 |
| 11.00 | 1.0821 | 14.13 | 22.25 | 1.1813 | 29.43 | 33.50 | 1.3004 | 47.49 |
| 11.25 | 1.0841 | 14.44 | 22.50 | 1.1837 | 29.78 | 33.75 | 1.3034 | 47.95 |
| 11.50 | 1.0861 | 14.76 | 22.75 | 1.1861 | 30.14 | 34.00 | 1.3063 | 48.42 |
| 11.75 | 1.0881 | 15.07 | 23.00 | 1.1885 | 30.49 | 34.25 | 1.3093 | 48.90 |
| 12.00 | 1.0902 | 15.41 | 23.25 | 1.1910 | 30.86 | 34.50 | 1.3122 | 49.35 |
| 12.25 | 1.0922 | 15.72 | 23.50 | 1.1934 | 31.21 | 34.75 | 1.3152 | 49.63 |
| 12.50 | 1.0943 | 16.05 | 23.75 | 1.1959 | 31.58 | 35.00 | 1.3182 | 50.32 |
| 12.75 | 1.0964 | 16.39 | 24.00 | 1.1983 | 31.94 | 35.25 | 1.3212 | 50.81 |
| 13.00 | 1.0985 | 16.72 | 24.25 | 1.2008 | 32.31 | 35.50 | 1.3242 | 51.30 |
| 13.25 | 1.1006 | 17.05 | 24.50 | 1.2033 | 32.68 | 35.75 | 1.3273 | 51.60 |
| 13.50 | 1.1027 | 17.58 | 24.75 | 1.2058 | 33.05 | 36.00 | 1.3303 | 52.30 |
| 13.75 | 1.1048 | 17.71 | 25.00 | 1.2083 | 33.42 | 36.25 | 1.3334 | 52.81 |
| 14.00 | 1.1069 | 18.04 | 25.25 | 1.2109 | 33.60 | 36.50 | 1.3364 | 53.32 |
| 14.25 | 1.1090 | 18.37 | 25.50 | 1.2134 | 34.17 | 36.75 | 1.3395 | 53.84 |
| 14.50 | 1.1111 | 18.70 | 25.75 | 1.2160 | 34.56 | 37.00 | 1.3426 | 54.36 |
| 14.75 | 1.1132 | 19.02 | 26.00 | 1.2185 | 34.94 | 37.25 | 1.3457 | 54.89 |
| 15.00 | 1.1154 | 19.36 | 26.25 | 1.2211 | 35.53 | 37.50 | 1.3468 | 55.43 |
| 15.25 | 1.1176 | 19.70 | 26.50 | 1.2236 | 35.70 | 37.75 | 1.3520 | 55.97 |
| 15.50 | 1.1197 | 20.02 | 26.75 | 1.2262 | 35.09 | 38.00 | 1.3551 | 56.52 |
| 15.75 | 1.1219 | 20.36 | 27.00 | 1.2288 | 36.48 | 38.25 | 1.3583 | 57.08 |
| 16.00 | 1.1290 | 20.69 | 27.25 | 1.2314 | 36.87 | 38.50 | 1.3615 | 57.65 |
| 16.25 | 1.1262 | 21.03 | 27.50 | 1.2340 | 37.26 | 38.75 | 1.3647 | 58.23 |
| 16.50 | 1.1284 | 21.36 | 27.75 | 1.2367 | 37.67 | 39.00 | 1.3679 | 58.82 |
| 16.75 | 1.1306 | 21.70 | 28.00 | 1.2393 | 38.06 | 39.25 | 1.3712 | 59.43 |
| 17.00 | 1.1328 | 22.04 | 28.25 | 1.2420 | 38.46 | 39.50 | 1.3744 | 60.06 |
| 17.25 | 1.1350 | 22.63 | 28.50 | 1.2446 | 38.85 | 39.75 | 1.3777 | 60.71 |
| 17.50 | 1.1373 | 22.74 | 28.75 | 1.2473 | 39.25 | 40.00 | 1.3810 | 61.36 |
| 17.75 | 1.1395 | 23.08 | 29.00 | 1.2500 | 39.66 | 40.25 | 1.3843 | 62.07 |
| 18.00 | 1.1417 | 23.42 | 29.25 | 1.2527 | 40.06 | 40.50 | 1.3876 | 62.77 |
| 18.25 | 1.1440 | 23.77 | 29.50 | 1.2554 | 40.47 | 40.75 | 1.3909 | 63.48 |
| 18.50 | 1.1462 | 24.11 | 29.75 | 1.2582 | 40.89 | 41.00 | 1.3942 | 64.20 |
| 18.75 | 1.1485 | 24.47 | 30.00 | 1.2609 | 41.30 | 41.25 | 1.3976 | 64.93 |
| 19.00 | 1.1508 | 24.82 | 30.25 | 1.2637 | 41.72 | 41.50 | 1.4010 | 65.67 |
| 19.25 | 1.1531 | 25.18 | 30.50 | 1.2664 | 42.14 | 41.75 | 1.4044 | 66.42 |
| 19.50 | 1.1554 | 25.53 | 30.75 | 1.2692 | 42.58 | 42.00 | 1.4078 | 67.18 |
| 19.75 | 1.1577 | 25.88 | 31.00 | 1.2719 | 43.00 | 42.25 | 1.4112 | 67.95 |
| 20.00 | 1.1600 | 26.24 | 31.25 | 1.2747 | 43.44 | 42.50 | 1.4146 | 68.73 |
| 20.25 | 1.1624 | 26.61 | 31.50 | 1.2775 | 43.89 | 42.75 | 1.4181 | 69.52 |
| 20.50 | 1.1647 | 26.96 | 31.75 | 1.2804 | 44.34 | 43.00 | 1.4212 | 70.33 |
| 20.75 | 1.1671 | 27.33 | 32.00 | 1.2832 | 44.78 | 43.25 | 1.4251 | 71.15 |
| 21.00 | 1.1694 | 27.67 | 32.25 | 1.2861 | 45.24 | 43.50 | 1.4286 | 71.98 |

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**Table B.2** Baumé Scale Conversion for Nitric Acid (Continued)

| Be° | Sp. gr. | % $HNO_3$ | Be° | Sp. gr. | % $HNO_3$ | Be° | Sp. gr. | % $HNO_3$ |
|---|---|---|---|---|---|---|---|---|
| 43.75 | 1.4321 | 72.82 | 45.50 | 1.4573 | 79.03 | 47.25 | 1.4834 | 86.98 |
| 44.00 | 1.4356 | 73.67 | 45.75 | 1.4610 | 80.04 | 47.50 | 1.4872 | 88.32 |
| 44.25 | 1.4392 | 74.53 | 46.00 | 1.4646 | 81.08 | 47.75 | 1.4910 | 89.76 |
| 44.50 | 1.4428 | 75.40 | 46.25 | 1.4684 | 82.16 | 48.00 | 1.4948 | 91.35 |
| 44.75 | 1.4464 | 76.28 | 46.50 | 1.4721 | 83.33 | 48.25 | 1.4987 | 93.13 |
| 45.00 | 1.4500 | 77.17 | 46.75 | 1.4758 | 83.48 | 48.50 | 1.5026 | 95.11 |
| 45.25 | 1.4536 | 78.07 | 47.00 | 1.4796 | 85.70 | | | |

**Table B.3** Baumé Scale Conversion for Sulfuric Acid

Based on Baumé hydrometers graduated using the following formula, which must be printed on the scale:

$$\text{Baumé} = 145 - \frac{145}{\text{sp. gr.}}$$

| Be° | Sp. gr. | % $H_2SO_4$ | Be° | Sp. gr. | % $H_2SO_4$ | Be° | Sp. gr. | % $H_2SO_4$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 1.0000 | 0.00 | 24 | 1.1983 | 27.03 | 48 | 1.4948 | 59.32 |
| 1 | 1.0069 | 1.02 | 25 | 1.2083 | 28.28 | 49 | 1.5104 | 60.75 |
| 2 | 1.0140 | 2.08 | 26 | 1.2185 | 29.53 | 50 | 1.5263 | 62.18 |
| 3 | 1.0211 | 3.13 | 27 | 1.2268 | 30.79 | 51 | 1.5426 | 63.66 |
| 4 | 1.0284 | 4.21 | 28 | 1.2393 | 32.05 | 52 | 1.5591 | 65.13 |
| 5 | 1.0357 | 5.28 | 29 | 1.2500 | 33.33 | 53 | 1.5761 | 66.63 |
| 6 | 1.0432 | 6.37 | 30 | 1.2609 | 34.63 | 54 | 1.5934 | 68.13 |
| 7 | 1.0507 | 7.45 | 31 | 1.2719 | 35.93 | 55 | 1.6110 | 69.65 |
| 8 | 1.0584 | 8.55 | 32 | 1.2832 | 37.26 | 56 | 1.6292 | 71.17 |
| 9 | 1.0602 | 9.66 | 33 | 1.2946 | 38.58 | 57 | 1.6477 | 72.75 |
| 10 | 1.0741 | 10.77 | 34 | 1.3063 | 39.92 | 58 | 1.6667 | 74.36 |
| 11 | 1.0821 | 11.89 | 35 | 1.3182 | 41.27 | 59 | 1.6860 | 75.99 |
| 12 | 1.0902 | 13.01 | 36 | 1.3303 | 42.63 | 60 | 1.7059 | 77.67 |
| 13 | 1.0985 | 14.13 | 37 | 1.3426 | 43.99 | 61 | 1.7262 | 79.43 |
| 14 | 1.1069 | 15.25 | 38 | 1.3551 | 45.35 | 62 | 1.7470 | 81.30 |
| 15 | 1.1154 | 16.38 | 39 | 1.3679 | 46.72 | 63 | 1.7683 | 83.34 |
| 16 | 1.1240 | 17.53 | 40 | 1.3810 | 48.10 | 64 | 1.7901 | 85.66 |
| 17 | 1.1328 | 18.71 | 41 | 1.3942 | 49.47 | 64.25 | 1.7957 | 86.33 |
| 18 | 1.1417 | 19.89 | 42 | 1.4078 | 50.87 | 64.50 | 1.8012 | 87.04 |
| 19 | 1.1508 | 21.07 | 43 | 1.4216 | 52.26 | 64.75 | 1.8068 | 87.81 |
| 20 | 1.1600 | 22.25 | 44 | 1.4356 | 53.66 | 65 | 1.8125 | 88.65 |
| 21 | 1.1694 | 23.43 | 45 | 1.4500 | 55.07 | 65.25 | 1.8182 | 89.55 |
| 22 | 1.1789 | 24.61 | 46 | 1.4646 | 55.48 | 65.50 | 1.8239 | 90.60 |
| 23 | 1.1885 | 25.81 | 47 | 1.4796 | 57.90 | 65.75 | 1.8297 | 91.80 |
| | | | | | | 66 | 1.8345 | 93.81 |

## BISPHENOL POLYESTERS

See also "Polymers and Thermoset Polymers."

The bisphenol polyesters are superior in their corrosion-resistant properties to the isophthalic polyesters. They show good performance with moderate alkaline solutions and excellent resistance to the various categories of bleaching agents. The bisphenol poly-

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esters will break down under highly concentrated acids or alkalies. These resins can be used in the handling of the following materials:

### Acids (to 200°F/93°C)

| | | |
|---|---|---|
| acetic | fatty acids | stearic |
| benzoic | hydrochloric (10%) | sulfonic (50%) |
| boric | lactic | tannic |
| butyric | maleic | tartaric |
| chloroacetic (15%) | oleic | trichloroacetic (50%) |
| chromic (5%) | oxalic | rayon spin bath |
| citric | phosphoric (80%) | |

### Salts (solution to 200°F/93°C)

| | |
|---|---|
| all aluminum salts | copper salts |
| most ammonium salts | iron salts |
| calcium salts | zinc salts |
| most plating solutions | |

### Solvents (all solvents shown are for the isophthalic resins)

| | |
|---|---|
| sour crude oil | linseed oil |
| alcohols at ambient temperature | glycerine |

### Alkalies

| | |
|---|---|
| ammonium hydroxide 5% | potassium hydroxide 25% |
| calcium hydroxide 25% | sodium hydroxide 25% |
| calcium hypochlorite 20% | chlorite |
| chlorine dioxide 15% | hydrosulfite |

Solvents such as benzene, carbon disulfide, ether, methyl ethyl ketone, toluene, xylene, trichloroethylene, and trichloroethane will attack the resin. Sulfuric acid above 70% concentration, 73% sodium hydroxide, and 30% chromic acid will also attack the resin. Refer to Table B.4 for the compatibility of bisphenol A–fumarate polyester with selected corrodents and Table B.5 for hydrogenated bisphenol A–bisphenol A resin with selected corrodents. Refer to Ref. 3 for the compatibility of the bisphenol esters with a wider range of selected corrodents.

See also Refs. 4–6.

## BLISTER CRACKING

Blister cracking is a hydrogen-induced failure in steels containing internal flaws by non-metallic inclusions due to superficial corrosion of the steel by an acid hydrogen sulfide environment liberating atomic hydrogen, which diffuses into the metal and is released at the inclusion metal interface as molecular hydrogen under high pressure.

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**Table B.4** Compatibility of Bisphenol A–Fumarate Polyester with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | x | x | Benzene | x | x |
| Acetic acid 10% | 220 | 104 | Benzene slfuric acid 10% | 200 | 93 |
| Acetic acid 50% | 160 | 171 | Benzoic acid | 180 | 82 |
| Acetic acid 80% | 160 | 171 | Benzyl alcohol | x | x |
| Acetic acid, glacial | x | x | Benzyl chloride | x | x |
| Acetic amhydride | 110 | 43 | Borax | 220 | 104 |
| Acetone | x | x | Boric acid | 220 | 104 |
| Acetyl chloride | x | x | Bromine gas, dry | 90 | 32 |
| Acrylic acid | 100 | 38 | Bromine gas, moist | 100 | 38 |
| Acrylonitrile | x | x | Bromine liquid | x | x |
| Adipic acid | 220 | 104 | Butyl acetate | 80 | 27 |
| Allyl alcohol | x | x | Butyl alcohol | 80 | 27 |
| Allyl chloride | x | x | *n*-Butylamine | x | x |
| Alum | 220 | 104 | Butyric acid | 220 | 93 |
| Aluminum chloride. aqueous | 200 | 93 | Calcium bisulfite | 180 | 82 |
| Aluminum fluoride 10% | 90 | 32 | Calcium carbonate | 210 | 99 |
| Aluminum hydroxide | 160 | 71 | Calcium chlorate | 200 | 93 |
| Aluminum nitrate | 200 | 93 | Calcium chloride | 220 | 104 |
| Aluminum sulfate | 200 | 93 | Calcium hydroxide 10% | 180 | 82 |
| Ammonia gas | 200 | 93 | Calcium hydroxide sat. | 160 | 71 |
| Ammonium carbonate | 90 | 32 | Calcium hypochlorite 10% | 80 | 27 |
| Ammonium chloride 10% | 200 | 93 | Calcium nitrate | 220 | 104 |
| Ammonium chloride 50% | 220 | 104 | Calcium sulfate | 220 | 104 |
| Ammonium chloride sat. | 220 | 104 | Caprylic acid | 160 | 71 |
| Ammonium fluoride 10% | 180 | 82 | Carbon bisulfide | x | x |
| Ammonium fluoride 25% | 120 | 49 | Carbon dioxide, dry | 350 | 177 |
| Ammonium hydroxide 25% | 100 | 38 | Carbon dioxide, wet | 210 | 99 |
| Ammonium hydroxide 20% | 140 | 60 | Carbon disulfide | x | x |
| Ammonium nitrate | 220 | 104 | Carbon monoxide | 350 | 177 |
| Ammonium persulfate | 180 | 82 | Carbon tetrachloride | 110 | 43 |
| Ammonium phosphate | 80 | 27 | Carbonic acid | 90 | 32 |
| Ammonium sulfate 10–40% | 220 | 104 | Cellosolve | 140 | 60 |
| Ammonium sulfide | 110 | 43 | Chloracetic acid, 50% water | 140 | 60 |
| Ammonium sulfite | 80 | 27 | Chloracetic acid to 25% | 80 | 27 |
| Amyl acetate | 80 | 27 | Chlorine gas dry | 200 | 93 |
| Amyl alcohol | 200 | 93 | Chlorine gas wet | 200 | 93 |
| Amyl chloride | x | x | Chlorine liquid | x | x |
| Aniline | x | x | Chlorobenzene | x | x |
| Antimony trichloride | 220 | 104 | Chloroform | x | x |
| Aqua regia 3:1 | x | x | Chlorosulfonic acid | x | x |
| Barium carbonate | 200 | 93 | Chromic acid 10% | x | x |
| Barium chloride | 220 | 104 | Chronic acid 50% | x | x |
| Barium hydroxide | 150 | 66 | Chromyl chloride | 150 | 66 |
| Barium sulfate | 220 | 104 | Citric acid 15% | 220 | 104 |
| Barium sulfide | 140 | 60 | Citric acid, concentrated | 220 | 104 |
| Benzaldehyde | x | x | Copper acetate | 180 | 82 |

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**Table B.4** Compatibility of Bisphenol A–Fumarate Polyester with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Copper chloride | 220 | 104 | Nitric acid 20% | 100 | 38 |
| Copper cyanide | 220 | 101 | Nitric acid 70% | x | x |
| Copper sulfate | 220 | 104 | Nitric acid, anhydrous | x | x |
| Cresol | x | x | Oleum | x | x |
| Cyclohexane | x | x | Phenol | x | x |
| Dichloroacetic acid | 100 | 38 | Phosphoric acid 50–80% | 220 | 104 |
| Dichloroethane (ethylene dichloride) | x | x | Picric acid | 110 | 43 |
| Ethylene glycol | 220 | 104 | Potassium bromide 30% | 200 | 93 |
| Ferric chloride | 220 | 104 | Salicylic acid | 150 | 66 |
| Ferric chloride 50% in water | 220 | 104 | Sodium carbonate | 160 | 71 |
| Ferric nitrate 10–50% | 220 | 104 | Sodium chloride | 220 | 104 |
| Ferrous chloride | 220 | 104 | Sodium hydroxide 10% | 130 | 54 |
| Ferrous nitrate | 220 | 104 | Sodium hydroxide 50% | 220 | 104 |
| Fluorine gas, moist | | | Sodium hydroxide, concentrated | 200 | 93 |
| Hydrobromic acid, dilute | 220 | 104 | Sodium hypochlorite 20% | x | x |
| Hydrobromic acid 20% | 220 | 104 | Sodium sulfide to 50% | 210 | 99 |
| Hydrobromic acid 50% | 160 | 71 | Stannic chloride | 200 | 93 |
| Hydrochloric acid 20% | 190 | 88 | Stannous chloride | 220 | 104 |
| Hydrochloric acid 38% | x | x | Sulfuric acid 10% | 220 | 104 |
| Hydrocyanic acid 10% | 200 | 93 | Sulfuric acid 50% | 220 | 104 |
| Hydrofluoric acid 30% | 90 | 32 | Sulfuric acid 70% | 160 | 71 |
| Hypochlorous acid 20% | 90 | 32 | Sulfuric acid 90% | x | x |
| Iodine solution 10% | 200 | 93 | Sulfuric acid 98% | x | x |
| Lactic acid 25% | 210 | 99 | Sulfuric acid 100% | x | x |
| Lactic acid, concentrated | 220 | 104 | Sulfuric acid fuming | x | x |
| Magnesium chloride | 220 | 104 | Sulfurous acid | 110 | 43 |
| Malic acid | 160 | 71 | Thionyl chloride | x | x |
| Methyl ethyl ketone | x | x | Toluene | x | x |
| Methyl isobutyl ketone | x | x | Trichloroacetic acid 50% | 180 | 82 |
| Muriatic acid | 130 | 54 | White liquor | 180 | 82 |
| Nitric acid 5% | 160 | 71 | Zinc chloride | 250 | 121 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable.

*Source:* PA Schweitzer, *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

## BLISTERING

Early stages of corrosion can be recognized as blistering. Frequently blistering occurs without external evidence of rusting or corrosion. Blistering is mainly the result of volume expansion due to swelling, gas inclusion, gas formation, soluble impurities at the film/support interface from osmotic processes, or electroosmotic effects. Water and chemical gases pass through the film, dissolve ionic material either from the film or from the substrate material, causing an osmotic pressure greater than that of the external face of the coating. This establishes a solute concentration gradient, with water building up at these sites until the film eventually blisters.

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**Table B.5** Compatibility of Hydrogenated Bisphenol A—Bisphenol A Polyester with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetic acid 10% | 200 | 93 | Copper acetate | 210 | 99 |
| Acetic acid 50% | 160 | 71 | Copper chloride | 210 | 99 |
| Acetic anhydride | x | x | Copper cyanide | 210 | 99 |
| Acetone | x | x | Copper sulfate | 210 | 99 |
| Acetyl chloride | x | x | Cresol | x | x |
| Acrylonitrile | x | x | Cyclohexane | 210 | 99 |
| Aluminum acetate | | | Dichloroethane (ethylene dichloride) | x | x |
| Aluminum chloride, aqueous | 200 | 93 | Ferric chloride | 210 | 99 |
| Aluminum fluoride | x | x | Ferric chloride 50% in water | 200 | 93 |
| Aluminum sulfate | 200 | 93 | Ferric nitrate 10–50% | 200 | 93 |
| Ammonium chloride, sat. | 200 | 93 | Ferrous chloride | 210 | 99 |
| Ammonium nitrate | 200 | 93 | Ferrous nitrate | 210 | 99 |
| Ammonium persulfate | 200 | 93 | Hydrobromic acid 20% | 90 | 32 |
| Ammonium sulfide | 100 | 38 | Hydrobromic acid 50% | 90 | 32 |
| Amyl acetate | x | x | Hydrochloric acid 20% | 180 | 82 |
| Amyl alcohol | 200 | 93 | Hydrochloric acid 38% | 190 | 88 |
| Amyl chloride | 90 | 32 | Hydrocyanic acid 10% | x | x |
| Aniline | x | x | Hydrofluoric acid 30% | x | x |
| Antimony trichloride | 80 | 27 | Hydrofluoric acid 70% | x | x |
| Aqua regia 3:1 | x | x | Hydrofluoric acid 100% | x | x |
| Barium carbonate | 180 | 82 | Hypochlorous acid 50% | 210 | 99 |
| Barium chloride | 200 | 93 | Lactic acid 25% | 210 | 99 |
| Benzaldehyde | x | x | Lactic acid, concentrated | 210 | 99 |
| Benzene | x | x | Magnesium chloride | 210 | 99 |
| Benzoic acid | 210 | 99 | Methyl ethyl ketone | x | x |
| Benzyl alcohol | x | x | Methyl isobutyl ketone | x | x |
| Benzyl chloride | x | x | Muriatic acid | 190 | 88 |
| Boric acid | 210 | 99 | Nitric acid 5% | 90 | 32 |
| Bromine liquid | x | x | Oleum | x | x |
| Butyl acetate | x | x | Perchloric acid 10% | x | x |
| *n*-Butylamine | x | x | Perchloric acid 70% | x | x |
| Butyric acid | x | x | Phenol | x | x |
| Calcium bisulfide | 120 | 49 | Phosphoric acid 50–80% | 210 | 99 |
| Calcium chlorate | 210 | 99 | Sodium carbonate 10% | 100 | 38 |
| Calcium chloride | 210 | 99 | Sodium chloride | 210 | 99 |
| Calcium hypochlorite 10% | 180 | 82 | Sodium hydroxide 50% | x | x |
| Carbon bisulfide | x | x | Sodium hydroxide 50% | x | x |
| Carbon disulfide | x | x | Sodium hydroxide, concentrated | x | x |
| Carbon tetrachloride | x | x | Sodium hypochlorite 10% | 160 | 71 |
| Chloracetic acid, 50% water | 90 | 32 | Sulfuric acid 10% | 210 | 99 |
| Chlorine gas, dry | 210 | 99 | Sulfuric acid 50% | 210 | 99 |
| Chlorine gas, wet | 210 | 99 | Sulfuric acid 70% | 90 | 32 |
| Chloroform | x | x | Sulfuric acid 90% | x | x |
| Chromic acid 50% | x | x | Sulfuric acid 98% | x | x |
| Citric acid 15% | 200 | 93 | Sulfuric acid 100% | x | x |
| Citric acid, concentrated | 210 | 99 | Sulfuric acid, fuming | x | x |

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**Table B.5** Compatibility of Hydrogenated Bisphenol A—Bisphenol A Polyester with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Sulfurous acid 25% | 210 | 99 | Trichloroacetic acid | 90 | 32 |
| Toluene | 90 | 32 | Zinc chloride | 200 | 93 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

Blistering is also an effect of hydrogen damage, particularly to low-strength alloys. This occurs when atomic hydrogen diffuses to internal defects and then precipitates as molecular hydrogen. See "Blister Cracking."

## BORON CARBIDE

Boron carbide is used as a high-strength reinforcing material for thermosetting resins. See "Thermoset Reinforcing Materials."

## BOROSILICATE GLASS

Of the many glass compositions available, the one most commonly used for corrosive applications is borosilicate glass. This particular composition has been selected because of its wide range of corrosion resistance, relatively high operating temperature, good heat resistance due to low thermal expansion, transparency to ultraviolet light, and ability to be prestressed.

The chemical stability of borosilicate glass is one of the most comprehensive of any known construction material. It is highly resistant to water, acids, salt solutions, organic substances, and even halogens like chlorine and bromine.

Only hydrofluoric acid, phosphoric acid with fluorides, or strong alkalies at temperatures above 102°F (49°C) can visibly affect the glass surface. Refer to Table B.6 for the compatibility of borosilicate glass with selected corrodents.

## BRASS

See "Copper-Zinc Alloys."

## BUTADIENE-STYRENE RUBBER (SBR, BUNA-S, GR-S)

During World War II a shortage of natural rubber was created when Japan occupied the Far Eastern nations from which natural rubber was obtained. Because of the great need for rubber, the U.S. government developed what was originally known as Government Rubber Styrene-Type because it was the most practical to put into rapid production on a wartime scale. It was later designated GR-S.

The rubber is produced by copolymerizing butadiene and styrene. As with natural rubber and the other synthetic elastomers, compounding with other ingredients will improve certain properties. Continued development since World War II has improved its properties considerably over what was initially produced by either Germany or the United States.

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**Table B.6** Compatibility of Borosilicate Glass with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | 450 | 232 | Benzyl alcohol | 200 | 93 |
| Acetamide | 270 | 132 | Benzyl chloride | 200 | 93 |
| Acetic acid 10% | 400 | 204 | Borax | 250 | 121 |
| Acetic acid 50% | 400 | 204 | Boric acid | 300 | 149 |
| Acetic acid 80% | 400 | 204 | Bromine gas, moist | 250 | 121 |
| Acetic acid, glacial | 400 | 204 | Bromine liquid | 90 | 32 |
| Acetic anhydride | 250 | 121 | Butadiene | 90 | 32 |
| Acetone | 250 | 121 | Butyl acetate | 250 | 121 |
| Adipic acid | 210 | 99 | Butyl alcohol | 200 | 93 |
| Allyl alcohol | 120 | 49 | Butyric acid | 200 | 93 |
| Allyl chloride | 250 | 121 | Calcium bisulfite | 250 | 121 |
| Alum | 250 | 121 | Calcium carbonate | 250 | 121 |
| Aluminum chloride, aqueous | 250 | 121 | Calcium chlorate | 200 | 93 |
| Aluminum chloride, dry | 180 | 82 | Calcium chloride | 200 | 93 |
| Aluminum fluoride | x | x | Calcium hydroxide 10% | 250 | 121 |
| Aluminum hydroxide | 250 | 121 | Calcium hydroxide, sat. | x | x |
| Aluminum nitrate | 100 | 38 | Calcium hypochlorite | 200 | 93 |
| Aluminum oxychloride | 190 | 88 | Calcium nitrate | 100 | 38 |
| Aluminum sulfate | 250 | 121 | Carbon bisulfide | 250 | 121 |
| Ammonium bifluoride | x | x | Carbon dioxide, dry | 160 | 71 |
| Ammonium carbonate | 250 | 121 | Carbon dioxide, wet | 160 | 71 |
| Ammonium chloride 10% | 250 | 121 | Carbon disulfide | 250 | 121 |
| Ammonium chloride 50% | 250 | 121 | Carbon monoxide | 450 | 232 |
| Ammonium chloride, sat. | 250 | 121 | Carbon tetrachloride | 200 | 93 |
| Ammonium fluoride 10% | x | x | Carbonic acid | 200 | 93 |
| Ammonium fluoride 25% | x | x | Cellosolve | 160 | 71 |
| Ammonium hydroxide 25% | 250 | 121 | Chloracetic acid, 50% water | 250 | 121 |
| Ammonium hydroxide, sat. | 250 | 121 | Chloracetic acid | 250 | 121 |
| Ammonium nitrate | 200 | 93 | Chlorine gas, dry | 450 | 232 |
| Ammonium persulfate | 200 | 93 | Chlorine gas, wet | 400 | 204 |
| Ammonium phosphate | 90 | 32 | Chlorine, liquid | 140 | 60 |
| Ammonium sulfate l0–40% | 200 | 93 | Chlorobenzene | 200 | 93 |
| Amyl acetate | 200 | 93 | Chloroform | 200 | 93 |
| Amyl alcohol | 250 | 121 | Chlorosulfonic acid | 200 | 93 |
| Amyl chloride | 250 | 121 | Chromic acid 10% | 200 | 93 |
| Aniline | 200 | 93 | Chromic acid 50% | 200 | 93 |
| Antimony trichloride | 250 | 121 | Citric acid 15% | 200 | 93 |
| Aqua regia 3:1 | 200 | 93 | Citric acid, concentrated | 200 | 93 |
| Barium carbonate | 250 | 121 | Copper chloride | 250 | 121 |
| Barium chloride | 250 | 121 | Copper sulfate | 200 | 93 |
| Barium hydroxide | 250 | 121 | Cresol | 200 | 93 |
| Barium sulfate | 250 | 121 | Cupric chloride 5% | 160 | 71 |
| Barium sulfide | 250 | 121 | Cupric chloride 50% | 160 | 71 |
| Benzaldehyde | 200 | 93 | Cyclohexane | 200 | 93 |
| Benzene | 200 | 93 | Cyclohexanol | | |
| Benzene sulfonic acid 10% | 200 | 93 | Dichloroacetic acid | 310 | 154 |
| Benzoic acid | 200 | 93 | Dichloroethane (ethylene dichloride) | 250 | 121 |

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**Table B.6** Compatibility of Borosilicate Glass with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Ethylene glycol | 210 | 99 | Oleum | 400 | 204 |
| Ferric chloride | 290 | 143 | Perchloric acid 10% | 200 | 93 |
| Ferric chloride 50% in water | 280 | 138 | Perchloric acid 70% | 200 | 93 |
| Ferric nitrate 10–50% | 180 | 82 | Phenol | 200 | 93 |
| Ferrous chloride | 200 | 93 | Phosphoric acid 50–80% | 300 | 149 |
| Fluorine gas, dry | 300 | 149 | Picric acid | 200 | 93 |
| Fluorine gas, moist | x | x | Potassium bromide 30% | 250 | 121 |
| Hydrobromic acid, dilute | 200 | 93 | Silver bromide 10% | | |
| Hydrobromic acid 20% | 200 | 93 | Sodium carbonate | 250 | 121 |
| Hydrobromic acid 50% | 200 | 93 | Sodium chloride | 250 | 121 |
| Hydrochloric acid 20% | 200 | 93 | Sodium hydroxide 10% | x | x |
| Hydrochloric acid 38% | 200 | 93 | Sodium hydroxide 50% | x | x |
| Hydrocyanic acid 10% | 200 | 93 | Sodium hydroxide, concentrated | x | x |
| Hydrofluoric acid 30% | x | x | Sodium hypochlorite 20% | 150 | 66 |
| Hydrofluoric acid 70% | x | x | Sodium hypochlorite, concentrated | 150 | 66 |
| Hydrofluoric acid 100% | x | x | Sodium sulfide to 50% | x | x |
| Hypochlorous acid | 190 | 88 | Stannic chloride | 210 | 99 |
| Iodine solution 10% | 200 | 93 | Stannous chloride | 210 | 99 |
| Ketones, general | 200 | 93 | Sulfuric acid 10% | 400 | 204 |
| Lactic acid 25% | 200 | 93 | Sulfuric acid 50% | 400 | 204 |
| Lactic acid, concentrated | 200 | 93 | Sulfuric acid 70% | 400 | 204 |
| Magnesium chloride | 250 | 121 | Sulfuric acid 90% | 400 | 204 |
| Malic acid | 160 | 72 | Sulfuric acid 98% | 400 | 204 |
| Methyl chloride | 200 | 93 | Sulfuric acid 100% | 400 | 204 |
| Methyl ethyl ketone | 200 | 93 | Sulfurous acid | 210 | 99 |
| Methyl isobutyl ketone | 200 | 93 | Thionyl chloride | 210 | 99 |
| Nitric acid 5% | 400 | 204 | Toluene | 250 | 121 |
| Nitric acid 20% | 400 | 204 | Trichloroacetic acid | 210 | 99 |
| Nitric acid 70% | 400 | 204 | White liquor | 210 | 99 |
| Nitric acid, anhydrous | 250 | 121 | Zinc chloride | 210 | 99 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable.

*Source:* PA Schweitzer. *Corrosion Resistance Tables*. 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

## Physical and Mechanical Properties

In general, Buna-S is very similar to natural rubber, although some of its physical and mechanical properties are inferior. It is lacking in tensile strength, elongation, resilience, hot tear, and hysteresis. These disadvantages are offset somewhat by its low cost, cleanliness, slightly better heat-aging properties, slightly better wear than natural rubber for passenger tires, and availability at a stable price. The electrical properties of SBR are generally good but are not outstanding in any one area.

Buna-S has a maximum operating temperature of 170°F (80°C), which is not exceptional. At reduced temperatures, below 0°F, Buna-S products are more flexible than those produced from natural rubber.

Butadiene-styrene rubber has poor flame resistance and will support combustion. Table B.7 lists the physical and mechanical properties of Buna-S.

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**Table B.7** Physical and Mechanical Properties of Butadiene-Styrene Rubber (SBR, Buna-S, GR-S)[a]

| | |
|---|---|
| Specific gravity | 0.94 |
| Refractive index | 1.53 |
| Specific heat, cal/g | 0.454 |
| Brittle point | –76°F (–60°C) |
| Insulation resistance, ohms/cm | $10^{15}$ |
| Dielectric constant at 50 Hz | 2.9 |
| Swelling, % by volume | |
| in kerosene at 77°F (25°C) | 100 |
| in benzene at 77°F (25°C) | 200 |
| in acetone at 77°F (25°C) | 30 |
| in mineral oil at 100°F (38°C) | 150 |
| Tear resistance, psi | 550 |
| Creep at 70°C | 14.6 |
| Tensile strength, psi | 1600–3700 |
| Elongation, % at break | 650 |
| Hardness, Shore A | 35–90 |
| Abrasion resistance | Excellent |
| Maximum temperature, continuous use | 175°F (80°C) |
| Resistance to compression set | Poor |
| Machining qualities | Can be ground |
| Resistance to sunlight | Deteriorates |
| Effect of aging | Little effect |
| Resistance to heat | Stiffens |

[a]These are representative values since they may be altered by compounding.

### Resistance to Sun, Weather, and Ozone

Butadiene-styrene rubber has poor weathering and aging properties. Sunlight will cause it to deteriorate. However, it does have better water resistance than natural rubber.

### Chemical Resistance

The chemical resistance of Buna-S is similar to that of natural rubber. It is resistant to water and exhibits fair to good resistance to dilute acids, alkalies, and alcohols. It is not resistant to oils, gasoline, hydrocarbons, or oxidizing agents.

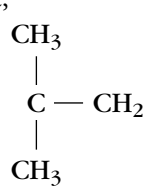
### Applications

The major use of Buna-S is in the manufacture of automobile tires, although Buna-S materials are also used to manufacture conveyor belts, hose, gaskets, and seals against air, moisture, sound, and dirt.

See Ref. 7.

## BUTYL RUBBER (IIR) AND CHLOROBUTYL RUBBER (CIIR)

Butyl rubber contains isobutylene,



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as its parent material, with small proportions of butadiene or isoprene added. Commercial butyl rubber may contain 5% butadiene as a copolymer. It is a general-purpose synthetic rubber whose outstanding physical properties are low permeability to air (approximately one-fifth that of natural rubber) and high energy absorption.

Chlorobutyl rubber is chlorinated isobutylene-isoprene. It has the same general properties as butyl rubber but with slightly higher allowable operating temperatures.

## Physical and Mechanical Properties

The single outstanding physical property of butyl rubber is its impermeability. It does not permit gases like hydrogen or air to diffuse through it nearly as rapidly as ordinary rubber does, and it has excellent resistance to the aging action of air. These properties make butyl rubber valuable in the production of life jackets (inflatable type), life rafts, and inner tubes for tires.

At room temperature the resiliency of butyl rubber is poor, but as the temperature increases the resiliency increases. At elevated temperatures butyl rubber exhibits good resiliency. Its abrasion resistance, tear resistance, tensile strength, and adhesion to fabrics and metals is good. Butyl rubber has a maximum continuous service temperature of 250–350°F (120–177°C), with good resistance to heat aging. Its electrical properties are generally good but not outstanding in any one category. The flame resistance of butyl rubber is poor.

Table B.8 lists the physical and mechanical properties of butyl rubber.

Chlorobutyl (CIIR) rubbers have a maximum operating temperature of 300°F (177°C) and can be operated as low as –30°F (–34°C). The other physical and mechanical properties are similar to those of butyl rubber.

## Resistance to Sun, Weather, and Ozone

Butyl rubber has excellent resistance to sun, weather, and ozone. Its weathering qualities are outstanding, as is its resistance to water absorption.

## Chemical Resistance

Butyl rubber is very nonpolar. It has exceptional resistance to dilute mineral acids, alkalies, phosphate ester oils, acetone, ethylene, ethylene glycol, and water. Resistance to concentrated acids, except nitric and sulfuric, is good. Unlike natural rubber, it is very

**Table B.8** Physical and Mechanical Properties of Butyl Rubber (IIR)[a]

| | |
|---|---|
| Specific gravity | 0.91 |
| Dielectric strength, V/mm | 25,000 |
| Tensile strength, psi | 500–3000 |
| Hardness, Shore A | 15–90 |
| Abrasion resistance | Excellent |
| Maximum temperature, continuous use | 250–35°F (120–177°C) |
| Machining qualities | Can be ground |
| Resistance to sunlight | Excellent |
| Effect of aging | Highly resistant |
| Resistance to heat | Stiffens slightly |

[a]These are representative values since they may he altered by compounding.

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resistant to swelling by vegetable and animal oils. It has poor resistance to petroleum oils, gasoline, and most solvents (except oxygenated solvents).

CIIR has the same general resistance as natural rubber but can be used at higher temperatures. Unlike butyl rubber, CIIR cannot be used with hydrochloric acid. Refer to Table B.9 for the compatibility of butyl rubber with selected corrodents and Table B.10 for the compatibility of chlorobutyl rubber with selected corrodents.

**Table B.9** Compatibility of Butyl Rubber with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetaldehyde | 80 | 27 | Benzaldehyde | 90 | 32 |
| Acetic acid 10% | 150 | 66 | Benzene | x | x |
| Acetic acid 50% | 110 | 43 | Benzene sulfonic acid 10% | 90 | 32 |
| Acetic acid 80% | 110 | 43 | Benzoic acid | 150 | 66 |
| Acetic acid, glacial | x | x | Benzyl alcohol | 190 | 88 |
| Acetic anhydride | x | x | Benzyl chloride | x | x |
| Acetone | 100 | 38 | Borax | 190 | 88 |
| Acrylonitrile | x | x | Boric acid | 150 | 66 |
| Adipic acid | x | x | Butyl acetate | x | x |
| Allyl alcohol | 190 | 88 | Butyl alcohol | 140 | 60 |
| Allyl chloride | x | x | Butyric acid | x | x |
| Alum | 200 | 93 | Calcium bisulfite | 120 | 49 |
| Aluminum acetate | 200 | 93 | Calcium carbonate | 150 | 66 |
| Aluminum chloride, aqueous | 200 | 93 | Calcium chlorate | 190 | 88 |
| Aluminum chloride, dry | 200 | 93 | Calcium chloride | 190 | 88 |
| Aluminum fluoride | 180 | 82 | Calcium hydroxide 10% | 190 | 88 |
| Aluminum hydroxide | 100 | 38 | Calcium hydroxide, sat. | 190 | 88 |
| Aluminum nitrate | 100 | 38 | Calcium hypochlorite | x | x |
| Aluminum sulfate | 200 | 93 | Calcium nitrate | 190 | 88 |
| Ammonium bifluoride | x | x | Calcium sulfate | 100 | 38 |
| Ammonium carbonate | 190 | 88 | Carbon dioxide, dry | 190 | 88 |
| Ammonium chloride 10% | 200 | 93 | Carbon dioxide, wet | 190 | 88 |
| Ammonium chloride 50% | 200 | 93 | Carbon disulfide | 190 | 88 |
| Ammonium chloride, sat. | 200 | 93 | Carbon monoxide | x | x |
| Ammonium fluoride 10% | 150 | 66 | Carbon tetrachloride | 90 | 32 |
| Ammonium fluoride 25% | 150 | 66 | Carbonic acid | 150 | 66 |
| Ammonium hydroxide 25% | 190 | 88 | Cellosolve | 150 | 66 |
| Ammonium hydroxide, sat. | 190 | 88 | Chloracetic acid, 50% water | 150 | 66 |
| Ammonium nitrate | 200 | 93 | Chloracetic acid | 100 | 38 |
| Ammonium persulfate | 190 | 88 | Chlorine gas, dry | x | x |
| Ammonium phosphate | 150 | 66 | Chlorine, liquid | x | x |
| Ammonium sulfate 10–40% | 150 | 66 | Chlorobenzene | x | x |
| Amyl acetate | x | x | Chloroform | x | x |
| Amyl alcohol | 150 | 66 | Chlorosulfonic acid | x | x |
| Aniline | 150 | 66 | Chromic acid 10% | x | x |
| Antimony trichloride | 150 | 66 | Chromic acid 50% | x | x |
| Barium chloride | 150 | 66 | Citric acid 15% | 190 | 88 |
| Barium hydroxide | 190 | 88 | Citric acid, concentrated | 190 | 88 |
| Barium sulfide | 190 | 88 | Copper chloride | 150 | 66 |

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**Table B.9** Compatibility of Butyl Rubber with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Copper sulfate | 190 | 88 | Nitric acid 5% | 200 | 93 |
| Cresol | x | x | Nitric acid 20% | 150 | 66 |
| Cupric chloride 5% | 150 | 66 | Nitric acid 70% | x | x |
| Cupric chloride 50% | 150 | 66 | Nitric acid, anhydrous | x | x |
| Cyclohexane | x | x | Nitrous acid, concentrated | 125 | 52 |
| Dichloroethane (ethylene dichloride) | x | x | Oleum | x | x |
| Ethylene glycol | 200 | 93 | Perchloric acid 10% | 150 | 66 |
| Ferric chloride | 175 | 79 | Phenol | 150 | 66 |
| Ferric chloride 50% in water | 160 | 71 | Phosphoric acid 50–80% | 150 | 66 |
| Ferric nitrate 10–50% | 190 | 88 | Salicylic acid | 80 | 27 |
| Ferrous chloride | 175 | 79 | Sodium chloride | 200 | 93 |
| Ferrous nitrate | 190 | 88 | Sodium hydroxide 10% | 150 | 66 |
| Fluorine gas, dry | x | x | Sodium hydroxide 50% | 150 | 66 |
| Hydrobromic acid, dilute | 125 | 52 | Sodium hydroxide, concentrated | 150 | 66 |
| Hydrobromic acid 20% | 125 | 52 | Sodium hypochlorite 20% | x | x |
| Hydrobromic acid 50% | 125 | 52 | Sodium hypochlorite, concentrated | x | x |
| Hydrochloric acid 20% | 125 | 52 | Sodium sulfide to 50% | 150 | 66 |
| Hydrochloric acid 38% | 125 | 52 | Stannic chloride | 150 | 66 |
| Hydrocyanic acid 10% | 140 | 60 | Stannous chloride | 150 | 66 |
| Hydrofluoric acid 30% | 150 | 66 | Sulfuric acid 10% | 200 | 93 |
| Hydrofluoric acid 70% | 150 | 66 | Sulfuric acid 50% | 150 | 66 |
| Hydrofluoric acid 100% | 150 | 66 | Sulfuric acid 70% | x | x |
| Hypochlorous acid | x | x | Sulfuric acid 90% | x | x |
| Lactic acid 25% | 125 | 52 | Sulfuric acid 98% | x | x |
| Lactic acid, concentrated | 125 | 52 | Sulfuric acid 100% | x | x |
| Magnesium chloride | 200 | 93 | Sulfuric acid, fuming | x | x |
| Malic acid | x | x | Sulfurous acid | 200 | 93 |
| Methyl chloride | 90 | 32 | Thionyl chloride | x | x |
| Methyl ethyl ketone | 100 | 38 | Toluene | x | x |
| Methyl isobutyl ketone | 80 | 27 | Trichloroacetic acid | x | x |
| Muriatic acid | x | x | Zinc chloride | 200 | 93 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

**Table B.10** Compatibility of Chlorobutyl Rubber with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetic acid 10% | 150 | 60 | Alum | 200 | 93 |
| Acetic acid 50% | 150 | 60 | Aluminum chloride, aqueous | 200 | 93 |
| Acetic acid 80% | 150 | 60 | Aluminum nitrate | 190 | 88 |
| Acetic acid, glacial | x | x | Aluminum sulfate | 200 | 93 |
| Acetic anhydride | x | x | Ammonium carbonate | 200 | 93 |
| Acetone | 100 | 38 | Ammonium chloride 10% | 200 | 93 |

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**Table B.10** Compatibility of Chlorobutyl Rubber with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Ammonium chloride 50% | 200 | 93 | Ferrous chloride | 175 | 79 |
| Ammonium chloride, sat. | 200 | 93 | Hydrobromic acid, dilute | 125 | 52 |
| Ammonium nitrate | 200 | 93 | Hydrobromic acid 20% | 125 | 52 |
| Ammonium phosphate | 150 | 66 | Hydrobromic acid 50% | 125 | 52 |
| Ammonium sulfate 10–40% | 150 | 66 | Hydrochloric acid 20% | x | x |
| Amyl alcohol | 150 | 66 | Hydrochloric acid 38% | x | x |
| Aniline | 150 | 66 | Hydrofluoric acid 70% | x | x |
| Antimony trichloride | 150 | 66 | Hydrofluoric acid 100% | x | x |
| Barium chloride | 150 | 66 | Lactic acid 25% | 125 | 52 |
| Benzoic acid | 150 | 66 | Lactic acid, concentrated | 125 | 52 |
| Boric acid | 150 | 66 | Magnesium chloride | 200 | 93 |
| Calcium chloride | 160 | 71 | Nitric acid 5% | 200 | 93 |
| Calcium nitrate | 160 | 71 | Nitric acid 20% | 150 | 66 |
| Calcium sulfate | 160 | 71 | Nitric acid 70% | x | x |
| Carbon monoxide | 100 | 38 | Nitric acid, anhydrous | x | x |
| Carbonic acid | 150 | 66 | Nitrous acid, concentrated | 125 | 52 |
| Chloracetic acid | 100 | 38 | Phenol | 150 | 66 |
| Chromic acid 10% | x | x | Phosphoric acid 50–80% | 150 | 66 |
| Chromic acid 50% | x | x | Sodium chloride | 200 | 93 |
| Citric acid 15% | 90 | 32 | Sodium hyroxide 10% | 150 | 66 |
| Copper chloride | 150 | 66 | Sodium sulfide to 50% | 150 | 66 |
| Copper cyanide | 160 | 71 | Sulfuric acid 10% | 200 | 93 |
| Copper sulfate | 160 | 71 | Sulfuric acid 70% | x | x |
| Cupric chloride 5% | 150 | 66 | Sulfuric acid 90% | x | x |
| Cupric chloride 50% | 150 | 66 | Sulfuric acid 98% | x | x |
| Ethylene glycol | 200 | 93 | Sulfuric acid 100% | x | x |
| Ferric chloride | 175 | 79 | Sulfuric acid, fuming | x | x |
| Ferric chloride 50% in water | 100 | 38 | Sulfurous acid | 200 | 93 |
| Ferric nitrate 10–50% | 160 | 71 | Zinc chloride | 200 | 93 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

## Applications

Because of its impermeability, butyl rubber finds many uses in the manufacture of inflatable items such as life jackets, lifeboats, balloons, and inner tubes. The excellent resistance it exhibits in the presence of water and steam makes it suitable for hoses and diaphragms. Applications are also found as flexible electrical insulation, shock and vibration absorbers, curing bags for tire vulcanization, and molding.

See Refs. 3 and 7.

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# C

## CADMIUM COATINGS

These coatings are produced almost exclusively by electrodeposition. A cadmium coating on steel does not provide as much protection to the steel as does a zinc coating, since the potential between cadmium and iron is not as great as that between zinc and iron. Therefore, it becomes important to minimize defects in the cadmium coating.

Unlike zinc, a cadmium coating will retain a bright metallic appearance. It is more resistant to attack by salt spray and atmospheric condensation. In aqueous solutions cadmium will resist attack by strong alkalies but will be corroded by dilute acids and aqueous ammonia.

Since cadmium salts are toxic, these coatings should not be allowed to come into contact with food products. This coating is commonly used on nuts and bolts.

See Refs. 1 and 2.

## CAPPED STEEL

See "Killed Carbon Steel."

## CARBIDE PRECIPITATION

Carbon is added to stainless steels as an alloying ingredient to increase strength. During melting and high-temperature working operations, such as welding, the carbon content in stainless steel is generally in solid solution. As the steel cools from a temperature of approximately 1600°F (872°C) there is a preference for the formation of a chromium carbide compound, which precipitates preferentially at grain boundaries.

The chromium carbides in themselves do not suffer from poor corrosion resistance. The problem lies in the fact that in the formation of these chromium carbides the chromium has been depleted from the surrounding matrix. This depletion can be to such an extent that the chromium content locally can be below 11%, which is considered the minimum value for stainless steel, leaving this area open to corrosion.

The problem of carbide precipitation can be alleviated by the addition of titanium or niobium (columbium) as an alloying ingredient. These elements tie up the carbon, preventing the precipitation of chromium carbide. Another approach is to reduce the carbon content in the alloy from the usual 0.08% to below 0.035%. This prevents the precipitation of harmful levels of chromium carbide precipitate. The latter approach results in stainless steels known as low carbon, carrying the suffix L after the grade, e.g., 304L, 316L.

See Ref. 3.



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## CARBON

Carbon has extremely good chemical resistance. It is produced from carbon particles bonded with materials that carbonize during subsequent heating. The operation is usually carried out below 2250°F (1230°C).

In an oxidizing atmosphere it may be used to 660°F (350°C), while in an inert or reducing environment it can be used to 5000°F (2760°C).

Table C.1 lists the compatibility of carbon in contact with selected corrodents. For a more complete listing see Ref. 4.

See also Ref. 5.

**Table C.1** Compatibility of Carbon with Selected Corrodents[a]

| | Max. temp. | |
|---|---|---|
| Chemical | °F | °C |
| Acetaldehyde | 340 | 171 |
| Acetamide | 340 | 171 |
| Acetic acid 10% | 340 | 171 |
| Acetic acid 50% | 340 | 171 |
| Acetic acid 80% | 340 | 171 |
| Acetic acid, glacial | 340 | 171 |
| Acetic anhydride | 340 | 171 |
| Acetone | 340 | 171 |
| Acetyl chloride | 340 | 171 |
| Acrylonitrile | 340 | 171 |
| Adipic acid | 340 | 171 |
| Allyl alcohol | 340 | 171 |
| Allyl chloride | 100 | 38 |
| Alum | 340 | 171 |
| Aluminum chloride, aqueous | 340 | 171 |
| Aluminum chloride, dry | 340 | 171 |
| Aluminum fluoride | 340 | 171 |
| Aluminum hydroxide | 340 | 171 |
| Aluminum nitrate | 340 | 171 |
| Ammonia gas | 340 | 171 |
| Ammonium bifluoride | 390 | 199 |
| Ammonium carbonate | 340 | 171 |
| Ammonium chloride 10% | 340 | 171 |
| Ammonium chloride 50% | 340 | 171 |
| Ammonium chloride, sat. | 340 | 171 |
| Ammonium fluoride 10% | 330 | 166 |
| Ammonium fluoride 25% | 340 | 171 |
| Ammonium hydroxide 25% | 200 | 93 |
| Ammonium hydroxide, sat. | 220 | 104 |
| Ammonium nitrate | 340 | 171 |
| Ammonium persulfate | 340 | 171 |
| Ammonium phosphate | 340 | 171 |
| Ammonium sulfate 10–40% | 340 | 171 |
| Ammonium sulfide | 340 | 171 |
| Amyl acetate | 340 | 171 |
| Amyl alcohol | 200 | 93 |

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**Table C.1** Compatibility of Carbon with Selected Corrodents[a] (Continued)

| Chemical | Max. temp. °F | °C |
|---|---|---|
| Amyl chloride | 210 | 99 |
| Aniline | 340 | 171 |
| Barium carbonate | 250 | 121 |
| Barium chloride | 250 | 121 |
| Barium hydroxide | 250 | 121 |
| Barium sulfate | 250 | 121 |
| Barium sulfide | 250 | 121 |
| Benzaldehyde | 340 | 171 |
| Benzene | 200 | 93 |
| Benzene sulfonic acid 10% | 340 | 171 |
| Benzoic acid | 350 | 177 |
| Borax | 250 | 121 |
| Boric acid | 210 | 99 |
| Bromine gas, dry | x | x |
| Bromine gas, moist | x | x |
| Bromine liquid | x | x |
| Butadiene | 340 | 171 |
| Butyl acetate | 340 | 171 |
| Butyl alcohol | 210 | 99 |
| *n*-Butylamine | 100 | 38 |
| Butyl phthalate | 90 | 32 |
| Butyric acid | 340 | 171 |
| Calcium bisulfide | 340 | 171 |
| Calcium bisulfite | 340 | 171 |
| Calcium carbonate | 340 | 171 |
| Calcium chlorate 10% | 140 | 60 |
| Calcium chloride | 340 | 171 |
| Calcium hydroxide 10% | 200 | 93 |
| Calcium hydroxide, sat. | 250 | 121 |
| Calcium hypochlorite | 170 | 77 |
| Calcium nitrate | 340 | 171 |
| Calcium oxide | 340 | 171 |
| Calcium sulfate | 340 | 171 |
| Caprylic acid | 340 | 171 |
| Carbon bisulfide | 340 | 171 |
| Carbon dioxide, dry | 340 | 171 |
| Carbon dioxide, wet | 340 | 171 |
| Carbon disulfide | 340 | 171 |
| Carbon monoxide | 340 | 171 |
| Carbon tetrachloride | 250 | 121 |
| Carbonic acid | 340 | 171 |
| Cellosolve | 200 | 93 |
| Chloracetic acid, 50% water | 340 | 171 |
| Chloracetic acid | 340 | 171 |
| Chlorine gas, dry | 180 | 82 |
| Chlorine gas, wet | 80 | 27 |
| Chlorobenzene | 340 | 171 |
| Chloroform | 340 | 171 |

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**Table C.1** Compatibility of Carbon with Selected Corrodents[a] (Continued)

| Chemical | Max. temp. °F | °C |
|---|---|---|
| Chlorosulfonic acid | 340 | 171 |
| Chromic acid 10% | x | x |
| Chromic acid 50% | x | x |
| Citric acid 15% | 340 | 171 |
| Citric acid, conc. | 340 | 171 |
| Copper carbonate | 340 | 171 |
| Copper chloride | 340 | 171 |
| Copper cyanide | 340 | 171 |
| Copper sulfate | 340 | 171 |
| Cresol | 400 | 238 |
| Cupric chloride 5% | 340 | 171 |
| Cupric chloride 50% | 340 | 171 |
| Cyclohexane | 340 | 171 |
| Ethylene glycol | 340 | 171 |
| Ferric chloride | 340 | 171 |
| Ferric chloride 50% in water | 340 | 171 |
| Ferric nitrate 10%–50% | 340 | 171 |
| Ferrous chloride | 340 | 171 |
| Ferrous nitrate | 340 | 171 |
| Fluorine gas, dry | x | x |
| Hydrobromic acid, dilute | 340 | 171 |
| Hydrobromic acid 20% | 340 | 171 |
| Hydrobromic acid 50% | 340 | 171 |
| Hydrochloric acid 20% | 340 | 171 |
| Hydrochloric acid 38% | 340 | 171 |
| Hydrocyanic acid 10% | 340 | 171 |
| Hydrofluoric acid 30% | 340 | 171 |
| Hydrofluoric acid 70% | x | x |
| Hydrofluoric acid 100% | x | x |
| Hypochlorous acid | 100 | 38 |
| Ketones, general | 340 | 171 |
| Lactic acid 25% | 340 | 171 |
| Lactic acid, concentrated | 340 | 171 |
| Magnesium chloride | 170 | 77 |
| Malic acid | 100 | 38 |
| Manganese chloride | 400 | 227 |
| Methyl chloride | 340 | 171 |
| Methyl ethyl ketone | 340 | 171 |
| Methyl isobutyl ketone | 340 | 171 |
| Muriatic acid | 340 | 171 |
| Nitric acid 5% | 180 | 82 |
| Nitric acid 20% | 140 | 60 |
| Nitric acid 70% | x | x |
| Nitric acid, anhydrous | x | x |
| Nitrous acid, concentrated | x | x |
| Perchloric acid 10% | 340 | 171 |
| Perchloric acid 70% | 340 | 171 |
| Phenol | 340 | 171 |

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**Table C.1** Compatibility of Carbon with Selected Corrodents[a] (Continued)

| Chemical | Max. temp. °F | °C |
|---|---|---|
| Phosphoric acid 50–80% | 200 | 93 |
| Picric acid | 100 | 38 |
| Potassium bromide 30% | 340 | 171 |
| Salicylic acid | 340 | 171 |
| Sodium bromide | 340 | 171 |
| Sodium carbonate | 340 | 171 |
| Sodium chloride | 340 | 171 |
| Sodium hydroxide 10% | 240 | 116 |
| Sodium hydroxide 50% | 270 | 132 |
| Sodium hydroxide, concentrated | 260 | 127 |
| Sodium hypochlorite 20% | x | x |
| Sodium hypochlorite, concentrated | x | x |
| Sodium sulfide to 50% | 120 | 49 |
| Stannic chloride | 340 | 171 |
| Sulfuric acid 10% | 340 | 171 |
| Sulfuric acid 50% | 340 | 171 |
| Sulfuric acid 70% | 340 | 171 |
| Sulfuric acid 90% | 180 | 82 |
| Sulfuric acid 98% | x | x |
| Sulfuric acid 100% | x | x |
| Sulfurous acid | 340 | 171 |
| Toluene | 340 | 171 |
| Trichloroacetic acid | 340 | 171 |
| White liquor | 100 | 38 |
| Zinc chloride | 340 | 171 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x.
*Source:* PA Schweitzer. *Corrosion Resistance Table*s. 4th ed. New York: Marcel Dekker, 1995.

## CARBON FIBERS

Carbon fibers are used to reinforce FRP laminates and to impart conductivity. See "Thermoset Reinforcing Materials."

## CARBON FIBER REINFORCED THERMOPLASTICS

See also "Zymaxx." There are many composite thermoplastic materials having carbon filler for reinforcement. Some typical examples of such thermoplastics are given in the table.

| | |
|---|---|
| Nylon 6 | Acetal |
| Nylon 6/6 | PBT |
| Nylon 6/10 | PPS |
| Nylon 6/12 | PEEK |
| ABS | Polycarbonate |
| Polyetherimide | Polysulfone |
| PES | ETFE |
| FEP | PFA |
| PVDF | |

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These basic resins are available with various degrees of carbon reinforcement and may also contain a secondary reinforcing material or a lubricant additive. In all cases the mechanical properties of the base resin are improved by the addition of the reinforcement.

## CARBON/GRAPHITE YARNS

For many years the predominant sealing material and mechanical material has been asbestos. However, the elimination of asbestos as an environmentally unsafe material has led to the acceptance of carbon/graphite as a reliable substitute. Carbon/graphite possesses the properties of strength, density, modulus, thermal conductivity, thermal stability, and corrosion resistance.

Its strong chemical resistance makes it ideally suited to the packing and sealing industries for use with acids, caustics, alkalies, and high-temperature applications. It is available in many styles and weights.

In general, it is inert to most chemicals in the pH range of 2–12. Typical examples are given in the table.

See Ref. 4.

| | Concentration | Temperature |
|---|---|---|
| Inorganic acids | | |
| Hydrochloric acid | all | boiling point |
| Hydrofluoric acid | all | boiling point |
| Phosphoric acid | all | boiling point |
| Sulfuric acid | 0–70% | boiling point |
| Chromic acid | 0–10% | 392°F (200°C) |
| Nitric acid | 0–10% | 185°F (85°C) |
| Nitric acid | 0–20% | 140°F (60°C) |
| Nitric acid | over 20% | 104°F (40°C) |
| Organic acids | | |
| Phenylsulfonic acid | 60% | boiling point |
| Acetic acid | all | boiling point |
| Acetic anhydride | 100% | boiling point |
| Chloracetic acid | all | boiling point |
| Amino acid | all | boiling point |
| Alkalies | | |
| Caustic soda | all | boiling point |
| Sodium hydroxide | solid | melting point |
| Solvents | | |
| Benzene | 0–100% | boiling point |
| Ethers | 0–100% | boiling point |
| Alcohols | 0–100% | boiling point |
| Esters | 0–100% | boiling point |
| Ketones | 0–100% | boiling point |
| Halogenated hydrocarbons | 0–100% | boiling point |
| Vinyl chloride | 0–100% | boiling point |
| Mineral oils | 0–100% | boiling point |

## CARBON AND LOW-ALLOY STEELS

Carbon and low-alloy steels are affected primarily by general corrosion. The corrosion of steel is the most common form of corrosion the average person sees. The steels tend to

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return to their oxide form by a process we call rusting. The most common corrosive solvent is water, in everything from dilute solutions to concentrated acids and salt solutions, but organic systems are capable of causing serious corrosion as well.

The carbon steels are subject to localized corrosion such as pitting, stress corrosion cracking, hydrogen embrittlement, and corrosion fatigue, as well as uniform corrosion.

Atmospheric corrosion of alloy steels is a prime factor in most applications. Fig. C.1 compares test results in a semi-industrial or industrial environment, of plain carbon steel with structural copper steel and high-strength–low-alloy (HSLA) steels. It is evident that the alloy steels are more resistant than the plain carbon steel. Table C.2 lists the average reduction in thickness for various steels in several environments.

The susceptibility of a low-alloy steel to stress corrosion cracking (SCC) depends on the strength level. The higher the tensile strength, the greater the susceptibility. General guidelines for steels such as AISI 4130 and AISI 4340 are as follows:

1. High SCC resistance: tensile strength below 180,000 psi
2. Moderate SCC resistance: tensile strength 180,000–200,000 psi
3. Low SCC resistance: tensile strength over 200,000 psi

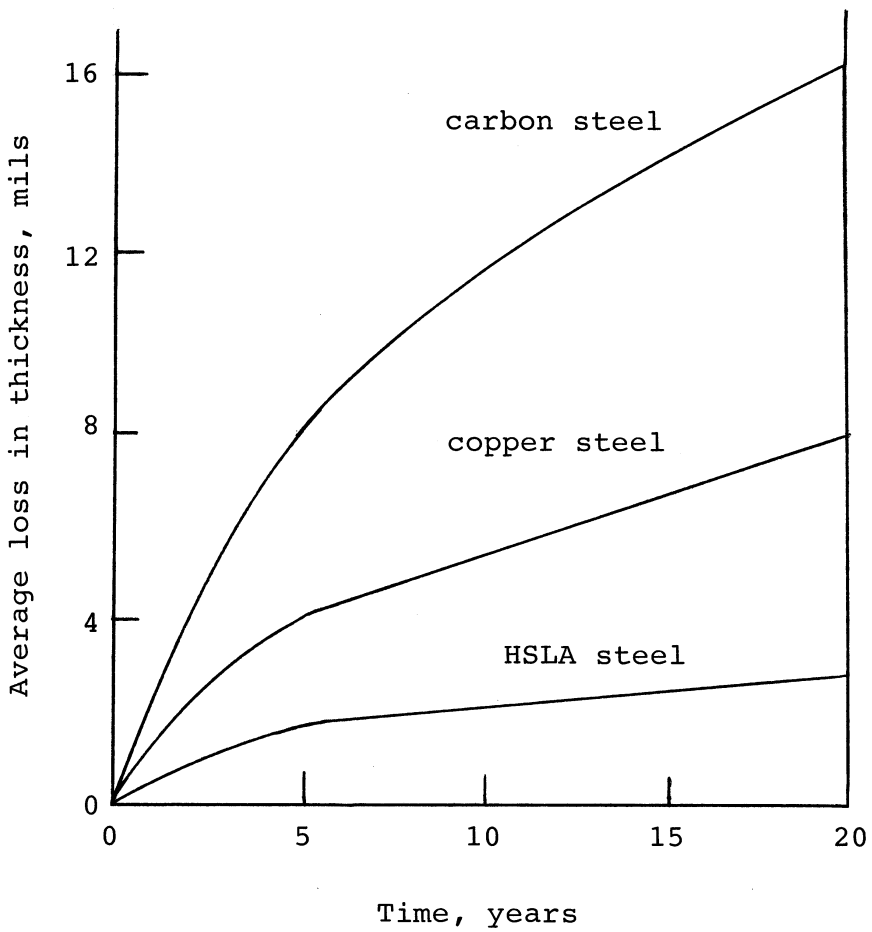



**Figure C.1** Atmospheric corrosion in a semi-industrial or industrial atmosphere.

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**Table C.2** Corrosion of Various Steels in Various Environments

| Environment | Exposure time (yr) | Average reduction in thickness (mils) | | |
|---|---|---|---|---|
| | | Carbon steel | A242(K11510) Cu-P steel | A588(K11430) Cr-V-Cu steel |
| Urban industrial | 3.5 | 3.3 | 1.3 | 1.8 |
| | 4.5 | 4.1 | 1.5 | 2.1 |
| Rural | 3.5 | 2.0 | 1.1 | 1.4 |
| | 7.5 | 3.0 | 1.3 | 1.5 |
| Severe marine | 0.5 | 7.2 | 2.2 | 3.8 |
| (80 ft from ocean) | 2.0 | 36.0 | 3.3 | 12.2 |
| | 3.5 | 57.0 | — | 28.7 |
| | 5.0 | D | 19.4 | 38.8 |
| Chloralkali plant | 0.5 | 4.1 | 2.4 | 2.7 |
| | 2.0 | 18.8 | 5.7 | 7.4 |
| Sulfur plant | 0.5 | 15.5 | 7.4 | 9.4 |
| | 2.0 | 43.3 | 20.4 | 32.4 |
| Chlorinated | 0.5 | 5.4 | 1.8 | 1.8 |
| hydrocarbon plant | 2.0 | 44.1 | 4.1 | 4.6 |
| Hydrochloric | 0.5 | 12.3 | 5.8 | 7.1 |
| acid plant | 2.0 | 49.8 | 25.2 | 31.6 |

D = Destroyed

Stress corrosion cracking can be induced in carbon or low-alloy steels, even at low concentrations, by the following chemical species:

Hydroxides, gaseous hydrogen
Gaseous chlorine, HCl, and HBr
Hydrogen sulfide gas, MnS and MnSe inclusions in alloy
Aqueous nitrate solution
As, Sb, and Bi ions in aqueous solutions
Carbon monoxide–carbon dioxide–water mixtures
Anhydrous ammonia

Carbon and low-alloy steels are also affected by pitting. One environment that pits steel is soil, which becomes a factor for buried pipelines. Other chemicals that cause pitting in steels include

Antimony trichloride
Carbonic acid–carbon dioxide
Epichlorohydrin
Methylamine
Nickel nitrate

Buried pipelines can best be protected with the application of protective coatings or by applying cathodic protection.

The diffusion of hydrogen through steel to affect mechanical properties involves nascent or atomic hydrogen since molecular hydrogen cannot diffuse through metals.

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Corrosion sources of atomic hydrogen include corrosion; misapplied cathodic protection; high-temperature, moist atmospheres; electroplating; and welding. Hydrogen blistering and hydrogen embrittlement are two forms of hydrogen damage.

During some acid services, such as acid pickling of steels, hydrogen atoms may enter the crystal lattice and collect in fissures or cavities in the steel. These atoms then combine into hydrogen gas molecules, eventually reaching pressures of several hundred thousand atmospheres and forming blisters on the steel surface.

Hydrogen embrittlement is another harmful effect of hydrogen penetration. This is a more complicated metallurgical effect, possibly involving the interaction of hydrogen atoms with the tip of an advancing crack. For the low-alloy steels the alloys are most susceptible in their highest strength levels. Alloys containing nickel or molybdenum are less susceptible.

If hydrogen is initially present in the steel—for example, from electroplating—the hydrogen can be baked out. This embrittlement decreases with increasing service temperature, especially above 150°F (65°C). Generally, hydrogen embrittlement is not a problem in steels having yield strengths below about 150,000 psi, but if hydrofluoric acid or hydrogen sulfide is present the yield strength must be below 80,000 psi. Welding conditions should be dry and low-hydrogen filler metal should be used to minimize hydrogen embrittlement.

High-temperature hydrogen attack is the result of a reaction between hydrogen and a component of the alloy. For example, in steels hydrogen reacts with iron carbide at high temperatures to form methane gas. Because methane cannot diffuse out of the steel, it accumulates and causes fissuring and blistering, which reduces alloy strength and ductility. Alloy steels containing chromium and molybdenum are helpful since the carbides formed by these alloying elements are more stable than iron carbide and therefore resist hydrogen attack.

Organic compounds can also be corrosive to steels, specifically those in the following categories:

1. Organic acids such as acetic and formic.
2. Compounds that hydrolyze to produce acids. These include chlorinated hydrocarbons such as carbon tetrachloride or trichloroethane, which react with water to produce hydrochloric acid. Other compounds are ethyl acetate, which hydrolyzes to produce acetic acid, and dimethyl sulfate, which hydrolyzes to produce sulfuric acid.
3. Chelating agents which take up or combine with transition elements.
4. Inorganic corrosives dissolved and dissociated in organic solvents. This may include hydrochloric acid dissolved in dimethylformamide. Other possibilities include chlorine, bromine, or iodine dissolved in methanol.

Reference 4 provides an extensive listing of the compatibility of carbon steel with selected corrodents.

## CARBURIZATION

Carburization is the absorption of carbon atoms into a metal surface at high temperature, which reduces the effectiveness of a prior oxide film by the formation of chromium carbides. This depletes the matrix of chromium.

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**Table C.3** Designation of Aluminum Castings

| Series | Alloy system |
|---|---|
| 1XX.X | 99.9% minimum aluminum |
| 2XX.X | Aluminum plus copper |
| 3XX.X | Aluminum plus silicon plus magnesium |
| | Aluminum plus silicon plus copper |
| | Aluminum plus silicon plus copper plus magnesium |
| 4XX.X | Aluminum plus silicon |
| 5XX.X | Aluminum plus magnesium |
| 6XX.X | Currently unused |
| 7XX.X | Aluminum plus zinc |
| 8XX.X | Aluminum plus tin |
| 9XX.X | Currently unused |

## CAST ALUMINUM

There is no single commercial designation system for aluminum castings. The most widely used system is that of the Aluminum Association. It consists of a four-digit numbering system incorporating a decimal point to separate the third and fourth digits. The first digit identifies the alloy group, as listed in Table C.3.

Aluminum castings are of two types: heat treatable, corresponding to the same type of wrought alloys where strengthening is produced by dissolution of soluble alloying elements and their subsequent precipitation, and non–heat treatable, in which strengthening is produced primarily by constituents of insoluble or undissolved alloying elements. Tempers of heat-treatable casting alloys are designated by an F. Alloys of the heat-treatable type are usually thermally treated subsequent to their casting, but for a few in which a considerable amount of alloying elements are retained in solution during casting, they may not be thermally treated after casting; thus they may be used in both the F and fully strengthened T tempers.

The 1XX.X series is assigned to pure aluminum. Besides ingot, the only major commercial use of pure aluminum castings is electrical conductor parts such as collector rings and bus bars. Because of their low strength these alloys are usually cast with integral steel stiffeners.

The 2XX.X series of the aluminum + copper alloys were the first type of casting alloys used commercially and are still used. They provide medium to high strength but are difficult to cast. These alloys are the least corrosion resistant and can be susceptible to SCC in the maximum strength of T6 temper.

The 3XX.X alloys provide the best combination of strength and corrosion resistance. They are produced in both as-cast (F) tempers and heat-treated tempers T5 through T7.

The 4XX.X castings are the most prevalent because of their superior casting characteristics. They provide reasonably good corrosion resistance but low to medium strength.

The 5XX.X castings provide the highest resistance to corrosion and good machinability and weldability. However, they have low to medium strength and are difficult to cast, being limited to sand castings or simple permanent mold shapes.

The 7XX.X castings find limited applications. They are difficult to cast and are limited to simple shapes. They have medium to good resistance to corrosion and high melting points.

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**Table C.4** Nominal Chemical Compositions of Representative Aluminum Casting Alloys

| | Alloying elements (%) | | | | |
|---|---|---|---|---|---|
| Alloy | Si | Cu | Mg | Ni | Zn |
| *Alloys not normally heat treated* | | | | | |
| 360.0 | 9.5 | | 0.5 | | |
| 380.0 | 8.5 | 3.5 | | | |
| 443.0 | 5.3 | | | | |
| 514.0 | | | 4.0 | | |
| 710.0 | | 0.5 | 0.7 | | 6.5 |
| *Alloys normally heat treated* | | | | | |
| 295.0 | 0.8 | 4.5 | | | |
| 336.0 | 12.0 | 1.0 | 1.0 | 2.5 | |
| 355.0 | 5.0 | 1.3 | 0.5 | | |
| 356.0 | 7.0 | | 0.3 | | |
| 357.0 | 7.0 | | 0.5 | | |

The 8XX.X castings were designed for bearings and bushings in internal combustion engines. Required properties are the ability to carry high compressive loads and good fatigue resistance.

Nominal chemical compositions of representative aluminum alloys are shown in Table C.4.

In general, the corrosion resistance of a cast aluminum alloy is equivalent to that of the comparable wrought aluminum alloy.

## CAST COPPER ALLOYS

The UNS designations for cast copper alloys consist of numbers C80000 through C99999. As with other metals, the composition of the cast copper alloys varies from that of the wrought alloys. Copper castings possess some advantages over wrought copper, in that the casting process permits greater latitude in alloying because hot- and cold-working properties are not important. This is particularly true relative to the use of lead as an alloying ingredient. The chemical compositions of the more common copper alloys are given in Table C.5. Commercially pure copper alloys are not normally cast.

Copper alloys are normally selected not because of their corrosion resistance alone, but rather for that characteristic plus one or more other properties. In many applications conductivity may be the deciding factor.

The brasses are the most useful of the copper alloys. They find application in seawater, with the higher-strength, higher-hardness materials used under high-velocity and turbulent conditions. In general, brass has less corrosion resistance in aqueous solution than the other copper alloys, although red brass is superior to copper for handling hard water. The addition of zinc does improve the resistance to sulfur compounds, but decreases the resistance to season cracking in ammonia. Refer to the section on dezincification under wrought copper alloys (see page 172). The brasses also find application in boric acid, neutral salts (such as magnesium chloride and barium chloride), organics (such as ethylene glycol and formaldehyde), and organic acids.

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**Table C.5** Chemical Composition of Cast Copper Alloys (wt%)

| UNS no. | ASTM spec. | Cu | Zn | Sn | Pb | Mn | Al | Fe | Si | Ni | Cb |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C83600 | B584 | 85 | 5 | 5 | 5 | — | — | — | — | — | — |
| C85200 | B584 | 72 | 24 | 1 | 3 | — | — | — | — | — | — |
| C85800 | B176 | 61 | 36 | 1 | 1 | — | — | — | — | — | — |
| C86200 | B584 | 63 | 27 | — | — | 3 | 4 | 3 | — | — | — |
| C86300 | B584 | 61 | 21 | — | — | 3 | 6 | 3 | — | — | — |
| C87200 | B584 | 89 | 5 | 1 | — | 1.5 | 1.5 | 2.5 | 3 | — | — |
| C87300 | B584 | 95 | — | — | — | 1 | — | — | 3 | — | — |
| C87800 | B176 | 87 | 14 | — | — | — | — | — | 4 | — | — |
| C90300 | B584 | 88 | 4 | 8 | — | — | — | — | — | — | — |
| C90500 | B584 | 88 | 2 | 10 | — | — | — | — | — | — | — |
| C92200 | B61 | 85 | 4 | 6 | 1.5 | — | — | — | — | — | — |
| C92300 | B584 | 83 | 3 | 7 | 7 | — | — | — | — | — | — |
| C95200 | B184 | 88 | — | — | — | — | 9 | 3 | — | — | — |
| C95400 | B148 | 85 | — | — | — | — | 11 | 4 | — | — | — |
| C95500 | B148 | 81 | — | — | — | — | 11 | 4 | — | 4 | — |
| C95800 | B148 | 81 | — | — | — | — | 9 | 4 | — | 4 | — |
| C96200 | B369 | 87.5 | — | — | — | 0.9 | — | 1.5 | 0.1 | 10 | — |
| C96400 | B369 | 68 | — | — | — | — | — | 1 | — | 30 | 1 |

The next major group of copper alloys are the bronzes, which from a corrosion standpoint are very similar to the brasses. Copper-aluminum (aluminum bronze), copper-silicon (silicon bronze), and copper-tin (tin bronze) are the main cast bronze alloys. The addition of aluminum to the bronzes improves resistance to high-temperature oxidation, increases the tensile strength properties, and provides excellent resistance to impingement corrosion. They are resistant to many nonoxidizing acids. Oxidizing acids and metallic salts will cause attack. Alloys having more than 8% aluminum should be heat treated since it improves corrosion resistance and toughness. Aluminum bronzes are susceptible to stress corrosion cracking in moist ammonia.

Silicon bronze has approximately the same corrosion resistance as copper but better mechanical properties and superior weldability. The corrosion rates are affected less by oxygen and carbon dioxide content than is the case with other copper alloys. Silicon bronzes can handle cold dilute hydrochloric acid, cold and hot dilute sulfuric acid, and cold concentrated sulfuric acid. They have better resistance to stress corrosion cracking than the common brasses. In the presence of high-pressure steam, silicon bronze is susceptible to embrittlement.

Tin bronze is less susceptible to stress corrosion cracking than brass, but has less resistance to corrosion by sulfur compounds. The addition of 8–10% tin provides good resistance to impingement attack. Tin bronze has good resistance to flowing seawater and some nonoxidizing acids (except hydrochloric acid).

The final group of copper alloys are the copper-nickel (cupronickels) alloys. They exhibit the best resistance to corrosion, impingement, and stress corrosion cracking of all the copper alloys. They are among the best alloys for seawater service and are immune to season cracking. Dilute hydrochloric, phosphoric, and sulfuric acids can be handled. They are almost as resistant as Monel to caustic soda.

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## CAST IRONS

The term cast iron is inclusive of a number of alloys of iron, carbon, and silicon. Typically these alloys have a carbon content of approximately 1.8% to 4.0% and a silicon content of 0.5% to 3.0%. This composition range describes all grades of cast irons from highly wear-resistant hard materials to ductile energy-absorbing alloys suitable for applications involving high stress and shock loads. The carbon content of the alloy can be in several forms: graphite flakes, irregular graphite modules, graphite spheres, iron carbides or cementite, or a combination of these. The basic types of cast irons are gray iron, ductile (nodular) iron, compacted graphite iron, white iron, malleable iron, and high-alloy cast irons.

### Gray Iron

This is the most common cast iron. When the material fractures it has a gray appearance—thus the name gray iron. Gray iron contains 1.7%–4.5% carbon and 1%–3% silicon. It is the least expensive of all the cast metals, and because of its properties it has become the most widely used cast material on a weight basis.

In gray iron the carbon is in the form of graphite flakes. Silicon additions assist in making the $Fe_3C$ unstable. As the metal slowly cools in the mold, the $Fe_3C$ decomposes to graphite. Gray iron has relatively poor toughness because of the stress concentration effect of the graphite flake tips. The mechanical properties vary with the cooling rate and are measured from separately cast bars poured from the same metal as the casting.

In general, gray iron castings are not recommended for applications where impact strength is required. Gray iron castings are normally used in neutral or compressive applications because the graphite flake form acts as an internal stress raiser. The graphite flake form provides advantages in machining, sound damping, and heat transfer applications.

Graphite is essentially an inert material and is cathodic to iron; consequently, the iron will suffer rapid attack in even mildly corrosive atmospheres. Gray iron is subject to a form of corrosion known as graphitization, which involves the selective leaching of the iron matrix, leaving only a graphite network. Even though no apparent dimensional change has taken place, there can be sufficient loss of section and strength to lead to failure. In general, gray iron is used in the same environments as carbon steel and low-alloy steels, although the corrosion resistance of gray iron is somewhat better than that of carbon steel. Corrosion rates in rural, industrial, and seacoast environments are generally acceptable. The advantage of gray iron over carbon steel in certain environments is due to a porous graphite-iron corrosion product film that forms on the surface. This film provides a particular advantage under velocity conditions, such as in pipelines. This is the reason for the widespread use of gray iron in underground water pipes.

Gray iron is not resistant to corrosion in acid except for concentrated acids, where a protective film is formed. It is not suitable for use with oleum. It has been known to rupture in this service with explosive violence.

Gray iron exhibits good resistance to alkaline solutions such as sodium hydroxide and molten caustic soda. Likewise, it exhibits good resistance to alkaline salt solutions such as cyanides, silicates, carbonates, and sulfides. Acids and oxidizing salts rapidly

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attack gray iron. Gray iron will contain sulfur at temperatures of 350–400°F (177–205°C). Molten sulfur must be air free and solid sulfur must be water free.

Gray iron finds application in flue gas handling such as in wood- and coal-fired furnaces and heat exchangers. Large quantities are also used to produce piping which is buried. Normally, gray iron pipe will outlast carbon steel pipe depending on soil type, drainage, and other factors.

## Ductile (Nodular) Iron

Ductile iron has basically the same chemical composition as gray iron with a small chemical modification. Just prior to pouring the molten iron, an appropriate inoculant such as magnesium is added. This alters the structure of iron to produce a microstructure in which the graphite form produced during the solidification process is spheroidal instead of flake form. The flake form has better machinability, but the spheroidal form yields much higher strength and ductility. The matrix can be ferritic, pearlitic, or martensitic depending on the heat treatment process. Graphite nodules surrounded by white ferrite, all in a pearlitic matrix, the most common form. Other elements can be used to produce the nodular graphite form, including yttrium, calcium, and cerium.

The corrosion resistance of ductile iron is comparable to that of gray iron, with one exception. Under velocity conditions the resistance of ductile iron may be slightly less than that of gray iron since it does not form the same type of film that is present on gray iron.

## Austenitic Gray Cast Iron

Austenitic cast iron is also referred to as an Ni-resist alloy. This group consists of high-nickel austenitic cast irons used primarily for their corrosion resistance. These alloys have improved toughness over unalloyed gray iron but relatively low tensile strengths, ranging from 20,000 to 30,000 psi.

The corrosion resistance lies between that of gray iron and the 300 series stainless steels. It finds wide application in hydrogen sulfide–containing oil field applications. Excessive attack is prevented by the formation of a protective film. It is superior to gray iron under exposure to atmospheric conditions, seawater, caustic soda, or sodium hydroxide, and dilute and concentrated (unaerated) sulfuric acid.

## Austenitic Ductile Cast Irons

These alloys are commonly called ductile Ni-resist. They are similar to the austenitic gray irons except that magnesium is added just prior to pouring to produce a nodular graphite structure. As a result of the nodular structure, higher strength and greater ductility are produced compared with the flake graphite structure. Although several grades are produced, type 2D is the most commonly used grade.

The corrosion resistance is similar to that of austenitic gray iron, although alloys containing 2% or more chromium are superior. The compatibility of Ni-resist with selected corrodents is shown in the following table:

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Compatability of Ni-Resist Alloy with Selected Corrodents

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetic anhydride | x | x | Ethanol amine | 200 | 93 |
| Acetone | 140 | 60 | Ethyl acetate | 90 | 32 |
| Acetylene | 90 | 32 | Ethyl chloride, dry | 90 | 32 |
| Alum | 100 | 38 | Ehtylene glycol | 460 | 238 |
| Aluminum hydroxide, 10% | 470 | 243 | Ethylene oxide | x | x |
| Aluminum potassium sulfate | 100 | 38 | Ferric sulfate | 460 | 238 |
| Ammonia, anhydrous | 460 | 238 | Ferrous sulfate | x | x |
| Ammonium carbonate, 1% | 90 | 32 | Fuel oil | x | x |
| Ammonium chloride | 210 | 99 | Fufural, 25% | 210 | 99 |
| Ammonium hydroxide | 90 | 32 | Gallic acid | 90 | 32 |
| Ammonium nitrate, 60% | 120 | 49 | Gas, natural | 90 | 32 |
| Ammonium persulfate, 60% | 120 | 49 | Gasoline, leaded | 400 | 204 |
| Ammonium phosphate | x | x | Gasoline, unleaded | 400 | 204 |
| Ammonium sulfate | 130 | 54 | Glycerine | 320 | 160 |
| Amyl acetate | 300 | 149 | Hydrochloric acid | x | x |
| Aniline | 100 | 38 | Hydrogen chlorine gas, dry | x | x |
| Arsenic acid | x | x | Hydrogen sulfide, dry | 460 | 238 |
| Barium carbonate | x | x | Hydrogen sulfide, wet | 460 | 238 |
| Barium chloride | x | x | Isooctane | 90 | 32 |
| Barium hydroxide | x | x | Magnesium hydroxide | x | x |
| Barium sulfate | x | x | Magnesium sulfate | 150 | 66 |
| Barium sulfide | x | x | Methyl alcohol | 160 | 71 |
| Benzene | 400 | 204 | Methyl chloride | x | x |
| Black liquor | 90 | 32 | Phosphoric acid | x | x |
| Boric acid | x | x | Sodium borate | 90 | 32 |
| Bromine gas | x | x | Sodium hydroxide, to 70% | 170 | 77 |
| Butyl acetate | x | x | Sodium nitrate | 90 | 32 |
| Calcium carbonate | 460 | 238 | Sodium nitrite | 90 | 32 |
| Calcium hydroxide | 90 | 32 | Sodium peroxide, 10% | 90 | 32 |
| Calcium nitrate | 210 | 99 | Sodium silicate | 90 | 32 |
| Calcium sulfate | 440 | 227 | Sodium sulfate | x | x |
| Carbon dioxide, dry | 300 | 149 | Sodium sulfide | x | x |
| Carbon dioxide, wet | x | x | Steam, low pressure | 350 | 177 |
| Carbon monoxide | 300 | 149 | Sulfate liquors | 100 | 38 |
| Carbon tetrachloride | 170 | 77 | Sulfur | 100 | 38 |
| Carbonic acid | 460 | 238 | Sulfur dioxide, dry | 90 | 32 |
| Chlorine gas, dry | 90 | 32 | Tartaric acid | 100 | 38 |
| Chromic acid | x | x | Tomato juice | 120 | 49 |
| Cyclohexane | 90 | 32 | Vinegar | 230 | 110 |
| Diethelylene glycol | 300 | 149 | Water, acid mine | 210 | 99 |
| Diphenyl | 210 | 99 | White liquor | 90 | 32 |

*Note:* The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. When compatible, corrosion rate is less than 20 mpy.
*Source:* Ref. 4.

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### White Iron

This alloy is also referred to as Ni-hard. The carbon in these alloys is essentially all in solution and the fracture surface appears white. These alloys contain nickel in the range of 4–5% and chromium in the range of 1.5–3.5%.

White iron solidifies with a "chilled" structure. Instead of forming free graphite, the carbon forms abrasion-resistant iron-chromium carbides. These alloys are used primarily for abrasive applications. After machining, the material is generally heat treated to form a martensitic matrix for maximum hardness and wear resistance.

### Malleable Iron

Malleable iron and ductile iron are very similar, but malleable iron is declining in use because of economic reasons. Malleable iron contains a carbon form referred to as "temper carbon" graphite. This carbon form is generated by a heat treatment of the as-cast product after solidification. It is the cost of this heat treatment operation that is the reason for the decline in usage.

In general, there is little difference in corrosion resistance between gray iron and malleable iron. Malleable iron may be inferior to gray iron in flowing conditions since there are no graphite flakes to hold the corrosion products in place; therefore the attack continues at a constant rate rather than declining with time.

## CAST NICKEL AND NICKEL BASE ALLOYS

The nickel base alloys are more difficult to cast than the austenitics. A wrought trade name should never be used when purchasing a nickel alloy casting.

Because of the high cost of these alloys, they are generally used only in specialty areas and very severe service. As with the stainless steels, ACI designations have been adopted for these alloys since their compositions and properties in many cases vary significantly from the wrought equivalents. ASTM standard A-94 covers cast nickel base alloys. The chemical compositions of the nickel base alloys can be found in Table C.6.

CZ-100 is the cast equivalent of wrought nickel 200. In order to ensure adequate castability, the carbon and silicon levels are higher in the cast grade than in the wrought grade. In the molten state the alloy is treated with magnesium, which causes the carbon to nodularize, leading to an increase in the mechanical properties, much as with ductile iron.

This alloy is used for dry halogen gases and liquids and ambient-temperature hydrofluoric acid, but its widest use is in alkaline services. It has excellent resistance to all bases except ammonium hydroxide, which will cause rapid attack at any concentration above 1%. CZ-100 is resistant to all concentrations and temperatures of sodium and potassium hydroxide. If chlorates or oxidizable sulfur compounds are present in caustic, the corrosion rate will be accelerated. CZ-100 also finds application in food processing where product purity is important.

M-35-l, M-35-2, M-30-G, and M-25-S cast alloys are the equivalent of wrought Monel 400. The most common cast grade is M-35-1. The lower level of silicon makes alloy M-35-1 suitable for the handling of air-free hydrofluoric acid. Since this alloy exhibits good resistance to fluorides, it finds application in uranium enrichment. The higher-silicon-grade alloy, M-30-H, is used for rotating parts and wear rings since it combines corrosion resistance with high strength. and wear resistance.

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**Table C.6** Cast Nickel Base Alloys

| Specification and grade | Wrought equivalent | C max. | Cr | Ni | Fe | Mo | Others |
|---|---|---|---|---|---|---|---|
| ASTM A494 Grade CZ100 | Nickel 200 | 1 | — | 95[a] | 3[a] | — | — |
| ASTM A494 Grade M35-1 | Monel 400 | 0.35 | — | Balance | 3.5[a] | — | Si 1.25[a] |
| ASTM A494 Grade M35-2 | Monel 400 | 0.35 | — | Balance | 3.5[a] | — | Si 2[a] |
| ASTM A494 Grade M30C | Monel 400 | 0.3 | — | Balance | 3.5[a] | — | Si 1–2, Cb 1–3 |
| ASTM A494 Grade M25S | S-Monel | 0.25 | — | Balance | 3.5[a] | — | Si 3.5–4.5 |
| ASTM A494 Grade CY40 | lnconel 600 | 0.4 | 14–17 | Balance | 11[a] | — | — |
| ASTM A494 Grade CW6MC | Inconel 625 | 0.06 | 20–23 | Balance | 5[a] | 8–10 | Cb 3.15–4.5 |
| ASTM A494 Grade CW2M | Hastelloy C | 0.02 | 15–17.5 | Balance | 2[a] | 15–17.5 | — |
| ASTM A494 Grade CX2MW | Hastelloy C22 | 0.02 | 20–22.5 | Balance | 2–6 | 12.5–14.5 | W 2.5–3.6 |
| ASTM A494 Grade CW6M | Chlorimet 3 | 0.07 | 17–20 | Balance | 3[a] | 17–20 | — |
| ASTM A494 Grade N7M | Hastelloy B2 | 0.07 | 1[a] | Balance | 3[a] | 30–33 | — |
| ASTM A494 Grade CY5SnBiM | Waukesha 88 | 0.05 | 11–14 | Balance | 2[a] | 2–3.5 | Bi 3–5, Sn 3–5 |

[a]Maximum content.

In general, the cast Monel alloys exhibit excellent resistance to mineral acids, organic acids, and salt solutions. These alloys are also used in sulfuric acid services where reducing conditions are present and in chlorinated solvents. Oxidizing conditions accelerate the corrosion rate in all services

CY-40 is the cast equivalent of wrought Inconel alloy 600. It is a nickel-chromium alloy without the molybdenum content of most nickel-chromium alloys. In order to provide castability, the carbon and silicon content are higher than in the wrought alloy. In order to maximize corrosion resistance, this alloy is solution annealed.

Applications for this alloy are found where oxidation resistance and strength retention at high temperatures are required. This alloy resists stress corrosion cracking in chloride environments and at times is substituted for CZ-l00 in caustic soda containing halogens. CY-40 is widely used in nuclear reactor service because of its resistance to chloride stress corrosion cracking and corrosion by high-purity water. It also finds application in steam, boiler feedwater, and alkaline solutions including ammonium hydroxide.

CW-12MW is the original cast equivalent of alloy 276. Because of segregation problems with the alloy, the corrosion resistance is inferior to wrought C-276.

CW-2M is essentially a low-carbon version of CW-12MW, having improved ductility and high-temperature service, and is the presently used cast version of wrought alloy

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276. This alloy may be used in corrosive environments in the welded condition without postweld heat treatment since it resists the formation of grain boundary precipitation. It has excellent corrosion resistance in hydrochloric and sulfuric acids at temperatures below 129°F (52°C), with a much higher temperature range at low concentrations. Excellent resistance is also exhibited in organic acids. Contamination by strong oxidizing species such as cupric and ferric ions will not cause accelerated attack of CW-2M as is experienced with other alloys. It is also resistant to most sources of stress corrosion cracking, including chloride, caustic, and hydrogen sulfide.

CW-6M is the cast version of Chlorimet 3 (Duriron Co.) and is intended primarily for corrosive services. The tungsten and vanadium have been removed and the chromium, molybdenum, and nickel levels raised. These modifications in the composition result in improved corrosion resistance.

CW-6MC is the cast equivalent of wrought Inconel 625. In order to maximize corrosion resistance, the alloy is solution annealed. The alloy is used primarily for oxidation resistance at high temperatures. Alloy CW-6MC has superior corrosion resistance compared with alloy CY-40.

CX-2MW is the cast version of alloy C-22 of Waukesha Foundry and is known as Waukesha 88. This alloy is not as corrosion resistant as other nickel base alloys but performs well in the food industry.

N-7M is the cast equivalent of alloy B-2 and is a nickel-molybdenum alloy. To ensure maximum corrosion resistance, solution annealing, heat treatment, and alloy purity are essential to produce a suitable microstructure.

This alloy is particularly recommended for handling hydrochloric acid at all concentrations and temperatures, including boiling. Oxidizing contaminants or conditions can lead to rapid failure. Accelerated corrosion will result when cupric or ferric chloride, hypochlorites, nitric acid, or even aeration are present. In 100% hydrochloric acid the maximum allowable ferric ion concentration is 5000 ppm at 78°F (26°C), while the maximum allowable concentration at 150°F (66°C) is less than 1000 ppm and at boiling less than 75 ppm. This alloy is also resistant to hot sulfuric acid as long as no oxidizing contaminants are present. Phosphoric acid in all concentrations up to 300°F (149°C) can be handled.

N-12MV is also a nickel-molybdenum alloy. This alloy is similar to N-7M but with less ductility. Its corrosion resistance is basically the same as that of N-7M.

## CAST STAINLESS STEELS

Iron-based alloys containing at least 11.5% chromium are referred to as stainless steels. This level of chromium is necessary to produce passivity. Cast stainless steels may be found in all grades comparable with the wrought grades plus many additional grades for special end-use applications. Cast alloys can be produced with improvement in specific properties, but the composition cannot be produced in the wrought form. Some alloys have high silicon and/or carbon content for superior corrosion abrasion resistance, but the low ductility and high strength may make rolling or forging impossible.

### Martensitic Alloys

The chemical composition of typical cast martensitic stainless steel alloys is found in Table C.7. Alloy CA-15 contains the minimum amount of chromium required to make it a rustproof alloy. It exhibits good resistance to atmospheric corrosion and finds applications in

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**Table C.7** Chemical Composition of Cast Martensitic Stainless Alloys

| | Alloy (wt%) | | | | |
|---|---|---|---|---|---|
| Chemical | CA-6NM | CA-15 | CA-15M | CA-28MWV | CA-40 |
| Carbon | 0.06 | 0.05 | 0.15 | 0.2–0.28 | 0.20–0.40 |
| Manganese | 1.00 | 1.00 | 1.00 | — | 1.00 |
| Silicon | 1.00 | 1.50 | 0.65 | — | 1.50 |
| Phosphorus | 0.04 | 0.04 | 0.04 | — | 0.04 |
| Sulfur | 0.03 | 0.04 | 0.04 | — | 0.04 |
| Chromium | 11.5–14.0 | 11.5–14.0 | 11.5–14.0 | 11.0–1 2.5 | 11.5–14.0 |
| Nickel | 3.5–4.5 | 1.00[a] | 1.00[a] | — | 1.0 |
| Molybdenum | 0.40–1.0 | 0.50 | 0.15–1.0 | 0.9–1.25 | 0.5 |
| Tungsten | — | — | — | 0.9–1.25 | — |
| Vanadium | — | — | — | 0.2–0.3 | — |
| Iron | Balance | Balance | Balance | Balance | Balance |

[a]Maximum unless otherwise indicated.

mildly corrosive organic services. Because the alloy is martensitic, it is used in some abrasive applications. Specific areas of application include alkaline liquids, ammonia water, boiler feedwater, pulp, steam, and food products.

Alloy CA-40 is a higher-carbon version of CA-15. The higher carbon content permits heat treatment to higher strength and hardness levels. The addition of molybdenum forms alloy CA-15M, which has improved elevated-temperature resistance over alloy CA-15. Alloys CA-40 and CA-15M each have a corrosion resistance comparable to that of alloy CA-15.

CA-6NM is an iron-chromium-nickel-molybdenum alloy that is hardenable by heat treatment. Its corrosion resistance is comparable to that of alloy CA-15 with improved corrosion resistance in seawater as a result of the molybdenum content. Typical applications include seawater, boiler feedwater, and other waters up to a temperature of 400°F (204°C).

Alloy CA-28MWV is a modified version of wrought alloy type 410 with improved high-temperature strength.

The martensitic grades are resistant to corrosion in mild atmospheres, water, steam, and other nonsevere environments. They will rust quickly in marine and humid industrial atmospheres and are attacked by most inorgnic acids. When used at high hardness levels, they are susceptible to several forms of stress corrosion cracking. Hardened martensitic grades have poor resistance to sour environments and may crack in humid industrial atmospheres. Resistance is greatly improved in the quenched and fully tempered condition (generally below Rockwell C-25), especially for CA-6NM. In general, the martensitic grades are less corrosion resistant than the austenitic grades.

## Ferritic Alloys

The ferritic stainless castings have properties much different from those of the austenitic stainless castings, some of which can be very advantageous in certain applications. The two most common cast ferritic stainless steels are CB-30 and CC-50. Their chemical compositions are found in Table C.8.

CB-30 is essentially all ferritic and therefore is nonhardenable. The chromium content of CB-30 is sufficient to give this alloy much better corrosion resistance in oxidizing environments. This alloy has found application in food products, nitric acid, steam, sulfur

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**Table C.8** Chemical Composition of Cast Ferritic Stainless Steels

| | Alloy (wt%) | |
|---|---|---|
| Chemical | CB-30 | CC-50 |
| Carbon | 0.3 | 0.5 |
| Manganese | 1.00 | 1.00 |
| Silicon | 1.50 | 1.50 |
| Phosphorus | 0.04 | 0.04 |
| Sulfur | 0.04 | 0.04 |
| Chromium | 18.0–21.0 | 26.0–30.0 |
| Nickel | 2.00 | 4.00 |
| Iron | Balance | Balance |

Maximum unless otherwise noted.

atmospheres, and other oxidizing atmospheres at temperatures up to 400°F (204°C). It is also resistant to alkaline solutions and many inorganic chemicals.

CC-50 has a higher chromium content than CB-30, which gives it improved corrosion resistance in oxidizing media. In addition, at least 2% nickel and 0.15% nitrogen are usually added to CC-50, giving it improved toughness. Applications for CC-50 include acid mine waters, sulfuric and nitric acid mixtures, alkaline liquors, and sulfurous liquors.

Because of the low nickel content, these alloys have better resistance to stress corrosion cracking than the austenitic alloys.

## Austenitic Alloys

The austenitic cast alloys represent the largest group of cast stainless steels in terms of both the number of compositions and the quantity of material produced. This group of alloys illustrates the differences that can exist between the so-called cast and wrought grades.

The austenitic cast alloys are the equivalents of the wrought 300 series stainless steels. Wrought 300 series stainless steels are fully austenitic. This structure is necessary to permit the hot and cold forming operations used to produce the various wrought shapes. Since castings are produced essentially to the finished shape, it is not necessary for the cast alloys to be fully austenitic. Even though these alloys are referred to as cast austenitic alloys, the cast compositions can be balanced such that the microstructure contains from 5% to 40% ferrite. Using Fig. C.2 as a guide, the amount of ferrite present can be estimated from the composition. The cast equivalents of the 300 series alloys can display a magnetic response from none to quite strong. The wrought 300 series contain no ferrite and in the annealed condition are nonmagnetic.

The presence of ferrite increases the resistance of the cast alloys to stress corrosion cracking compared with the fully austenitic wrought equivalents. It is possible to specify castings with specific ferrite levels.

The high-temperature service of these alloys is limited because of the presence of a continuous phase of ferrite. Above 600°F (315°C) chromium precipitates in the ferrite phase, which embrittles the ferrite. A noncontinuous ferrite phase can be provided as long as the ferrite number is maintained below 10%.

Table C.9 provides the chemical composition of the cast austenitic stainless steels. The CF series of cast alloys makes up the majority of the corrosion-resistant casting

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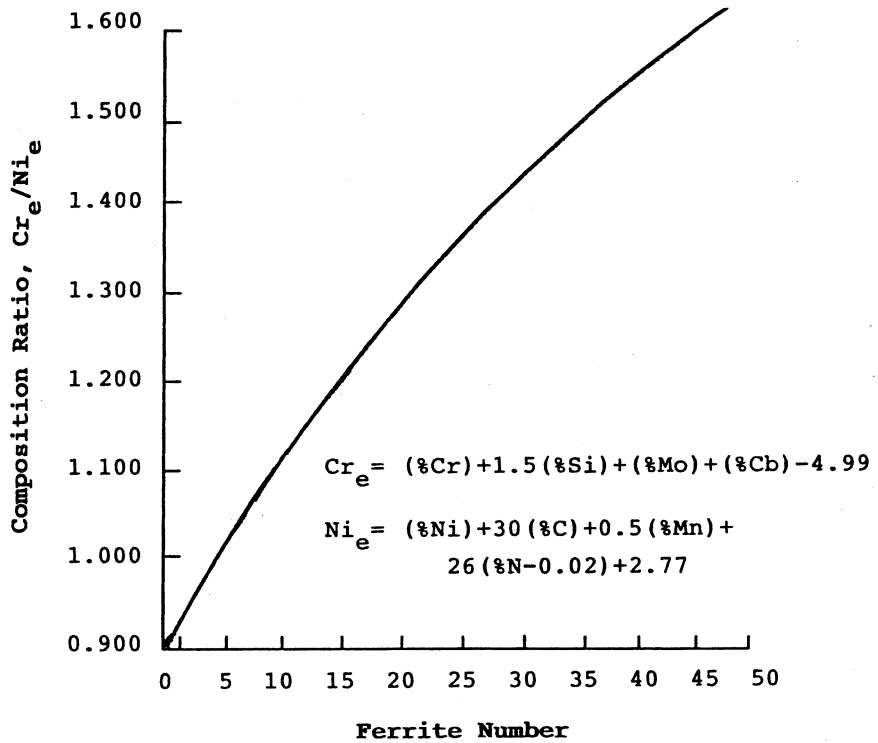



**Figure C.2** Diagram for estimating ferrite content in cast stainless steel.

alloys. These are 19% chromium/9% nickel materials. The alloys are generally ferrite in austenite, with the composition balanced to provide 5% to 25% ferrite. Fully austenitic castings can be provided. However, because of the many benefits derived from the presence of ferrite in the structure, it is usually present in the alloy.

These alloys are furnished in the fully solution-annealed condition in order to provide the maximum corrosion resistance, which is at least equal to that of its wrought equivalent.

CF-8 is the base composition for the CF alloy group, and its wrought equivalent is type 304. Like wrought 304 alloy, CF-8 is resistant to strongly oxidizing media, such as boiling nitric acid. Other typical applications include adipic acid, copper sulfate, fatty acids, organic acid and liquids, sewage, sodium sulfite, sodium carbonate, vinegars, and white liquor.

CF-3 is a low-carbon version of CF-8 and is equivalent to wrought 304L. For the optimum corrosion resistance the casting should be solution annealed. The overall corrosion resistance of CF-3 is somewhat better than that of CF-8, but in general they are used in the same applications.

CF-8C is the stabilized grade of CF-8 and is equivalent to wrought 347. Carbon in the alloy is tied up to prevent the formation of chromium carbides by the addition of niobium or niobium plus tantalum. This alloy finds application in the same areas as alloy CF-3 and has the equivalent corrosion resistance of CF-8.

CF-8A and CF-3A are controlled ferrite grades. By controlling the composition and thus the percentage of ferrite present, an increase in resistance to stress corrosion

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**Table C.9** Chemical Composition of Cast Austenitic Stainless Steels

| | Chemical (wt%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Alloy | C | Mn | Si | P | S | Cr | Ni | Mo | Other |
| CE-30 | 0.30 | 1.50 | 2.00 | 0.04 | 0.04 | 26.0–30.0 | 8.0–11.0 | — | — |
| CF-3 | 0.03 | 1.50 | 2.00 | 0.04 | 0.04 | 12.0–21.0 | 8.0–12.0 | 0.5 | — |
| CF-3A | 0.03 | 1.50 | 2.00 | 0.04 | 0.04 | 17.0–21.0 | 8.0–12.0 | 0.5 | — |
| CF-3M | 0.03 | 1.50 | 1.50 | 0.04 | 0.04 | 17.0–21.0 | 9.0–13.0 | 2.0–3.0 | |
| CF-8 | 0.08 | 1.50 | 2.00 | 0.04 | 0.04 | 18.0–21.0 | 8.0–11.0 | 0.5 | — |
| CF-8A | 0.08 | 1.50 | 2.00 | 0.04 | 0.04 | 18.0–21.0 | 8.0–11.0 | 0.5 | — |
| CF-20 | 0.20 | 1.50 | 2.00 | 0.04 | 0.04 | 18.0–21.0 | 8.0–11.0 | — | — |
| CF-3MA | 0.03 | 1.50 | 1.50 | 0.04 | 0.04 | 12.0–21.0 | 9.0–13.0 | 2.0–3.0 | — |
| CF-8M | 0.08 | 1.50 | 2.00 | 0.04 | 0.04 | 18.0–21.0 | 9.0–12.0 | 2.0–3.0 | — |
| CF-8C | 0.08 | 1.50 | 2.00 | 0.04 | 0.04 | 18.0–21.0 | 9.0–12.0 | 0.5 | 8 × C Cb, 1.0 Cb |
| CF-10MC | 0.10 | 1.50 | 1.50 | 0.04 | 0.04 | 15.0–18.0 | 13.0–16.0 | 1.75–2.25 | 10 ×C Cb, 1.2 Cb |
| CF-10SMMN | 0.1 | 7–9 | 3.5–4.5 | — | — | 16.0–18.0 | 8.0–9.0 | — | 0.08–0.18 N |
| CF-16F | 0.16 | 1.50 | 2.00 | 0.17 | 0.04 | 18.0–21.0 | 9.0–12.0 | 1.50 | 0.20–0.35 Se |
| CG-6MMN | 0.06 | 4–6 | — | — | — | 20.5–23.5 | 11.5–13.5 | 1.5–3 | 0.1–0.3 Cb, 0.1–0.3 V, 0.2–0.4 N |
| CG-8M | 0.08 | 1.50 | 1.50 | 0.04 | 0.04 | 18.0–21.0 | 9.0–13.0 | 3.0–4.0 | |
| CG-12 | 0.12 | 1.50 | 2.00 | 0.04 | 0.04 | 20.0–23.0 | 10.0–13.0 | — | — |
| CH-20 | 0.20 | 1.50 | 2.00 | 0.04 | 0.04 | 22.0–26.0 | 12.0–15.0 | 0.05 | — |
| CK-20 | 0.20 | 2.00 | 2.00 | 0.04 | 0.04 | 23.0–27.0 | 19.0–22.0 | 0.05 | — |

Maximum unless otherwise specified; iron balance in all cases.

cracking is achieved without any loss in corrosion resistance. Mechanical properties are also improved. CF-3A finds application in nuclear power plant construction.

CF-20 is a high-carbon version of CF-8 and is equivlent to wrought type 302. This alloy is resistant to moderately oxidizing environments. The alloy is fully austenitic and is nonmagnetic. Applications include caustic salts, food products, sulfite liquors, and sulfurous acid.

CF-8 is the cast equivalent of wrought type 316. It contains slightly more nickel than CF-8 to offset the ferritizing influence of the molybdenum and thus maintain a comparable ferrite level in the microstructure. This alloy can be made fully austenitic and nonmagnetic. Addition of the molybdenum improves the general corrosion resistance, provides greater elevated-temperature strength, and particularly improves pitting resistance in chloride environments. By adding the molybdenum, some resistance to strongly oxidizing environments is sacrificed, such as in boiling nitric acid. However, passivity is increased in weakly oxidizing conditions compared with CF-8. This alloy has good resistance in the presence of reducing media. Overall corrosion resistance is equal to or better than that of wrought 316. Typical services include acetic acid, acetone, black liquor, chloride solution, hot dyes, fatty acids, phosphoric acid, sulfurous acid, and vinyl alcohol. The alloy is supplied in the solution-annealed condition.

CF-8M has excellent corrosion resistance in normal atmospheric conditions, including seacoast exposure. It also resists hot water and brines at ambient temperature.

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Under low flow or at stagnant conditions, or at elevated temperatures, seawater may cause pitting. One application of CF-8M is the handling of 80–100% sulfuric acid at ambient temperature. Good resistance is also exhibited to phosphoric acid at all concentrations up to 170°F (77°C). It is also used for nitric acid up to boiling at all concentrations to 65%. Although CF-8M is not attacked by organic solvents, chlorinated organics may attack CF-8M, particularly under condensing conditions such as when water may be present.

CF-8M resists many alkaline solutions and alkaline salts, ammonium hydroxide at all concentrations to boiling, and sodium hydroxide at all concentrations to 150°F (65°C), above which stress corrosion cracking may occur.

Metallic chloride salts, such as ferric chloride and cupric chloride, can be very corrosive to CF-8M. Chloride can cause stress corrosion cracking above 160°F (71°C). The combination of chlorides, oxygen, water, and surface tensile stress can result in cracking at stresses far below the tensile stress of all austenitic stainless steels. Whenever chlorides are present at a few hundred ppm and the temperature exceeds 160°F (71°C), there is the possibile development of stress corrosion cracking.

CF-3M is the cast equivalent of 316L and is intended for use where postweld heat treatment is not possible. The areas of application for CF-3M are essentially the same as for CF-8M.

CF-3MA is a controlled ferrite grade with improved yield and tensile strengths.

CF-1OMC is the stabilized grade of CF-8M for field welding applications.

CF-16F is the cast equivalent of wrought type 303. It is a free-machining stainless steel. This alloy and CF-20 are used in similar applications, although the corrosion resistance of CF-16F is inferior to that of CF-20.

CG-8M is the cast version of wrought type 317. This alloy is resistant to reducing media and is resistant to sulfuric and sulfurous acids. It also resists the pitting of halogen compounds. Strongly oxidizing environments will attack CG-8M. As a result of the high ferrite content, this alloy exhibits very good stress corrosion cracking resistance but also has an upper temperature limit of 800°F (425°C). Applications are found in the pulp and paper industry, where it resists attack from pulping liquors and bleach-containing water.

CE-30 is a high-carbon cast stainless steel. The alloy has a microstructure of ferrite in austenite with carbide precipitates present in the as-cast condition. Resistance to intergranular corrosion is not seriously impaired since there is sufficient chromium present. Since the alloy does retain good corrosion resistance as cast, it is useful where heat treatment is not possible or where heat treatment following welding cannot be performed. By solution annealing of the casting, corrosion resistance and ductility can be greatly improved.

This alloy is resistant to sulfurous acid, sulfites, mixtures of sulfurous and sulfuric acids, and sulfuric and nitric acids.

CF-30A, which is a controlled ferrite grade, is resistant to stress corrosion cracking in polythionic acid and chlorides. Other applications are found in pulp and paper manufacture, caustic soda, organic acids, and acid mine water.

CH-20 is similar to CE-30 but has a composition containing a greater amount of nickel and a lesser amount of chromium. This alloy is considerably more corrosion resistant than CF-8 and less susceptible to intergranular corrosion than CF-8 after exposure to sensitizing temperatures. The alloy must be solution annealed to achieve the maximum corrosion resistance.

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CK-20 is used in the same applications as CH-20 but at higher temperatures.

CG-6MMN is the cast equivalent of nitronic 50 (Armco Inc.). This alloy is used in place of CF-8M when higher strength and/or better corrosion resistance is required.

CF-1OSMMN is the cast equivalent of nitronic 60 (Armco Inc.). The corrosion resistance is similar to CF-8 but not as good in hot nitric acid. This alloy does have the advantage of better galling resistance than the other CF grades.

## Duplex Alloys

Stainless steels with approximately 50% ferrite and 50% austenite are known as duplex stainless steels. These alloys have superior corrosion resistance and higher yield strength than the austenitics with lower alloy content. Refer to Table C.10 for the chemical composition of the cast duplex stainless steels.

These alloys are limited to a maximum operating temperature of 500°F (260°C) as a result of the formation of a sigma phase at elevated temperatures. Both toughness and corrosion resistance are adversely affected by the formation of a sigma phase. Welding of duplex alloys is somewhat difficult because of the potential of the formation of a sigma phase.

The duplex alloys exhibit improved resistance to erosion and velocity conditions as a result of increased hardness. They also exhibit exceptional resistance to chloride stress cracking.

The duplex alloys are completely resistant to corrosion from atmospheric and marine environments, fresh water, brine, boiler feedwater, and steam. They are especially suitable for high-temperature chloride-containing environments where stress corrosion cracking and pitting are common causes of failure of other stainless steels. The two phases of the duplex alloys result in inherently better stress corrosion cracking resistance compared with single-phase alloys. Usually at least one of the phases is resistant to cracking in a given environment. These alloys are highly resistant to acetic, formic, and other organic acids and compounds.

CD-4MCu is the cast equivalent of Ferralium 255. Its high chromium level makes it particularly useful in oxidizing media such as nitric acid. This alloy can also be used in

**Table C.10** Chemical Composition of Cast Duplex Stainless Steel

| | Alloy (wt%) | | | |
|---|---|---|---|---|
| Chemical | CD-4MCu | CD-3MN | CD-3MWN | Z6CNDU 20.08M |
| Carbon | 0.04 | 0.03 | 0.03 | 0.08 |
| Manganese | 1.00 | — | — | — |
| Silicon | 1.00 | — | — | — |
| Phosphorus | 0.04 | — | — | — |
| Sulfur | 0.04 | — | — | — |
| Chromium | 24.5–26.5 | 21–23.5 | 24–26 | 19–23 |
| Nickel | 4.75–6.00 | 4.5–6.5 | 6.5–8.5 | 7–9 |
| Molybdenum | 1.75–2.25 | 2.5–3.5 | 3–4 | 2.3 |
| Copper | 2.75–3.25 | — | 0.0–1 | 1.2 |
| Nitrogen | — | 0.1–0.3 | 0.2–0.3 | — |
| Tungsten | — | — | 0.5–1 | — |
| Iron | Balance | Balance | Balance | Balance |

Maximum unless otherwise noted.

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reducing environments. CD-4MCu has been widely used in dilute sulfuric acid services up to fairly high temperatures. It has also performed well in fertilizer production and in the wet process method for producing phosphoric acid. This alloy also performs well in sodium hydroxide even though it is low in nickel content. Other services for which this alloy is suitable include concentrated brines, fatty acids, seawater, hot oils, pulp liquors, scrubber solutions containing alumina and hydrofluoric acid, and dye slurries.

CD-3MN is the cast version of wrought UNS 31803 or 2205. Compared with the other duplex grades it has a lower alloy content. Consequently, its cost is lower, but some corrosion resistance is sacrificed.

CD-3MWN is the cast version of wrought zeron 100. It has a corrosion resistance nearly as good as that of the superaustenitic alloys.

Z6CNDU 20.08M is the cast version of Uranus 50M. In terms of corrosion resistance it is slightly better than CF-8M but inferior to the other duplex stainless steels.

## Superaustenitic Alloys

Superaustenitic alloys are those austenitic stainless steels having alloying elements, particularly nickel and/or molybdenum, in higher percentages than the conventional 300 series stainless steels. Table C.11 lists the chemical compositions of these cast alloys. In some instances these alloys have been classified as nickel alloys. As can be seen in Table C.11 these alloys contain 16–25% chromium, 30–35% nickel, molybdenum, and nitrogen, and some also contain copper. No single element exceeds 50%.

Added resistance to reducing environments is provided by the additional nickel, while the extra molybdenum, copper, and nitrogen increase the resistance to pitting in chlorides. These alloys are fully austenitic, which makes them more difficult to cast than the ferrite-containing grades.

Superaustenitics are used for high-temperature chloride-containing environments where pitting and stress corrosion cracking are common causes of failure of other stainless steels. These alloys resist chloride stress corrosion cracking above 250°F (121°C). They also exhibit excellent resistance to sulfide stress cracking.

**Table C.11** Chemical Composition of Cast Superaustenitic Stainless Steel

| | Alloy (wt%) | | | | |
|---|---|---|---|---|---|
| Chemical | CD-7M | CN-7MS | CK-3MCuN | CE-3MN | CU-MCuC |
| Carbon | 0.07 | 0.07 | 0.025 | 0.03 | 0.05 |
| Manganese | 1.50 | — | — | — | — |
| Silicon | 1.50 | — | — | — | — |
| Phosphorus | 0.04 | — | — | — | — |
| Sulfur | 0.04 | — | — | — | — |
| Chromium | 19.0–22.0 | 18.0–20.0 | 19.5–20.5 | 20.0–22.0 | 19.5–23.5 |
| Nickel | 27.5–30.5 | 22.0–25.0 | 17.5–19.5 | 23.5–25.5 | 38.0–46.0 |
| Molybdenum | 2.0–3.0 | 2.5–3.0 | 6.0–7.0 | 6.0–7.0 | 2.50–3.50 |
| Copper | 3.0–4.0 | 1.5–2.0 | 0.5–1.0 | — | 1.50–3.50 |
| Nitrogen | — | — | 0.18–0.24 | 0.18–0.26 | — |
| Columbium | — | — | — | — | 0.6–1.2 |
| Iron | Balance | Balance | Balance | — | — |

Maximum unless otherwise noted.

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CN-7M is the cast equivalent of wrought alloy 20Cb3. This alloy resists sulfuric acid in all concentrations at temperatures up to 150°F (65°C) and higher for most concentrations. The high nickel content of CN-7M imparts excellent resistance to alkaline environments, such as sodium hydroxide, where it can be used up to 73% and at temperatures to 300°F (149°C). The chromium content of this alloy makes it superior to the CF grades in nitric acid—even better than CF-3, which is generally considered the best alloy for this service. Hydrochloric acid, certain chlorides, and strong reducing agents such as hydrogen sulfide, carbon disulfide, and sulfur dioxide will accelerate corrosion. Applications for CN-7M have also included hot acetic acid, dilute hydrofluoric and hydrofluosilicic acids, nitric-hydrofluoric pickling solutions, phosphoric acid, and plating solutions.

Alloy CN-7MS is a modified version of alloy CN-7M.

Alloys CK-3MCuN and CE-3MN are superior for chloride environments and are the cast equivalents of wrought alloys 254SM0 and A16XN, respectively.

CU-5MCuC is the cast version of wrought alloy 825, although niobium is substituted for titanium. Titanium will oxidize rapidly during air melting, while niobium will not. This alloy is similar in corrosion resistance to CN-7M. See Refs. 6 and 7.

## Precipitation Hardening Alloys

Table C.12 lists the cast precipitation-hardening stainless steels and gives their chemical compositions.

CB-7Cu is the cast equivalent of wrought alloy 326. The alloy is martensitic with minor amounts of retained austenite present in the microstructure. In the age-hardened condition this alloy exhibits corrosion resistance superior to the straight martensitic and ferritic grades. This alloy is used where moderate corrosion resistance and high strength are required. Typical applications include aircraft parts, pump shafting, and food processing equipment.

CB-7Cu-1 and CB-7Cu-2 are cast versions of wrought alloys 17-4PH and 15-5PH. CB-7Cu-1 is more commonly cast than CB-7Cu-2.

These alloys are similar in corrosion resistance to alloys CF-8 and wrought type 304, and better than the 400 series of stainless steels. They will resist atmospheric attack in all but the most severe environments. When in contact with seawater the alloys will pit, but they are resistant to natural water. Applications include uses in steam, boiler feedwater, condensate, and dry gases.

**Table C.12** Chemical Composition of Cast Precipitation-Hardening Stainless Steels

| | Alloy (wt%) | | |
|---|---|---|---|
| Chemical | CB-7Cu | CB-7Cu-1 | CB-7Cu-2 |
| Carbon | 0.07 | 0.07 | 0.07 |
| Manganese | 1.00 | — | — |
| Silicon | 1.00 | — | — |
| Phosphorus | 0.04 | — | — |
| Sulfur | 0.04 | — | — |
| Chromium | 15.5–17.0 | 15.5–17.7 | 14.0–15.5 |
| Nickel | 3.6–4.6 | 3.6–4.6 | 4.5–5.5 |
| Copper | 2.3–3.3 | 2.5–3.2 | 2.5–3.2 |
| Columbium | — | 0.15–0.35 | 0.15–0.35 |
| Iron | Balance | Balance | Balance |

Maximum unless otherwise noted.

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## CATHODE

A cathode is a negatively charged electrode where reduction is the principal reaction.

## CATHODIC CORROSION

Cathodic corrosion is an unusual condition in which metal loss is accelerated at the cathode as a result of the alkaline condition there being corrosive to certain amphoteric metals, primarily aluminum, zinc, and lead.

## CATHODIC DELAMINATION

Cathodic delamination is the loss of adhesion of a paint film adjacent to defects, when cathodic protection is applied to a coated metal.

## CATHODIC PROTECTION

When dissimilar metals are in physical or electrical contact (the latter via a conductive electrolyte), such as a process fluid or soil, galvanic corrosion can take place. The galvanic corrosion process is similar to the action of a simple DC cell in which the more active metal becomes an anode, and corrodes, while the less active metal becomes a cathode, and is protected. It is possible to predict which metals will corrode when in contact with others based on the galvanic series shown in the table.

| Galvanic Series | |
|---|---|
| *Anodic end* | |
| Magnesium | Hastelloy C (active) |
| Magnesium alloys | Brasses |
| Zinc | Copper |
| Aluminum 5052 | Bronzes |
| Aluminum 6061 | Cupronickel alloys |
| Cadmium | Monel |
| Aluminum AA2017 | Silver solder |
| Iron and carbon steel | Nickel (passive) |
| Copper steel | Inconel (passive) |
| 4–6% chromium steel | Ferritic stainless (passive) |
| Ferritic stainless (active) 400 series | Austenitic stainless (passive) |
| Austenitic stainless (active) 18-8 series | Titanium |
| Lead-tin solder | Hastelloy C (passive) |
| Lead | Silver |
| Tin | Graphite |
| Nickel (active) | Gold |
| Iconel (active) | Platinum |
| | *Cathodic end* |

All metals and alloys have certain inherent properties that cause them to react as anodes or cathodes when in contact with dissimilar metals or alloys. Whether a particular material will react as a cathode or an anode can be determined from its relative position in

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the galvanic series. The further apart two materials are from each other in the galvanic series, all other factors being equal, the greater the rate of corrosion. The material closest to the anodic end will be the one to corrode. For example, if tin and zinc were in contact, the zinc would corrode, whereas if tin and copper were in contact, the tin would corrode.

The rate of attack is also affected by the relative size of the material and the specific electrolyte present. A small anode area in contact with a large cathode area will result in a rapid severe attack. Conversely, a large anode area in contact with a small cathode area will lessen the rate of galvanic attack since the same total emf driving force of corrosion will be spread out over a larger area. Also, the higher the degree of ionization of the electrolyte, the greater the rate of attack.

Galvanic corrosion can also take place when metals having the same analysis have different surface conditions and an electrolyte is present. In general, the formation of a corrosion cell is induced by the nonuniformity of the surface condition, such as with defects in the surface oxide film, localized distribution of elements, and difference in crystal face or phase. These nonuniformities of surface cause potential difference between portions of the surface and thereby promote the formation of a corrosion cell.

Galvanic corrosion can be stopped by means of cathodic protection, which is an electrochemical technique. It can be applied to metals immersed in water, buried in soil, or in contact with electrolytes in a process application. Cathodic protection consists of a cathodic current flowing through the metal electrolyte interface, favoring the reduction reaction over the anodic metal dissolution. The entire structure works as a cathode.

This electrochemical technique was developed by Sir Humphrey Davy in 1824. The British Admiralty had blocks of iron attached to the hulls of copper-sheathed vessels to provide cathodic protection. Unfortunately, cathodically protected copper is subject to fouling by marine life, which reduced the speed of vessels under sail and forced the Admiralty to discontinue the practice. Unprotected copper provides a sufficient number of copper ions to poison fouling organisms. However, the corrosion rate of the copper had been appreciably reduced.

In 1829 Edmund Davy was successful in protecting the iron portions of buoys by using zinc blocks, and in 1840 Robert Mallet produced a zinc alloy that was particularly suited as a sacrificial anode. As steel hulls replaced wooden hulls, the fitting of zinc slabs to the steel hulls, to provide cathodic protection, became standard practice.

In 1950 the Canadian Navy determined that the proper use of antifouling paints in conjunction with corrosion-resisting paints made cathodic protection of ships feasible and could reduce maintenance costs.

Cathodic protection is achieved by applying electrochemical principles to metallic components buried in soil or immersed in water. It is accomplished by flowing a cathodic current through a metal-electrolyte interface, favoring the reduction reaction over the anodic metal dissolution. This enables the entire structure to work as a cathode.

The basis of cathodic protection is shown in the polarization diagram for a copper-zinc cell in Fig. C.3. If polarization of the cathode is continued by use of an external current beyond the corrosion potential to the open-circuit potential of the anode, both electrodes reach the same potential and no corrosion of the zinc can take place.

Cathodic protection is accomplished by supplying an external current to the corroding metal on the surface of which local action cells operate, as shown in Fig. C.4. Current flows from the auxiliary anode and enters the anodic and cathodic areas of the corrosion cells, returning to the source of the DC current (B). Local action current will

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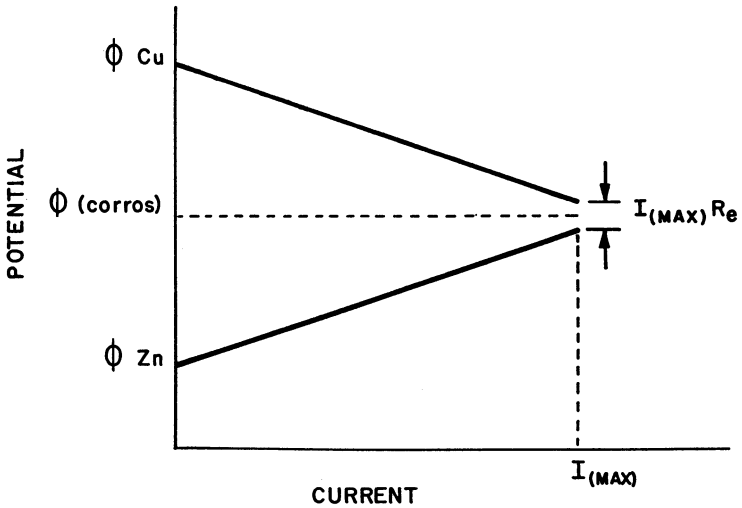



**Figure C.3** Polarization of copper-zinc cell.

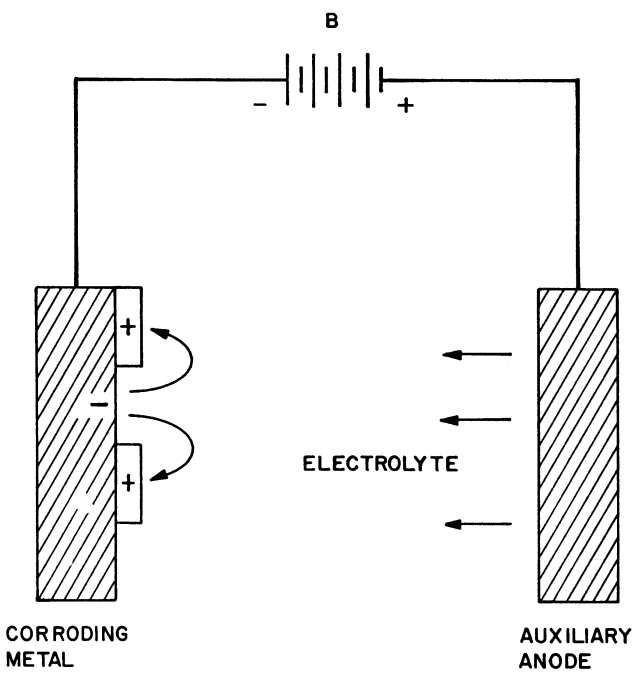



**Figure C.4** Cathodic protection using impressed current on local action cell.

cease to flow when all the metal surface is at the same potential as a result of the cathodic areas being polarized by an external current to the open-circuit potential of the anodes. As long as this external current is maintained, the metal cannot corrode.

There are two methods by which cathodic protection can be accomplished. One is by coupling the structure with a more active metal, such as zinc or magnesium. This

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produces a galvanic cell in which the active metal works as an anode and provides a flux of electrons to the structure. The structure then becomes the cathode and is protected, while the anode is destroyed progressively and is called a sacrificial anode.

The second method is to impress a direct current between an inert anode and the structure. The structure receives the excess of electrons, which protects it. About 1910–1912 the first application of cathodic protection by means of an impressed electric current was undertaken in England and the United States. Since that time the general use of cathodic protection has been widespread. There are thousands of miles of buried pipelines and cables that are protected in this manner. This form of protection is also used for water tanks, submarines, canal gates, marine piping, condensers, and chemical equipment.

## Sacrificial Anodes

In cathodic protection, the structure to be protected must receive a cathodic current flow so that it operates as a cathode. The need for an external DC current to accomplish this can be eliminated by selecting an anode constructed of a metal that is more active in the galvanic series than the metal to be protected. A galvanic cell will be established with the current direction as required. These sacrificial anodes are usually composed of magnesium or magnesium-based alloys. On occasion zinc or aluminum have been used.

Magnesium is more active than steel, it has a greater tendency to ionize, and its potential is more active than iron. The open-circuit potential difference between magnesium and steel is about 1 volt. This means that one anode can protect only a limited length of pipeline. This low voltage can have an advantage over higher impressed voltages in that the danger of overprotection to some portions of the structure is less and because the total current per anode is limited; the danger of stray-current damage to adjoining metal structures is reduced.

Magnesium rods have also been placed in steel hot water tanks to increase their life. The greatest degree of protection is afforded in hard waters, since the degree of conductivity is greater than in soft waters.

## Sacrificial Anode Requirements

To provide cathodic protection, a current density of a few milliamps (mA) is required. In order to determine the anodic requirement, it is necessary to know the energy content of the anode and its efficiency. With this information it is possible to determine the size of the anode required, its expected life, and the number of anodes required.

The three most common metals used as sacrificial anodes are magnesium, zinc, and aluminum. The energy content and efficiency of these metals are shown in the table.

| Metal | Theoretical energy content (A h/lb) | Anodic efficiency % | Practical energy content (A h/lb) (PE) |
|---|---|---|---|
| Magnesium | 1000 | 50 | 500 |
| Zinc | 370 | 90 | 333 |
| Aluminum | 1345 | 60 | 810 |

Zinc is more economical to use than magnesium, but because of the relatively small cell voltage it produces, it is primarily useful under special circumstances, such as to protect ships in seawater or to prevent corrosion of systems with low current requirements.

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Although magnesium is more expensive than zinc, and although it is consumed faster than zinc or aluminum, it does provide the largest cell voltage and the largest current. Care must be taken not to use aluminum in environments having a pH of 8 or greater, since alkaline conditions will produce a rapid self-corrosion of aluminum.

In determining anodic requirements to provide cathodic protection, several calculations are required. The number of pounds of metal required to provide a current of 1 A for one year is calculated as

$$\text{lb metal/A-yr} = \frac{8760 \text{ h/yr}}{\text{PE}}$$

For magnesium this would be

$$\text{lb Mg/A-yr} = \frac{8760}{500} = 17.52$$

The number of years (YN) for which 1 lb of metal can produce a current of 1 mA is determined from

$$\text{YN} = \frac{\text{PE}}{10^{-3}\text{A } 8760 \text{ hr/yr}}$$

For magnesium this would be

$$\text{YN} = \frac{500}{10^{-3}(8760)} = 60 \text{ yr}$$

The current density requirements for cathodic protection is on the order of a few milliamps. The life expectancy ($L$) of an anode of $W$ lb delivering a current of 1 mA is calculated as

$$L = \frac{\text{YN}(W)}{i}$$

For magnesium this would be

$$L = \frac{60W}{i}$$

which is based on 50% anodic efficiency. Since actual efficiencies tend to be somewhat less, it is advisable to apply a safety factor and multiply the result by 0.75.

The current required to secure protection of a structure and the available cell voltage between the metal structure and the sacrificial anode determine the number of anodes required. This can be illustrated by the following example.

Assume that an underground pipeline has an external area of 200 sq ft and a soil resistivity of 600 ohm cm. Field tests indicate that 6 mA/sq ft is required for protection. To provide protection for the entire pipeline,

$$(6 \text{ mA/ft}^2)(200 \text{ ft}^2) = 1200 \text{ mA}$$

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is required. Magnesium anodes used in this particular soil have a voltage of –1.65 V or a galvanic cell voltage of

$$\begin{aligned} E_{\text{calc}} &= E_c - E_a \\ &= -0.85 - (-1.65) \\ &= +0.8V \end{aligned}$$

Therefore, the resistance is

$$R = \frac{V}{I} = \frac{0.8}{1.2} = 0.67 \text{ ohm}$$

As the number of anodes is increased, the total resistance of the system decreases. Each anode that is added provides a new path for current flow, parallel to the existing system. The relationship between the resistance of the system and the number of anodes is shown in the Sunde equation:

$$R = \frac{0.00521P}{NL}\left(2.3\log\frac{8L}{d-1} + \frac{2L}{S}\,2.3\log 0.656N\right)$$

where

$R$ = resistance (ohms)
$P$ = soil resistivity (ohm-cm)
$N$ = number of anodes
$L$ = anode length (ft)
$d$ = diameter of anode (ft)
$S$ = distance between anodes (ft)

Fig. C.5 shows the typical plotting of the results of this equation. Different anodic shapes will have different curves.

## Impressed Current Systems

For these systems the source of electricity is external. A rectifier converts high voltage to a low-voltage DC current. This direct current is impressed between buried anodes and the structure to be protected.

It is preferable to use inert anodes, which will last for the longest possible time. Typical materials used for these anodes are graphite, silicon, titanium, and niobium plated with platinum.

For a given applied voltage, the current is limited by electrolyte resistivity and by the anodic and cathodic polarization. With the impressed current system it is possible to impose whatever potential is necessary to obtain the current density required by means of the rectifier.

Electric current flows in the soil from the buried anode to the underground structure to be protected. Therefore, the anode must be connected to the positive pole of the rectifier and the structure to the negative pole. All cables from the rectifier to the anode and to the structure must be electrically insulated. If not, those from the rectifier to the anode will act as an anode and deteriorate rapidly, while those from the rectifier to the structure may pick up some of the electric current, which would then be lost for protection.

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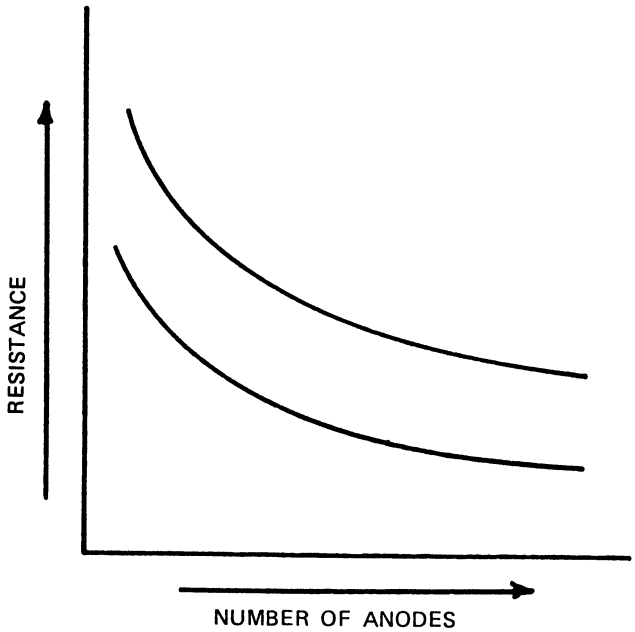



**Figure C.5** Plot of Sunde equation.

## Current Requirements

The specific metal and the environment will determine the current density required for complete protection. The applied current density must always exceed the current density equivalent to the measured corrosion rate under the same conditions. Therefore, as the corrosion rate increases, the impressed current density must be increased to provide protection.

Factors that affect current requirements are

1. The nature of the electrolyte
2. The soil resistivity
3. The degree of aeration

The more acid the electrolyte, the greater will be the potential for corrosion and the greater will be the current requirement. Soils that exhibit a high resistance require a lower cathodic current to provide protection. In the area of violent agitation or high aeration, an increase in current will be required. The required current to provide cathodic protection can vary from 0.5 to 20 mA/sq ft of bare surface.

Field testing may be required to determine the necessary current density to provide cathodic protection in a specific area. These testing techniques will only provide an approximation. After completion of the installation, it will be necessary to conduct a potential survey and make the necessary adjustments to provide the desired degree of protection.

## Anode Materials and Backfill

Although it is generally preferred to use inert anodes, it is possible to use scrap iron. Scrap iron is consumed at a considerably faster rate than graphite or other inert anode materials.

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The advantage of scrap iron is its lower initial cost and lower operating cost, since its power requirements are less. In areas where replacement poses a problem, the cost of the use of the more inert anodes outweighs the reduced cost of the scrap iron.

Platinum clad or 2% silver-lead electrodes have been used for protection of structures in seawater and are estimated to last 10 years, whereas sacrificial magnesium anodes have a life of 2 years.

Since the effective resistivity of soil surrounding an anode is limited to the immediate area of the electrode, this local resistance is usually reduced by using backfill. The anode is usually surrounded by a thick bed of coke mixed with 3 or 4 parts of gypsum to one part of sodium chloride. The consumption of the anode itself is reduced somewhat, since the coke backfill carries a part of the current. Backfill is not required when the anode is immersed in a river bed, lake, or ocean.

## Testing for Completeness of Protection

Once the system has been installed, it must be tested for completeness of protection. The preferred method is to take potential measurements. By measuring the potential of the protected structure, the degree of protection including overprotection can be determined. The basis for this determination is the fundamental concept that cathodic protection is complete when the protected structure is polarized to the open-circuit anodic potential of the local action cells.

The reference electrode is placed as closely as possible to the protected structure to avoid and to minimize an error caused by internal resistance (IR) drop through the soil. For buried pipelines a compromise location is directly over the buried pipe at the soil surface because cathodic protection currents flow mostly to the lower surface and are minimum at the upper surface of the pipe buried a few feet below the surface.

The potential for steel is equal to –0.85 V versus the copper-saturated copper sulfate half-cell, or 0.53 V on the standard hydrogen scale. The theoretical open-circuit anodic potential for other metals may be calculated using the Nernst equation. Several typical calculated values are shown in the table.

| Metal | E° (V) | Solubility product $M(OH)_2$ | $OH_2$ scale (V) | O vs. Cu–$CuSO_4$ reference (V) |
|---|---|---|---|---|
| Iron | 0.440 | $1.8 \times 10^{-15}$ | –0.59 | –0.91 |
| Copper | –0.337 | $1.6 \times 10^{-19}$ | 0.16 | –0.16 |
| Zinc | 0.763 | $4.5 \times 10^{-17}$ | –0.93 | –1.25 |
| Lead | 0.126 | $4.2 \times 10^{-15}$ | –0.27 | –0.59 |

Overprotection of steel structures, to a moderate degree, does not cause any problems. The primary disadvantages are waste of electric power and increased consumption of auxiliary anodes. When overprotection is excessive, hydrogen can be generated at the protected structure in sufficient quantities to cause blistering of organic coatings, hydrogen embrittlement of the steel, or hydrogen cracking.

Overprotection of systems with amphoteric metals (e.g., aluminum, zinc, lead, tin) will damage the metal by causing increased attack instead of reduction of corrosion. This stresses the need for making potential measurements of protected structures.

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### Use with Coatings

It is advantageous to use insulating coatings with sacrificial anodes or impressed current systems when supplying cathodic protection. These coatings need not be pore free, because the protective current flows preferentially to the exposed metal areas, which require the protection. Coatings are useful in distributing the protective current, in reducing total current requirements, and in extending the life of the anode. Compared to a bare pipeline, the current distribution in a coated pipeline is greatly improved, the total number of anodes required is reduced, and the total current required is less. In addition, one anode can protect a much longer section of pipeline. For example, one magnesium anode is capable of protecting approximately 100 feet (30 m) of a bare pipeline, whereas the same anode can provide protection for approximately 5 miles of a coated pipeline.

In a hot water tank coated with glass or an organic coating, the life of the magnesium anode is increased and more uniform protection is supplied to the tank. Without the coating the tendency is for excess current to flow to the side, and insufficient current flows to the top and bottom.

Because of these factors cathodic protection is usually provided with coated surfaces.

### Economics

The installation of cathodic protection systems has made it economically feasible to transport oil and high-pressure natural gas across the American continent by

1. Guaranteeing there will be no corrosion on the soil side of the pipe
2. Permitting the use of thinner-walled pipe
3. Eliminating the need for an external corrosion allowance
4. Reducing maintenance costs
5. Permitting longer operating periods between routine inspections and maintenance periods

The cost of the cathodic protection system is more than recovered as a result of the above savings. Similar savings and advantages have been realized on other types of installations where cathodic protection systems have been installed.

See Refs. 1, 8–10.

## CAUSTIC EMBRITTLEMENT

Caustic embrittlement is a form of stress corrosion cracking occurring in metals in contact with caustic under certain conditions. The developing cracks result from the combined actions of tensile stress and corrosion. The cracking can he intergranular or transgranular.

See "Stress Corrosion Cracking."

## CAVITATION CORROSION

This form of corrosion is similar to erosion corrosion. It is caused by the formation and collapse of tiny vapor bubbles near a metallic surface in the presence of a corrodent. The protective film is damaged by the high pressure caused by the collapse of the bubbles. This form of corrosion is found quite frequently on pump impellers and condensers.

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## CELL POTENTIALS

A reaction will occur only if there is a negative free energy change ($\Delta G$). For electrochemical reactions the free energy change is calculated by

$$\Delta G = -nFE$$

where $n$ is the number of electrons, $F$ is Faraday's constant, and $E$ is the cell potential.

For a given reaction to take place the cell potential must be positive. The cell potential is the difference between the two half-cell reactions, the one at the cathode minus the one at the anode.

The cell potential for iron corroding freely in acid is calculated to be

$$E = \text{cathode half-cell} - \text{anode half-cell}$$

$$E = E(H^{1}/H_2) - E(Fe/Fe^{21})$$

$$E = (0) - (-0.440) = +0.44$$

The reaction can take place because the cell potential is positive. The larger the potential difference, the greater the driving force for the reaction. In order for corrosion to occur, there must be a current flow and a completed circuit, which is then governed by Ohm's law:

$$I = \frac{E}{R}$$

The cell potential calculated here represents the peak value for the case of the two independent reactions. If the resistance were infinite, the cell potential would remain as calculated, but there would be no corrosion at all. If the resistance of the circuit were zero, the potentials of each half-cell would approach the other while the rate of corrosion would be infinite.

See Refs. 10, 11.

## CERAMIC MATERIALS

Ceramic materials are various hard, brittle, heat-resistant, and corrosion-resistant materials produced by firing (heat treating) clay, other minerals, or synthetic inorganic compositions. They usually consist of one or more metals in combination with a nonmetal, usually oxygen.

Ceramics are subject to many of the forms of corrosion that metals are subject to, including uniform corrosion, crevice corrosion, pitting, cavitation corrosion, erosion corrosion, galvanic corrosion, intergranular corrosion, and corrosion-assisted cracking.

Corrosion data reported on ceramic materials presents two problems: the wide variety of units used and the use of units that make it difficult to compare results from different investigators. From an engineering and practical aspect, for ceramics the two main criteria for corrosion performance are loss of physical dimension and loss of mechanical properties.

The preferred units for measuring loss of physical dimension are penetration rates, such as mils per year (mpy). This is comparable to the measurement used for metallic corrosion.

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Corrosion of ceramic materials is a complicated process. It can take place by any one or a combination of mechanisms. In general, the environment will attack the ceramic, forming a reaction product that may be a gas, a liquid, a solid, or a combination. When the reaction product formed is a solid, it may form a protective layer preventing further corrosion. If the reaction product formed is a combination of a solid and a liquid, the protective layer formed may be removed by the process of erosion.

Some of the fundamental concepts of chemistry will help to permit understanding of the corrosion of a ceramic section. A ceramic with acidic character tends to be attacked by an environment with a basic character, and vice versa; ionic materials tend to be soluble in polar solvents while covalent materials tend to be soluble in nonpolar solvents; the solubility of solids in liquids generally increases with increasing temperatures.

## Crystalline Materials

Polycrystalline materials are made up of several components. Corrosive attack on these materials starts with the least corrosion-resistant component, which normally is the ingredient used for bonding, or more generally the minor component of the material.

The corrosion of a solid crystalline material by a liquid can result from either indirect dissolution or direct dissolution. In the former, an interface or reaction product is formed between the solid crystalline material and the solvent. This reaction product, being less soluble than the bulk solid, may or may not form an attached surface layer. In direct dissolution the solid crystalline material dissolves directly into the solvent.

When a silicate is leached by an aqueous solution, an ion is removed from a site within the crystal structure and is placed into the aqueous phase. Whether or not leaching occurs will depend upon the ease with which the ions can be removed from the crystal structure.

The corrosion of polycrystalline ceramic by a vapor can be more serious than attack by either liquids or solids. Porosity or permeability of the ceramic is one of the most important properties related to its corrosion by a vapor or gas. If the vapor can penetrate the material, the surface area exposed to attack is greatly increased and corrosion proceeds rapidly. A combined attack of vapor may also take place. In this situation the vapor may penetrate the material under a thermal gradient to a lower temperature, condense, and then dissolve material by liquid solution. The liquid solution can then penetrate further along temperature gradients until it freezes. If the thermal gradient is changed, it is possible for the solid reaction products to melt, causing excessive corrosion and spalling at the point of melting.

If two dissimilar solid materials react when in contact with each other, corrosion can take place. Common types of reactions involve the formation of a solid, a liquid, or a gas. Solid-solid reactions are predominantly reactions involving diffusion.

Porosity plays an important role in the corrosion resistance of ceramics. The greater the porosity, the greater will be the corrosion. The fact that one material may yield a better corrosion resistance than another does not necessarily make it a better material, if the two materials have different porosities.

Ceramics that have an acid or base characteristic similar to the corrodent will tend to resist corrosion the best. In some cases the minor components of a ceramic, such as the

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bonding agent, may have a different acid/base character than the major component. In this instance the acid/base character of the corrodent will determine which phase corrodes first.

In the area of corrosion resistance of ceramics we will be dealing with the so-called traditional ceramics, which include brick-type products.

Common bricks, though hard to the touch, have a high water adsorption (anywhere from 8% to 15%) and are leached or destroyed by exposure to strong acid or alkali. Acid bricks, whether of shale or fireclay body, are made from selected clays containing few acid-soluble components. These bricks are fired for a longer period of time at higher temperatures than the same clay when used to make common brick. This firing eliminates any organics that may be present and produces a brick with a much lower absorption rate, under 1% for best-quality red shale and under 5% for high-quality fireclay. See "Acid Brick."

Zirconia-containing materials will be attacked by alkali solutions containing lithium, potassium, or sodium hydroxide, and potassium carbonate.

The transition metal carbides and nitrides are chemically stable at room temperature but exhibit some attack by concentrated acid solutions. The normally protective layer of silicon oxide that forms on the surface of silicon carbide and silicon nitride can exhibit accelerated corrosion when various molten salts are present. None of the carbides or nitrides are stable in oxygen-containing environments. Under certain conditions some carbides and nitrides form a protective metal oxide layer that allows them to exhibit reasonably good oxidation resistance. Silicon carbide and nitride are reasonably inert to most silicate liquors as long as they do not contain significant amounts of iron oxide.

Quartz (silica) is not attacked by hydrochloric, nitric, or sulfuric acids at room temperature but will be slowly attacked by alkaline solutions. At elevated temperatures, quartz is readily attacked by sodium hydroxide, potassium hydroxide, sodium carbonate, and sodium borate. The presence of organics dissolved in the water increases the solubility of silica. Fused silica is attacked by molten sodium sulfate.

Tables C.13a, 13b, and 13c show the compatibility of various ceramic materials with selected corrodents.

## Glassy Materials

Typical glassy materials consist of silicate glasses, borosilicate glasses, lead-containing glasses, phosphor-containing glasses, fluoride glasses, and chalcogenide-halide glasses.

Glassy materials corrode primarily through the action of aqueous media. In general, the very high silica glasses (96% $Si0_2$) such as aluminosilicate and borosilicate compositions have excellent resistance to a variety of corrodents.

Borosilicate glass is the primary composition used in the corrosion resistance field. It is resistant to all chemicals except hydrofluoric acid, fluorides, and such strong caustics as sodium or potassium hydroxide. However, caustics of even up to 50% concentration at room temperature will not be detrimental to borosilicate glass.

Because of its inertness, borosilicate glass has found wide usage in contact with high-purity products. The glass will not impart contamination to the material it comes into contact with. See "Borosilicate Glass."

There are many glass compositions. A list of about 30 glass compositions with their resistance to weathering, water, and acid may be found on page 572 of *Encyclopedia of Glass Technology,* 2nd ed., vol. 10, published by Wiley in New York.

See Refs. 12 and 13.

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## C-GLASS

This is a calcium aluminosilicate glass used for reinforcing thermosetting resins. See "Thermoset Reinforcing Materials."

**Table C.13a** Chemical Resistance of Various Ceramic Materials

| | Resistance to | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Slags | | Molten metals | | | | | |
| Material | Acid | Basic | Al | Fe | Na | Pb | Zn | Mg |
| Zircon | G | F | G | G | P | G | G | F |
| Bonded 99% alumina | G | G | G | G | P | G | G | G |
| Fused cast alumina | EX | G | G | G | F | G | G | EX |
| Zirconia stabilized | G | P | G | G | P | G | G | F |
| Silicon carbide | G | F | G | P | P | | EX | G |
| Silicon nitride bonded silicon carbide | EX | F | EX | P | P | | EX | G |
| Magnesite | P | G | F | G | P | G | F | F |
| Chrome | P | F | P | G | P | G | F | F |
| Fosterite | P | F | F | G | P | G | F | F |
| Synthetic mullite | G | G | F | G | P | G | G | F |
| Converted mullite | G | F | F | G | P | G | G | F |
| Silica | G | F | P | G | P | F | G | P |
| Fireclay | G | F | F | G | P | F | G | P |

EX = Excellent, G = Good, F = Fair, P = Poor.

**Table C.13b** Chemical Resistance of Various Ceramic Materials: Resistance to Gases

| Material | $CO_2$ | CO | Steam | $Cl_2$ | $H_2$ | HCl | $NH_3$ | $SO_2$ | S |
|---|---|---|---|---|---|---|---|---|---|
| Zircon | A | A | A | B–D | E | A | A | A | B–D |
| Bonded 99% alumina | A | A | A | A | A | A | A | A | A |
| Fused cast alumina | A | A | A | A–D | A | A | A | A | A–C |
| Zirconia stabilized | A | A | B–C | B | E | A | E | A | A–B |
| Silicon carbide | B | B | B | D | | A | A | A | D |
| Silicon nitride bonded silicon carbide | B | B | B | D | | A | A | A | A–C |
| Magnesite | A | B–C | A | D | | D | A | C–D | B–D |
| Chrome | A | B–C | A | C–D | | C–D | A | C–D | B–C |
| Fosterite | A | A | A | C–D | | C–D | A | C–D | B–C |
| Synthetic mullite | A | A | A | B–D | | A | A–C | A | A |
| Converted mullite | A | B–C | A | B–E | | A | A–C | A–C | A–C |
| Silica | A | A | A | C–E | | A | A–C | B–C | B–C |
| Fireclay | A | C | A | C–E | | A | A–C | B–C | B–C |

A = No reaction, material stable; B = Slight reaction, material suitable; C = Reaction, material suitable under certain conditions: D = Reaction, material not suited unless tested under operating conditions; E = Rapid reaction, material not suitable.

1. Chlorine attacks silicates above 1300°F (704°C).
2. Nascent or atomic hydrogen attacks silica and iron.
3. Sulfur in strong concentrations reacts with silica above 1700°F (927°C).

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**Table C.13c** Chemical Resistance of Various Ceramic Materials: Resistance to Heated Acids

| Material | Nitric | Sulfuric | Hydrochloric | Hydrofluoric | Phosphoric | Hydrocarbons |
|---|---|---|---|---|---|---|
| Zircon | A | A | A | B–C | A–B | A–D |
| Bonded 99% alumina | A | A | A | A–C | A | A |
| Fused cast alumina | A | A | A | A–C | A | A |
| Zirconia stabilized | A | A | A | B–C | A | A |
| Silicon carbide | A | A | A | B–D | A–B | A–D |
| Silicon nitride bonded silicon carbide | A | A | A | C–D | A | A–C |
| Magnesite | D | D | D | D | D | B–C |
| Chrome | B–C | B–D | B–D | B–E | B–D | B–C |
| Fosterite | B–D | B–D | B–D | B–E | B–E | B–C |
| Synthetic mullite | A | A | A | C–E | A–B | A–D |
| Converted mullite | A | A | A | C–E | A–B | A–D |
| Silica | A–C | A–C | A–C | E | A–C | B–D |
| Fireclay | A–C | A–C | A–C | E | A–C | B–D |

A = No reaction, material stable; B = Slight reaction, material suitable; C = Reaction, material suitable under certain conditions; D = Reaction, material not suited unless tested under operating conditions; F = Rapid reaction, material not suitable.

## CHECKING

Checking is the development of slight breaks in a coating film that do not penetrate to the underlying surface. It is also cracking in a crosshatch manner resembling mud cracking. It usually forms as the coating ages and becomes harder and more brittle as a result of shrinkage of the film.

## CHEMICAL SYNONYMS

| Chemical | Synonym |
|---|---|
| Acetic acid, crude | Pyroligneous acid |
| Acetic acid amide | Acetamide |
| Acetic ether | Ethyl acetate |
| Acetol | Diacetone alcohol |
| Acetylbenzene | Acetophenone |
| Acetylene tetrachloride | Tetrachloroethane |
| Almond oil | Benzaldehyde |
| Aluminum hydrate | Aluminum hydroxide |
| Aluminum potassium chrome | Chrome alum |
| Alum potash | Aluminum potassium sulfate |
| Amino benzene | Aniline |
| Ammonium fluoride, acid | Ammonium bifluoride |
| Baking soda | Sodium carbonate |
| Benzene carbonal | Benzaldehyde |
| Benzene carboxylic acid | Benzoic acid |
| Benzol | Benzene |
| Boracic acid | Boric acid |

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| Chemical | Synonym |
|---|---|
| Bromomethane | Methyl bromide |
| Butanoic acid | Butyric acid |
| Butanol-1 | Butyl alcohol |
| Butanone | Methyl ethyl ketone |
| Butter of antimony | Antimony trichloride |
| Butyl phthalate | Dibutyl phthalate |
| Calcium sulfide | Lime sulfur |
| Carbamide | Urea |
| Carbolic acid | Phenol |
| Carbonyl chloride | Phosgene |
| Caustic potash | Potassium hydroxide |
| Caustic soda | Sodium hydroxide |
| Chlorobenzene | Monochlorobenzene |
| 1-Chlorobutane | Butyl chloride |
| Chloroethane | Ethyl chloride |
| Chloroethanoic acid | Chloroacetic acid |
| Chloromethane | Methyl chloride |
| Chloropentane | Amyl chloride |
| 3-Chloropropene-1 | Allyl chloride |
| Chlorotoluene | Benzyl chloride |
| Chromium trioxide | Chromic acid |
| Cupric acetate | Copper acetate |
| Cupric carbonate | Copper carbonate |
| Cupric fluoride | Copper fluoride |
| Cupric nitrate | Copper nitrate |
| Cupric sulfate | Copper sulfate |
| Cuprous chloride | Copper chloride |
| Diacetone | Diacetone alcohol |
| Dibromomethane | Ethylene bromide |
| Dibutyl ether | Butyl ether |
| Dichloroethane | Ethylene dichloride |
| Dichloroethane | Dichloroethylene |
| Dichloromethane | Methylene chloride |
| Diethyl | Butane |
| Diethylene dioxide | Dioxane |
| Diethylenimide oxide | Morpholine |
| Dihydroxy ethane | Ethylene glycol |
| Dimethylbenzene | Xylene |
| Dimethyl polysiloxane | Silicone oil |
| Dipropyl | Hexane |
| Dipropyl ether | Isopropyl ether |
| Dowtherm | Diphenyl |
| Epsom salt | Magnesium sulfate |
| Ethanal | Acetaldehyde |
| Ethanamide | Acetamide |
| Ethanoic acid | Acetic acid |
| Ethnoic anhydride | Acetic anhydride |
| Ethanol | Ethyl alcohol |
| Ethanonitrile | Acetonitrile |
| Ethanoxy ethanol | Cellosolve |
| Ethanoyl chloride | Acetyl chloride |

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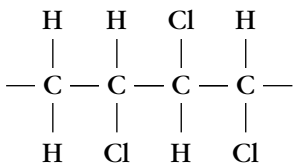
| Chemical | Synonym |
|---|---|
| Ethylene chloride | Ethylene dichloride |
| Ethyl ether | Diethyl ether |
| Formalin | Formaldehyde |
| Furfuraldehyde | Furfural |
| Furfurol | Furfural |
| Glucose | Dextrose |
| Glycerol | Glycerine |
| Glycol | Ethylene glycol |
| Glycol ether | Diethylene glycol |
| Glycol methyl ether | Methyl Cellosolve |
| Hexamethylene | Cyclohexane |
| Hexandioic acid | Adipic acid |
| Hexose | Dextrose |
| Hexyl alcohol | Hexanol |
| Hydroxybenzoic acid | Salicylic acid |
| Hypo photographic solution | Sodium bisulfate |
| Lime | Calcium oxide |
| Marsh gas | Methane |
| Methanal | Formaldehyde |
| Methanoic acid | Formic acid |
| Methanol | Methyl alcohol |
| Methylbenzene | Toluene |
| Methyl chloroform | Trichloroethane |
| Methyl cyanide | Acetonitrile |
| Methyl phenol | Cresol |
| Methyl l phenol ketone | Acetophenone |
| Methyl phthalate | Dimethyl phthalate |
| Methyl propane–2 | Butyl alcohol, tertiary |
| Muriatic acid | Hydrochloric acid |
| Nitrogen trioxide | Nitrous acid |
| Oil of mirbane | Nitrobenzene |
| Oil of wintergreen | Methyl salicylate |
| Oxalic nitrile | Cyanogen |
| Phenylamine | Aniline |
| Phenyl bromide | Bromobenzene |
| Phenyl carbinol | Benzyl alcohol |
| Phenyl chloride | Chlorobenzene |
| Phenyl ethane | Ethylbenzene |
| Pimelic ketone | Cyclohexanone |
| Propanoic acid | Propionic acid |
| Propanol | Propyl alcohol |
| Propanone | Acetone |
| Propenyl alcohol | Allyl alcohol |
| Propenoic acid | Acrylic acid |
| Propyl acetate | Isopropyl acetate |
| Prussic acid | Hydrocyanic acid |
| Pyrogallol | Progallic acid |
| Red oil | Oleic acid |
| Sal ammoniac | Ammonium chloride |
| Sodium borate, tetra | Borax |
| Sodium phosphate, diabasic | Disodium phosphate |

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| Chemical | Synonym |
|---|---|
| Starch gum | Dextrin |
| Sugar of lead | Lead acetate |
| Sulfuric chlorohydrin | Chlorosulfonic acid |
| Tannin | Tannic acid |
| Tetrachloroethylene | Perchloroethylene |
| Tetrachloromethane | Carbon tetrachloride |
| Trichloromethane | Chloroform |
| Trihydroxybenzene | Pyrogaflic acid |
| Trihydroxybenzoic acid | Gallic acid |
| Trinitrophenol | Picric acid |
| Vinyl cyanide | Acrylonitrile |
| Water glass | Sodium silicate |

## CHLORINATED POLYVINYL CHLORIDE (CPVC)

See also "Polymers." When acetylene and hydrochloric acid are reacted to produce polyvinyl chloride, the chlorination is approximately 56.8%. Further chlorination of the PVC to approximately 67% produces CPVC, whose chemical structure is as follows



The additional chlorine increases the heat deflection temperature and permits a higher allowable operating temperature. While PVC is limited to a maximum operating temperature of l40°F (60°C), CPVC has a maximum operating temperature of 180°F (82°C). Because of the higher operating temperature. CPVC finds application as piping for condensate return lines in areas having corrosive external conditions. It has also found application for hot water piping. The physical and mechanical properties are given in Table C.14.

The corrosion resistance of CPVC is similar to that of PVC but not identical. CPVC can be used to handle most acids, alkalies, salts, halogens, and many corrosive wastes. In general it cannot be used in contact with most polar organic materials, including chlorinated or aromatic hydrocarbons, esters, and ketones. Refer to Table C.15 for the compatibility of CPVC with selected corrodents. Reference 4 provides a more comprehensive listing of the compatibility of CPVC with selected corrodents.

See also Ref. 14.

## CHLOROBUTYL RUBBER

See "Butyl Rubber and Chlorobutyl Rubber."

## CHLOROSULFONATED POLYETHYLENE RUBBER (HYPALON)

Chlorosulfonated polyethylene rubber (CSM) is manufactured by DuPont under the trade name Hypalon. In many respects it is similar to neoprene, but it does possess some advantages over neoprene in certain types of service. It has better heat and ozone resistance, better electrical properties, better color stability, and better chemical resistance.

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**Table C.14** Physical and Mechanical Properties of CPVC

| | |
|---|---|
| Specific gravity | 155 |
| Water absorption 24 h at 73°F (23°C), % | 0.03 |
| Tensile strength at 73°F (23°C), psi | 8000 |
| Modulus of elasticity in tension at 73°F (23°C) $\times 10^5$ | 4.15 |
| Compressive strength at 73°F (23°C), psi | 9000 |
| Flexural strength, psi | 15,100 |
| Izod impact strength at 73°F (23°C) | 1.5 |
| Coefficient of thermal expansion | |
| in./in.–°F $\times 10^{-5}$ | 3.4 |
| in./10°F/100 ft | 0.034 |
| Thermal conductivity Btu/h/sq ft/°F/in. | 0.95 |
| Heat distortion temperature, °F/°C | |
| at 66 psi | 238/114 |
| at 264 psi | 217/102 |
| Resistance to heat at continuous drainage, °F/°C | 200/93 |
| Limiting oxygen index, % | 60 |
| Flame spread | 15 |
| Underwriters lab rating (U.L. 94) | VO;5VA;5VB |

*Source:* Courtesy of B. F. Goodrich. Specialty Polymers and Chemical Division.

**Table C.15** Compatibility of CPVC with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetaldehyde | x | x | Ammonium carbonate | 200 | 93 |
| Acetic acid 10% | 90 | 32 | Ammonium chloride 10% | 180 | 82 |
| Acetic acid 50% | x | x | Ammonium chloride 50% | 180 | 82 |
| Acetic acid 80% | x | x | Ammonium chloride, sat. | 200 | 93 |
| Acetic acid, glacial | x | x | Ammonium fluoride 10% | 200 | 93 |
| Acetic anhydride | x | x | Ammonium fluoride 25% | 200 | 93 |
| Acetone | x | x | Ammonium hydroxide 25% | x | x |
| Acetyl chloride | x | x | Ammonium hydroxide, sat. | x | x |
| Acrylic acid | x | x | Ammonium nitrate | 200 | 93 |
| Acrylonitrile | x | x | Ammonium persulfate | 200 | 93 |
| Adipic acid | 200 | 93 | Ammonium phosphate | 200 | 93 |
| Allyl alcohol 96% | 200 | 93 | Ammonium sulfate 10–40% | 200 | 93 |
| Allyl chloride | x | x | Ammonium sulfide | 200 | 93 |
| Alum | 200 | 93 | Ammonium sulfite | 160 | 71 |
| Aluminum acetate | 100 | 38 | Amyl acetate | x | x |
| Aluminum chloride, aqueous | 200 | 93 | Amyl alcohol | 130 | 54 |
| Aluminum chloride, dry | 180 | 82 | Amyl chloride | x | x |
| Aluminum fluoride | 200 | 93 | Aniline | x | x |
| Aluminum hydroxide | 200 | 93 | Antimony trichloride | 200 | 93 |
| Aluminum nitrate | 200 | 93 | Aqua regia 3:1 | 80 | 27 |
| Aluminum oxychloride | 200 | 93 | Barium carbonate | 200 | 93 |
| Aluminum sulfate | 200 | 93 | Barium chloride | 180 | 82 |
| Ammonia gas, dry | 200 | 93 | Barium hydroxide | 180 | 82 |
| Ammonium bifluoride | 140 | 60 | Barium sulfate | 180 | 82 |

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**Table C.15** Compatibility of CPVC with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Barium sulfide | 180 | 82 | Citric acid 15% | 180 | 82 |
| Benzaldehyde | x | x | Citric acid, conc. | 180 | 82 |
| Benzene | x | x | Copper acetate | 80 | 27 |
| Benzene sulfonic acid 10% | 180 | 82 | Copper carbonate | 180 | 82 |
| Benzoic acid | 200 | 93 | Copper chloride | 210 | 99 |
| Benzyl alcohol | x | x | Copper cyanide | 180 | 82 |
| Benzyl chloride | x | x | Copper sulfate | 210 | 99 |
| Borax | 200 | 93 | Cresol | x | x |
| Boric acid | 210 | 99 | Cupric chloride 5% | 180 | 82 |
| Bromine gas, dry | x | x | Cupric chloride 50% | 180 | 82 |
| Bromine gas, moist | x | x | Cyclohexane | x | x |
| Bromine liquid | x | x | Cyclohexanol | x | x |
| Butadiene | 150 | 66 | Dichloroacetic acid, 20% | 100 | 38 |
| Butyl acetate | x | x | Dichloroethane (ethylene dichloride) | x | x |
| Butyl alcohol | 140 | 60 | Ethylene glycol | 210 | 99 |
| *n*-Butylamine | x | x | Ferric chloride | 210 | 99 |
| Butyric acid | 140 | 60 | Ferric chloride 50% in water | 180 | 82 |
| Calcium bisulfide | 180 | 82 | Ferric nitrate l0–50% | 180 | 82 |
| Calcium bisulfite | 210 | 99 | Ferrous chloride | 210 | 99 |
| Calcium carbonate | 210 | 99 | Ferrous nitrate | 180 | 82 |
| Calcium chlorate | 180 | 82 | Fluorine gas, dry | x | x |
| Calcium chloride | 180 | 82 | Fluorine gas, moist | 80 | 27 |
| Calcium hydroxide 10% | 170 | 77 | Hydrobromic acid, dilute | 130 | 54 |
| Calcium hydroxide, sat. | 210 | 99 | Hydrobromic acid 20% | 180 | 82 |
| Calcium hypochlorite | 200 | 93 | Hydrobromic acid 50% | 190 | 88 |
| Calcium nitrate | 180 | 82 | Hydrochloric acid 20% | 180 | 82 |
| Calcium oxide | 180 | 82 | Hydrochloric acid 38% | 170 | 77 |
| Calcium sulfate | 180 | 82 | Hydrocyanic acid 10% | 80 | 27 |
| Caprylic acid | 180 | 82 | Hydrofluoric acid 30% | x | x |
| Carbon bisulfide | x | x | Hydrofluoric acid 70% | 90 | 32 |
| Carbon dioxide, dry | 210 | 99 | Hydrofluoric acid 100% | x | x |
| Carbon dioxide, wet | 160 | 71 | Hypochlorous acid | 180 | 82 |
| Carbon disulfide | x | x | Ketones, general | x | x |
| Carbon monoxide | 210 | 99 | Lactic acid 25% | 180 | 82 |
| Carbon tetrachloride | x | x | Lactic acid, concentrated | 100 | 38 |
| Carbonic acid | 180 | 82 | Magnesium chloride | 230 | 110 |
| Cellosolve | 180 | 82 | Malic acid | 180 | 82 |
| Chloracetic acid, 50% water | 100 | 38 | Manganese chloride | 180 | 82 |
| Chloracetic acid | x | x | Methyl chloride | x | x |
| Chlorine gas, dry | 140 | 60 | Methyl ethyl ketone | x | x |
| Chlorine gas, wet | x | x | Methyl isobutyl ketone | x | x |
| Chlorine, liquid | x | x | Muriatic acid | 170 | 77 |
| Chlorobenzene | x | x | Nitric acid 5% | 180 | 82 |
| Chloroform | x | x | Nitric acid 20% | 160 | 71 |
| Chlorosulfonic acid | x | x | Nitric acid 70% | 180 | 82 |
| Chromic acid 10% | 210 | 99 | Nitric acid, anhydrous | x | x |
| Chromic acid 50% | 210 | 99 | Nitrous acid, concentrated | 80 | 27 |
| Chromyl chloride | 180 | 82 | Oleum | x | x |

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**Table C.15** Compatibility of CPVC with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Perchloric acid 10% | 180 | 82 | Stannic chloride | 180 | 82 |
| Perchloric acid 70% | 180 | 82 | Stannous chloride | 180 | 82 |
| Phenol | 140 | 60 | Sulfuric acid 10% | 180 | 82 |
| Phosphoric acid 50–80% | 180 | 82 | Sulfuric acid 50% | 180 | 82 |
| Picric acid | x | x | Sulfuric acid 70% | 200 | 93 |
| Potassium bromide 30% | 180 | 82 | Sulfuric acid 90% | x | x |
| Salicylic acid | x | x | Sulfuric acid 98% | x | x |
| Silver bromide 10% | 170 | 77 | Sulfuric acid 100% | x | x |
| Sodium carbonate | 210 | 99 | Sulfuric acid, fuming | x | x |
| Sodium chloride | 210 | 99 | Sulfurous acid | 180 | 82 |
| Sodium hydroxide 10% | 190 | 88 | Thionyl chloride | x | x |
| Sodium hydroxide 50% | 180 | 82 | Toluene | x | x |
| Sodium hydroxide, concentrated | 190 | 88 | Trichloroacetic acid, 20% | 140 | 60 |
| Sodium hypochlorite 20% | 190 | 88 | White liquor | 180 | 82 |
| Sodium hypochlorite, concentrated | 180 | 82 | Zinc chloride | 180 | 82 |
| Sodium sulfide to 50% | 180 | 82 | | | |

The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

Hypalon, when properly compounded, also exhibits good resistance to wear and abrasion, good flex life, high impact resistance, and good resistance to permanent deformation under heavy loading.

## Physical and Mechanical Properties

The ability of Hypalon to retain its electrical properties after long-term exposure to heat, water immersion, and weathering is outstanding. These properties make the elastomer useful as insulation for low-voltage applications (less than 600 V), particularly as a covering for power and control cable, mine trailing cable, locomotive wire, nuclear power station cable, and motor lead wire. Because of Hypalon's outstanding weathering resistance, it is used as an outer protective jacket in high-voltage applications. The elastomer also exhibits excellent resistance to corona discharge.

Another property of Hypalon that is important in electrical applications is its ability to be colored and not discolor or fade when exposed to sunlight and ultraviolet light for long periods of time. The white raw polymer will accept any color, including light pastels, without impairing the true brilliance or hue. Because of the polymer's natural ozone resistance, it is not necessary to add antiozonates during compounding. The antiozonates are strong discoloring agents and when added to elastomers will cause colors to fade and become unstable.

When coloring agents are added to most elastomers it is usually necessary to sacrifice some physical properties. This is not the case with Hypalon. Except in cases where the elastomer is being specially compounded for exceptionally high heat resistance or set characteristics, its physical properties will be unaffected by the addition of coloring agents. In these special cases a black material must be used if the maximum performance is to be gotten from the elastomer.

Hypalon will burn in an actual fire situation but is classified as self-extinguishing. If the flame is removed, the elastomer will stop burning. This phenomenon is due to its chlorine content, which makes it more resistant to burning than exclusively hydrocarbon polymers.

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Hypalon's resistance to abrasion is superior to that of natural rubber and many other elastomers by as much as 2 to 1. It also possesses high resistance to fatigue cracking and cut growth from constant flexing. These latter properties make Hypalon suitable for products intended for dynamic operation. Good resistance to impact, crushing, cutting, gouging, and other types of physical abuse is also present in rubber parts produced from this elastomer.

The chlorine content of the elastomer protects it against the attack of microorganisms, and it will not promote the growth of mold, mildew, fungus, or bacteria. This feature is important when the elastomer is to be used in coating fabrics. To maintain this property it is important that proper compounding procedures be followed. The addition of wax and those plasticizers that provide food for microorganisms should be avoided if the maximum resistance to mold, mildew, and fungus is to be maintained.

On the low-temperature side, conventional compounds can be used continuously down to 0 to –20°F (–18 to –28°C). Special compounds can be produced that will retain their flexibility down to –40°F (–40°C), but to produce such a compound it is necessary to sacrifice performance of some of the other properties.

Heat aging does not have any effect on the tensile strength of Hypalon, since it acts as additional heat curing. However, the elongation at break does not decrease as the temperature increases.

Hypalon exhibits good recovery from deformation after being subjected to a heavy load or a prolonged deflection. Refer to Table C.16 for compression set values.

## Resistance to Sun, Weather, and Ozone

Hypalon is one of the most weather-resistant elastomers available. Oxidation takes place at a very slow rate. Sunlight and ultraviolet light have little if any adverse effect on its physical properties. It is also inherently resistant to ozone attack without the need for the addition of special antioxidants or antiozonates to the formulation.

**Table C.16** Physical and Mechanical Properties of Chlorosulfonated Polyethylene (Hypalon; CSM)[a]

| | |
|---|---|
| Specific gravity | 1.08–1.28 |
| Brittle point | –40 to –80°F (–40 to –62°C) |
| Dielectric strength, V/mil | 500 |
| Dielectric constant at 1000 Hz | $8^{-10}$ |
| Dissipation factor at 1000 Hz | 0.05–0.07 |
| Tensile strength, psi | 2500 |
| Elongation, % at break | 430–540 |
| Hardness, Shore A | 60 |
| Abrasion resistance | Excellent |
| Maximum temperature, continuous use | 250°F (121°C) |
| Impact resistance | Good |
| Compression set, % | |
| at 158°F (70°C) | 16 |
| at 212°F (100°C) | 25 |
| at 250°F (121°C) | 44 |
| Resistance to sunlight | Excellent |
| Effect of aging | None |
| Resistance to heat | Good |

[a]These are representative values since they may be altered by compounding.

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Many elastomers are degraded by ozone concentrations of less than 1 part per million parts of air. Hypalon, however, is unaffected by concentrations as high as 1 part per 100 parts of air.

## Chemical Resistance

When properly compounded, Hypalon is highly resistant to attack by hydrocarbon oils and fuels, even at elevated temperatures. It is also resistant to such oxidizing chemicals as sodium hypochlorite, sodium peroxide, ferric chloride, and sulfuric, chromic, and hydrofluoric acids. Concentrated hydrochloric acid (37%) at elevated temperatures above 158°F (70°C) will attack Hypalon, but it can be handled without adverse effect at all concentrations below this temperature. Nitric acid at room temperature and up to 60% concentration can also be handled without adverse effects.

Hypalon is also resistant to salt solutions, alcohols, and both weak and concentrated alkalies and is generally unaffected by soil chemicals, moisture, and other deteriorating factors associated with burial in the earth. Long-term contact with water has little or no effect on Hypalon. It is also resistant to radiation.

Hypalon has poor resistance to aliphatic, aromatic, and chlorinated hydrocarbons, aldehydes, and ketones.

Fabrics coated with Hypalon are highly resistant to soiling and staining from atmospheric deposits and from abrasive contact with soiling agents. Most deposits left on the elastomeric surface can he removed by the application of soap and water. Stubborn deposits can he removed when necessary with detergents, dry cleaning fluids, bleaches, and other cleaning agents without causing damage to the elastomers.

Table C.16 lists the physical and mechanical properties of Hypalon.

Hypalon has a broad range of service temperatures with excellent thermal properties. General-purpose compounds can operate continuously at temperatures of 248–275°F (120–135°C). Special compounds can be formulated that can be used intermittently up to 302°F (150°C).

Refer to Table C.17 for the compatibility of Hypalon with selected corrodents.

**Table C.17** Compatibility of Hypalon with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | 60 | 16 | Aluminum sulfate | 180 | 82 |
| Acetamide | x | x | Ammonia gas | 90 | 32 |
| Acetic acid 10% | 200 | 93 | Ammonia carbonate | 140 | 60 |
| Acetic acid 50% | 200 | 93 | Ammonium chloride 10% | 190 | 88 |
| Acetic acid 80% | 200 | 93 | Ammonium chloride 50% | 190 | 88 |
| Acetic acid, glacial | x | x | Ammonium chloride, sat. | 190 | 88 |
| Acetic anhydride | 200 | 93 | Ammonium fluoride 10% | 200 | 93 |
| Acetone | x | x | Ammonium hydroxide 25% | 200 | 93 |
| Acetyl chloride | x | x | Ammonium hydroxide, sat. | 200 | 93 |
| Acrylonitrile | 140 | 60 | Ammonium nitrate | 200 | 93 |
| Adipic acid | 140 | 60 | Ammonium persulfate | 80 | 27 |
| Allyl alcohol | 200 | 93 | Ammonium phosphate | 140 | 60 |
| Aluminum fluoride | 200 | 93 | Ammonium sulfate 10–40% | 200 | 93 |
| Aluminum hydroxide | 200 | 93 | Ammonium sulfide | 200 | 93 |
| Aluminum nitrate | 200 | 93 | Amyl acetate | 60 | 16 |

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**Table C.17** Compatibility of Hypalon with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Amyl alcohol | 200 | 93 | Chromyl chloride | | |
| Amyl chloride | x | x | Citric acid 15% | 200 | 93 |
| Aniline | 140 | 60 | Citric acid, concentrated | 200 | 93 |
| Antimony trichloride | 140 | 60 | Copper chloride | 200 | 93 |
| Barium carbonate | 200 | 93 | Copper acetate | x | x |
| Barium chloride | 200 | 93 | Copper cyanide | 200 | 93 |
| Barium hydroxide | 200 | 93 | Copper sulfate | 200 | 93 |
| Barium sulfate | 200 | 93 | Cresol | x | x |
| Barium sulfide | 200 | 93 | Cupric chloride 5% | 200 | 93 |
| Benzaldehyde | x | x | Cupric chloride 50% | 200 | 93 |
| Benzene | x | x | Cyclohexane | x | x |
| Benzene sulfonic acid 10% | x | x | Cyclohexanol | x | x |
| Benzoic acid | 200 | 93 | Dichloroethane (ethylene dichloride) | x | x |
| Benzyl alcohol | 140 | 60 | Ethylene glycol | 200 | 93 |
| Benzyl chloride | x | x | Ferric chloride | 200 | 93 |
| Borax | 200 | 93 | Ferric chloride 50% in water | 200 | 93 |
| Boric acid | 200 | 93 | Ferric nitrate 10–50% | 200 | 93 |
| Bromine gas, dry | 60 | 16 | Ferrous chloride | 200 | 93 |
| Bromine gas, moist | 60 | 16 | Fluorine gas, dry | 140 | 60 |
| Bromine liquid | 60 | 16 | Hydrobromic acid, dilute | 90 | 32 |
| Butadiene | x | x | Hydrobromic acid 20% | 100 | 38 |
| Butyl acetate | 60 | 16 | Hydrobromic acid 50% | 100 | 38 |
| Butyl alcohol | 200 | 93 | Hydrochloric acid 20% | 160 | 71 |
| Butyric acid | x | x | Hydrochloric acid 38% | 140 | 60 |
| Calcium bisulfite | 200 | 93 | Hydrocyanic acid 10% | 90 | 32 |
| Calcium carbonate | 90 | 32 | Hydrofluoric acid 30% | 90 | 32 |
| Calcium chlorate | 90 | 32 | Hydrofluoric acid 70% | 90 | 32 |
| Calcium chloride | 200 | 93 | Hydrofluoric acid 100% | 90 | 32 |
| Calcium hydroxide 10% | 200 | 93 | Hypochlorous acid | x | x |
| Calcium hydroxide, sat. | 200 | 93 | Ketones, general | x | x |
| Calcium hypochlorite | 200 | 93 | Lactic acid 25% | 140 | 60 |
| Calcium nitrate | 100 | 38 | Lactic acid, concentrated | 80 | 27 |
| Calcium oxide | 200 | 93 | Magnesium chloride | 200 | 93 |
| Calcium sulfate | 200 | 93 | Manganese chloride | 180 | 82 |
| Caprylic acid | x | x | Methyl chloride | x | x |
| Carbon dioxide, dry | 200 | 93 | Methyl ethyl ketone | x | x |
| Carbon dioxide, wet | 200 | 93 | Methyl isobutyl ketone | x | x |
| Carbon disulfide | 200 | 93 | Muriatic acid | 140 | 60 |
| Carbon monoxide | x | x | Nitric acid 5% | 100 | 38 |
| Carbon tetrachloride | 200 | 93 | Nitric acid 20% | 100 | 38 |
| Carbonic acid | x | x | Nitric acid 70% | x | x |
| Chloracetic acid | x | x | Nitric acid, anhydrous | x | x |
| Chlorine gas, dry | x | x | Oleum | x | x |
| Chlorine gas, wet | 90 | 32 | Perchloric acid 10% | 100 | 38 |
| Chlorobenzene | x | x | Perchloric acid 70% | 90 | 32 |
| Chloroform | x | x | Phenol | x | x |
| Chlorosulfonic acid | x | x | Phosphoric acid 50–80% | 200 | 93 |
| Chromic acid 10% | 150 | 66 | Picric acid | 80 | 27 |
| Chromic acid 50% | 150 | 66 | Potassium bromide 30% | 200 | 93 |

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**Table C.17** Compatibility of Hypalon with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Sodium carbonate | 200 | 93 | Sulfuric acid 10% | 200 | 93 |
| Sodium chloride | 200 | 93 | Sulfuric acid 50% | 200 | 93 |
| Sodium hydroxide 10% | 200 | 93 | Sulfuric acid 70% | 160 | 71 |
| Sodium hydroxide 50% | 200 | 93 | Sulfuric acid 90% | x | x |
| Sodium hydroxide, concentrated | 200 | 93 | Sulfuric acid 98% | x | x |
| Sodium hypochlorite 20% | 200 | 93 | Sulfuric acid 100% | x | x |
| Sodium hypochlorite, concentrated | | | Sulfurous acid | 160 | 71 |
| Sodium sulfide to 50% | 200 | 93 | Toluene | x | x |
| Stannic chloride | 90 | 32 | Zinc chloride | 200 | 93 |
| Stannous chloride | 200 | 93 | | | |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates data unavailable.

*Source:* PA Schweitzer. *Corrosion Resistance Tables,* 4th ed Vols. 1–3. New York: Marcel Dekker, 1995.

## Applications

Hypalon finds useful applications in many industries and many fields. Because of its outstanding resistance to oxidizing acids, it has found widespread use as acid transfer hose. For the same reason it is used to line railroad tank cars and other tanks containing acids and other oxidizing chemicals. Its physical and mechanical properties make it suitable for use in hoses undergoing continuous flexing and/or those carrying hot water or steam.

The electrical industry makes use of Hypalon to cover automotive ignition and primary wire, nuclear power station cable, control cable, and welding cable. As an added protection from storms at sea, power and lighting cable on off-shore oil platforms is sheathed with Hypalon. Because of its heat and radiation resistance, it is also used as a jacketing material on heating cable imbedded in roadways to melt ice and on x-ray machine cable leads. It is also used in appliance cord, insulating hoods and blankets, and many other electrical accessories.

In the automotive industry, advantage is taken of Hypalon's color stability and good weathering properties by using the elastomer for exterior parts on cars, trucks, and other commercial vehicles. Its resistance to heat, ozone, oil, and grease makes it useful for application under the hood for such components as emission control hose, tubing, ignition wire jacketing. spark plug boots, and air-conditioning and power steering hoses. The ability to remain soil-free and easily cleanable makes it suitable for tire whitewalls.

When combined with cork, Hypalon provides a compressible set-resistant gasket suitable for automobile crankcase and rocker pans. The Hypalon protects the cork from oxidation at elevated temperatures and also provides excellent resistance to oil, grease, and fuels.

The construction industry has made use of Hypalon for sheet roofing, pond liners, reservoir covers, curtain wall gaskets, floor tiles, escalator rails, and decorative and maintenance coatings. In these applications the properties of color stability, excellent weatherability, abrasion resistance, useful temperature range, light weight, flexibility, and good aging characteristics are of importance.

Application is also found in the coating of fabrics that are used for inflatable structures, flexible fuel tanks, tarpaulins, and hatch and boat covers. These products offer the advantages of being

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lightweight and colorful. Consumer items such as awnings, boating garb, convertible tops, and other products also make use of fabrics coated with this elastomer.

See Refs. 4, 15.

## CHROMATING

Chromating is a process for producing a conversion coating containing chromium compounds on metal surfaces. The chromate conversion coatings are applied to the protective top coats of metallic products and are the bases for organic coatings. The coating processes are dipping, electrolysis, and roll coating. The metals usually chromated include aluminum, copper, magnesium, cadmium, silver, zinc, and their alloys.

See Ref. 1.

## CHROMIUM COATINGS

Chromium coatings are for decorative purposes; they are used mostly on duplex nickel or copper strike undercoat. Decorative chromium coatings are used for bicycle parts and electric components.

See Ref. 1.

## CLAD STEELS

A clad steel plate is a composite plate made of carbon steel with a cladding of corrosion-resistant or heat-resistant metal on one or both sides. The clad steels are used in place of solid corrosion-resistant or heat-resistant materials, particularly when relatively thick sections are required because of high-pressure applications in processing vessels, in order to reduce the cost. They also find application where corrosion is a minor problem but where freedom from contamination of the materials handled is essential. In addition to the savings in material costs, the clad steels are frequently easier to fabricate than solid plates of the cladding material, resulting in reduced labor costs. Their high heat conductivity is another reason for their selection for many applications.

Various grades of stainless steels, nickel, Monel, Inconel, cupronickel, titanium, or silver may be used as a cladding material. The thickness of the cladding material is normally held to 10% to 20% of the thickness of the clad plate, but it may vary from 5% to 50%. Clad steels are available in the form of sheet, plate, and strip and may be obtained also as wire.

Clad steels are used for processing equipment in the chemical, food, beverage, drug, paper, textile, oil, and associated industries.

Cladding can be applied in any one of six methods, from the insertion of a loose liner to explosion cladding.

The least expensive form of cladding is the installation of a thin corrosion-resistant liner inside a process vessel constructed of a less expensive base metal. With this type of cladding the liner is normally relatively thin, anywhere from 0.3 to 2 mm thick, and is used only for corrosion resistance. The base metal provides all of the structural strength. The advantages of this method are

1. Relatively low cost.
2. Availability. When the base metal and the liner material are available, the finished piece of equipment can be produced in a short time.

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3. Repairs can be made relatively easily.
4. Base metal and liner material do not have to be metallurgically compatible.

The disadvantages of a loose liner are

1. Heat transfer is reduced.
2. The liner is easily damaged.
3. A vacuum will cause the liner to collapse. This disadvantage can be overcome by periodically attaching the liner to the base metal or by increasing its thickness, but this does increase the cost.

## Roll Cladding

Roll cladding produces full-sized sheets of clad material that a fabricator then forms into a finished product. These sheets are rolled at the mill. The bond formed is partly mechanical and partly metallurgical, and consequently metallurgically incompatible materials normally cannot be produced. One exception is the production of titanium-clad sheets by Nippon Kokan KK of Tokyo. Cladding thicknesses range from 5% to 50% of the compatible thickness.

Composites are produced with cladding designed to resist wear, abrasion, or corrosion.

## Explosion Cladding

Explosion cladding produces full-sized sheets of clad material, as roll cladding does, that a fabricator then forms and welds into a finished product.

The explosion bonding technique was originally developed by DuPont. In this process, detonation of an explosive presses the plates together with such force that the lower elastic limit of the metals is exceeded, and the unmelted surface metal is jetted through the rapidly closing space between the plates, destroying interfering layers of metal and resulting in a metallurgical bond with a relatively smooth surface.

Metallurgically incompatible metals can be coupled by use of an intermediate material.

Thick plates up to 510 mm may be produced by this method, but unless relatively thick sections are required, this process is not economical.

## Weld Overlaying

Weld overlaying is used with cladding materials and base metals that are metallurgically compatible and is best restricted for use on small, complex parts. Readily available commercial alloys, such as stainless steels and nickel- and copper-based alloys, can be used to provide a corrosion-resistant overlay.

Because of the heat required for welding, care must be taken not to distort the member being clad.

## Thermal Spraying

Thermal spraying can also produce a clad material. It is accomplished by heating the metal cladding (or nonmetallic) particles to a molten state and spraying them on the prepared surface of the base metal. As the molten particles impact on the surface of the base metal, they form an overlapping multilayered cladding, ranging in thickness from 0.2 to 2.5 mm, One of the advantages of this process is that the temperature of

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the base metal normally does not exceed 300 to 410°F (150 to 200°C), which minimizes thermal distortion of the base metal. This also does not permit the coating to become diluted, which is essential when the cladding material and the base metal are not metallurgically compatible. Combinations of certain metals form mixtures that are affected adversely by the intermixing or interaction of the components. For example, nickel and copper are metallurgically compatible, whereas steel and zirconium are not. This process is relatively inexpensive and is a common operation performed by many shops.

Certain disadvantages are prevalent with these spraying processes. The claddings or coatings have a tendency to be porous. This can be overcome somewhat by increasing the density of the coating. In addition, the bond between the coating/cladding is mechanical, and any leakage of corrodent to the base metal through a porous section of the coating can cause the coating to spall off. It is also very difficult, and at times impossible, to clad complex shapes.

### Resistance Cladding

Resistance cladding provides a means of applying a lining to a base metal regardless of whether the base metal and the liner material are metallurgically compatible. In this process, use is made of resistance welding and proprietary intermediate materials to bond thin-gauge corrosion-resistant materials to heavier, less expensive base metals.

This type of cladding can be applied to completed fabrications of equipment or to components during fabrication. It is also possible to apply this cladding to existing used equipment. Completed fabrications are relatively inexpensive.

Because of the relatively thin layer of cladding, the corrosion rate of the process must be low. The process also does not lend itself to providing a finished surface. Economics do not favor this process unless the cladding material is expensive.

## COATINGS

The development of new and improved coatings has been increasing over the past several years. New technologies have evolved that have expanded the usage of these materials. By incorporating these coatings with a substrate having the required physical and mechanical properties, it is possible to obtain the desired strength and the optimum corrosion resistance at an economical cost.

The available coatings can be categorized as metallic, inorganic, or organic in nature. Each category has its own specific area of application, with a range of properties dependent on the specific material.

### Metallic Coatings

There are several methods by which metallic coatings may be applied:

1. Brief immersion in a molten bath of metal, called hot dipping
2. Electroplating from an aqueous electrolyte
3. Spraying, in which a gun is used that simultaneously melts and propels small droplets of metal onto the surface to be coated, as with spray painting
4. Cementation, in which the material to be coated is tumbled in a mixture of metal powder and an appropriate flux at elevated temperatures, which allows the metal to diffuse into the base metal

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5. Gas phase reaction
6. Chemical reduction of metal-salt solutions, the precipitated metal forming an overlay on the base metal (nickel coatings of this type are referred to as "electroless" nickel plate)

Coatings from a corrosion viewpoint are classified as either noble or sacrificial. All metal coatings contain some degree of porosity. Coating performance is therefore determined by the degree of galvanic action that takes place at the base of a pore, scratch, or other imperfection in the coating.

Noble coatings, consisting of nickel, silver, copper, lead, or chromium on steel, are noble in the galvanic series with respect to steel, resulting in galvanic current attack at the base of the pores of the base metal and eventually undermining the coating. See Fig. C.6.

In order to reduce this rate of attack it is important that this type of coating be prepared with a minimum number of pores and that any pores present be as small as possible. This can be accomplished by increased coating thickness.

In sacrificial coatings, consisting of zinc, cadmium, and in certain environments aluminum and tin on steel, the base metal is noble in the galvanic series to the coating material, resulting in cathodic protection to the base metal and attack on the coating material. See Fig. C.7.

As long as sufficient current flows and the coating remains in electrical contact, the base metal willbe protected from corrosion. Contrary to noble coatings, the degree of

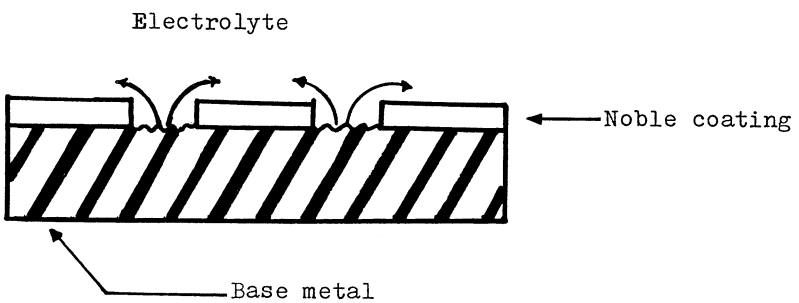



**Figure C.6** Galvanic action with a noble coating.

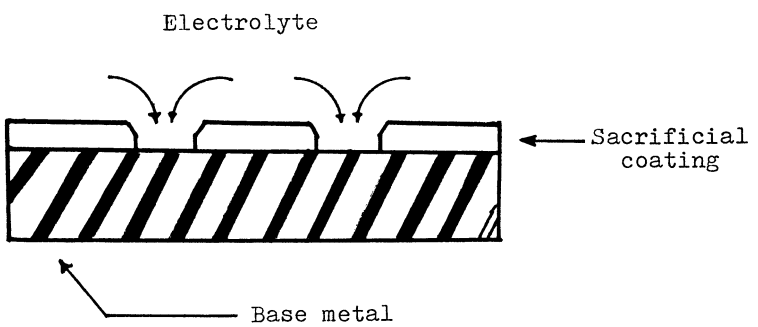



**Figure C.7** Galvanic action with a sacrificial coating.

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porosity of sacrificial coatings is relatively insignificant. However, the thicker the coating, the longer cathodic protection will be provided to the base metal.

### Nickel Coatings

The most common method of applying nickel coatings is by electroplating, either directly on steel or over an intermediate coating of copper. Copper is used as an underlayer to facilitate buffing, since it is softer than steel, and to increase the required coating thickness with a material less expensive than nickel.

### Zinc Coatings

Galvanized or zinc coating is probably one of the most common coatings. It is applied by either hot dipping or electrodeposition. Electrodeposited coatings tend to be more ductile than hot-dipped coatings, but otherwise they are comparable in corrosion resistance, with one exception. Hot-dipped coatings tend to pit less in hot or cold water and soils than coatings applied by other methods.

Zinc coatings stand up extremely well in rural atmospheres and in marine atmospheres except when salt water spray comes into direct contact with the coating.

In aqueous environments at room temperatures within a pH range of 7 to 12, good corrosion resistance will be obtained.

Any welding or forming should, if possible, be performed prior to the galvanizing operation.

### Cadmium Coatings

These coatings are produced almost exclusively by electrodeposition. A cadmium coating on steel does not provide as much cathodic protection to the steel as does a zinc coating, since the potential between cadmium and iron is not as great as between zinc and iron. Therefore it becomes important to minimize defects in the cadmium coating.

Unlike zinc, a cadmium coating will retain a bright metallic appearance. It is more resistant to attack by salt spray and atmospheric condensation. In aqueous solutions cadmium will resist attack by strong alkalies but will be corroded by dilute acids and aqueous ammonia.

Since cadmium salts are toxic, these coatings should not be allowed to come into contact with food products. This coating is commonly used on nuts and bolts.

### Tin Coatings

Most of the tinplate (tin coating on steel) is used for the manufacture of food containers (tin cans). The nontoxic nature of tin salts makes tinplate an ideal material for the handling of foods and beverages.

An inspection of the galvanic series will indicate that tin is more noble than steel and consequently the steel corrodes at the base of the pores. On the outside of the tinned container this is what happens—the tin is cathodic to the steel. However, on the inside of the container there is a reversal of the polarity due to the complexing of the stannous ions by many food products. This greatly reduces the activity of the stannous ion, resulting in a change in the potential of tin in the active direction.

This change in polarity is absolutely necessary, since most tin coatings are thin and therefore porous. In order to avoid perforation of the can, the tin must act as a sacrificial

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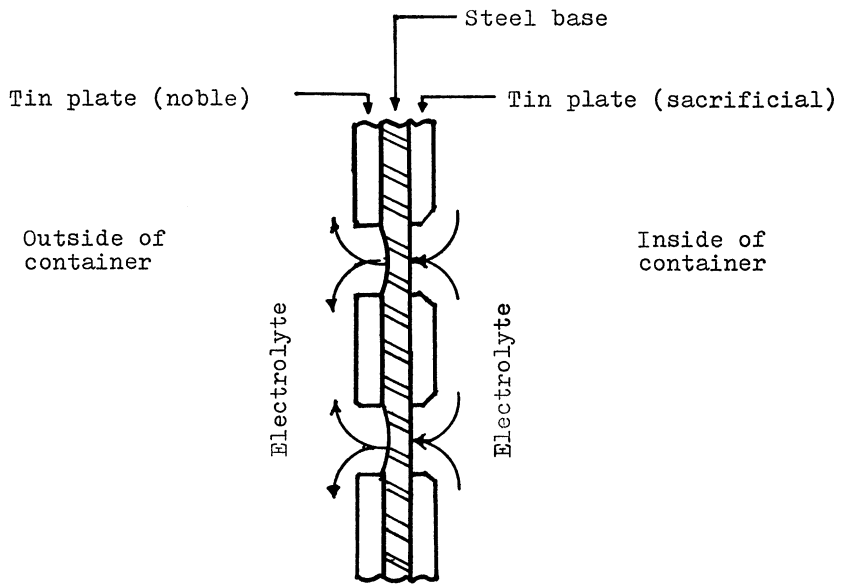



**Figure C.8** Tin acting as both a noble and a sacrificial coating.

coating. Figure C.8 illustrates this reversal of activity between the outside and inside of the can.

Tin will react with both acids and alkalies but is relatively resistant to neutral or near neutral media.

It is extremely resistant to soft waters and consequently has found wide usage as a piping material for distilled water. Only its cost and availability have precluded it from monopolizing this market.

## Aluminum Coatings

Aluminum coatings on steel are applied primarily by hot dipping or by spraying. Silicon is usually added to the molten bath so as to retard the formation of a brittle alloy layer. Organic lacquers or paints are used as sealers over sprayed coatings.

Hot-dipped coatings are used mostly to provide oxidation resistance at moderately elevated temperatures (e.g., oven construction). They find limited applications as protection against atmospheric corrosion because they are more expensive than zinc and have a variable performance.

## Vitreous Enamels

Vitreous enamels, glass linings, or porcelain enamels are all essentially glass coatings that have been fused on metals. Powdered glass is applied to a pickled or otherwise prepared metal surface and heated in a furnace at a temperature that softens the glass and permits it to bond to the metal. Several thin coats are applied to provide the required final thickness. These coatings are normally applied to steel, but some coatings can be applied to brass, aluminum, and copper.

There are many glass formulations, but those with very high silica (<96% $SiO_2$), aluminosilicate, and borosilicate compositions have the highest corrosion resistance to a

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wide range of corrosive environments. Glass is assumed to be inert to most liquids, but in reality it slowly dissolves.

The greatest danger of failure of a glass coating comes from mechanical damage or from cracking as a result of thermal shock. Thus care must be taken in handling glassed equipment so as not to damage the lining, and sudden temperature changes in the operation must be avoided, particularly cold shock, which poses a greater danger of failure than hot shock.

Cold shock is the sudden introduction of a cold material onto a hot glassed surface; hot shock is the reverse. Manufacturers of this type of equipment will specify the maximum allowable thermal shock. These precautions must be followed.

## Masonry

Monolithic corrosion-resistant masonry linings are normally applied by means of pneumatic gunning (guniting), although they may be troweled on. Thicknesses vary from 1/2 in. up to several inches. When a thickness greater than 1 in. is to be applied, it is necessary to anchor the lining in place using wire mesh and studs. There should be a minimum of 1/2 in. cover over the highest point.

This type of lining has three main advantages:

1. Curved or irregular surfaces can be covered uniformly.
2. Monolithic linings bond to steel, brick, and concrete.
3. Monolithic linings can be gunited horizontally, vertically, or overhead without the need for complex forms, supports, or scaffolds.

## Sodium Silicate Base Monolithics

This material is supplied as two separate components, a powder and a liquid. The two components are mixed and applied for use. Hardening occurs as a result of a chemical reaction. Application can be by means of casting, pouring into forms, or guniting. Its resistance to acid is excellent over a pH range of 0.0 to 7.0.

## Modified Silicate Base Monolithics

There are two types of modified silicate base materials available, both of which are supplied in powder form and must be mixed with water prior to application. Application is by guniting.

The first type is unaffected by acids (except hydrofluoric), mild alkalies, water, and solvents and can be operated up to a temperature of 1740°F (950°C) through a pH range of 0.0 to 9.0. It weighs approximately 135 $lb/ft^3$.

The second type is lighter in weight, weighing approximately 98 $lb/ft^3$, and is thermally insulating. It has a K factor of 2.25 to 2.50. This type can be operated up to a temperature of 1695°F (925°C) through a pH range of 0.0 to 9.0.

## Calcium Aluminate Base Monolithics

This type consists of a calcium aluminate base cement to which various inert aggregates have been added. It is supplied in powder form and mixed with water when used, and may be cast, poured, or gunited into place. These monolithics are similar to portland cement in that they are hydraulic in nature and consume water in their reaction mechanism to form

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hydrated phases. In contrast to portland cement, their rates of hardening are very rapid, and full strength is usually attained within 24 hours at room temperatures of 73°F (23°C).

They are not useful in contact with acids below a pH of 5, although they do exhibit better mild acid resistance than portland cement. These types should not be used for halogen service or for alkali service above a pH of 12.

## Portland Cement Coatings

Although portland cement does not have the corrosion resistance of other monolithics, it does have the advantage of low cost and ease of repair when accessible. The coatings can be applied by centrifugal casting, troweling, or guniting. Thicknesses usually range from 1/4 to more than 1 in. The thicker coatings are reinforced with wire mesh.

Primary applications for portland cement linings are the protection of hot or cold water tanks, oil tanks, and chemical storage tanks. The disadvantage of portland cement coatings is their sensitivity to damage by mechanical shock.

Since cement compositions may vary, care should he taken that the proper selection is made for the specific application.

## Chemical Conversion Coatings

These are protective coatings formed by a chemical reaction taking place on the surface of the metal. Included in this category are phosphate coatings on steel (sometimes referred to as "parkerizing" or "bonderizing"), oxide coatings on steel and aluminum, and chromate coatings on zinc.

### *Phosphate Coatings*

These coatings are not used to provide corrosion protection since they offer little. They are used to provide a base for the application of paints, by providing good adherence of the paint to the steel and decreasing the tendency for corrosion to undercut the paint film at scratches or defects.

### *Oxide Coatings*

Oxide coatings are not applied for providing increased corrosion resistance since they do not appreciably improve the resistance of the base metal. Oxide coatings produced on aluminum result in a product known as anodized aluminum. During this process the oxide coating can be dyed various colors, for aesthetic purposes.

As with phosphate coatings, the main advantage lies in providing an improved base for paints.

### *Chromate Coatings*

These coatings are produced on zinc, imparting a slight yellow color and protecting the metal against spotting or staining by condensed moisture. The coating will extend the life of zinc somewhat, when exposed to the atmosphere.

## Organic Coatings

Organic coatings are widely used to protect metallic surfaces from corrosion. The effectiveness of such coatings is dependent not only on the properties of the coatings, which are related to the polymeric network and possible flaws in this network, but also on the

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character of the metal substrate, the surface pretreatment, and the application procedures. Therefore, when considering the application of a coating it is necessary to take into account the properties of the entire system.

Organic coatings provide protection either by the formation of a barrier action from the layer or from active corrosion inhibition provided by pigments in the coating. In actual practice the barrier properties are limited since all organic coatings are permeable to water and oxygen to some extent. The average transmission rate of water through a coating is about 10 to 100 times larger than the water consumption rate of a freely corroding surface, and in normal outdoor conditions an organic coating is saturated with water at least half its service life. For the remainder of the time it contains a quantity of water comparable in its behavior to an atmosphere of high humidity. It has also been determined that in most cases the diffusion of oxygen through the coating is large enough to allow unlimited corrosion. Taking these factors into account indicates that the physical barrier properties alone do not account for the protective action of coatings.

Additional protection may be supplied by resistance inhibition, which is also a part of the barrier mechanism. Retardation of the corrosion action is accomplished by inhibiting the charge transport between cathodic and anodic sites. The reaction rate may be reduced by an increase in the electronic resistance and/or the ionic resistance in the corrosion cycle. Applying an organic coating on a metal surface increases the ionic resistance. The electronic resistance may be increased by the formation of an oxide film on the metal. This is the case for aluminum substrates.

Organic coatings are relatively easily damaged under mechanical and thermal load, which may lead to corrosion under the paint film at or near the site. Under these conditions the otherwise adequate barrier properties of the coating will no longer provide adequate protection. In an attempt to compensate for this, active pigments are incorporated in the matrix of the primer (first coating layer). These pigments provide protection through an active inhibitive mechanism immediately when water and some corrosive agent reach the metal surface. The protection provided is of a passivating, blocking, or galvanic action.

In order for the coating to provide protection, the adhesion of the coating must be good. The quality of the coating is determined to some extent by the mechanical properties of the polymer that determine the formability of coated substances and also the sensitivity to external damage.

## Water Permeation and Underfilm Corrosion Initiation

In order for corrosion to take place under a coating it is necessary for an electrochemical double layer to be established. In order for this to occur it is necessary for the adhesion between the coating and the substrate to be broken. When this happens a thin water layer at the interface can be formed when the water permeates the coating. All organic coatings are permeable to water to some degree. The permeability of a coating is often given in terms of the permeation coefficient P. This is defined as the product of the solubility of water in the coating (S, $kg/cm^3$), the diffusion coefficient of water in the coating (D, $m^2/s$), and the specific mass of water (p, $kg/m^2$). Therefore, different coatings can have the same permeation coefficient even though the solubility and the diffusion coefficient, both being material constants, are very different. This limits the usefulness of the permeation coefficient.

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Water permeation takes place under the influence of several driving forces:

1. A concentration gradient during immersion or during exposure to a humid atmosphere, resulting in true diffusion through the polymer
2. Capillary forces in the coating resulting from poor curing, improper solvent evaporation, bad interaction between binder and additives, or entrapment of air during application
3. Osmosis due to impurities, or corrosion products at the interface between the metal and the coating

Given sufficient time a coating system that is exposed to an aqueous solution or a humid atmosphere will be permeated. Water molecules will eventually reach the coating's substrate interface. Saturation will occur after a relatively short period of time (of the order of one hour) depending on the values for D and S and the thickness of the layer. Typical values for D and S are $10^{-13}$ $m^2/s$ and 3%. Periods of saturation under atmospheric exposure are determined by the actual cyclic behavior of the temperature and the humidity. In any case, situations will develop in which water molecules reach the coating–metal interface, where they can interfere with the bonding between the coating and the substrate, eventually resulting in loss of adhesion and corrosion initiation, provided that a cathodic reaction can take place. A constant supply of water or oxygen is required for the corrosion reaction to proceed. Water permeation may also result in the build-up of high osmotic pressures, resulting in blistering and delamination.

## Wet Adhesion

Adhesion between the coating and the substrate may be affected when water molecules have reached the substrate—coating interface. The degree to which permeated water may change the adhesion properties of a coated system is referred to as wet adhesion. Two different theories have been proposed for the mechanism for the loss of adhesion due to water:

1. Chemical disbondment resulting from the chemical interaction of water molecules with covalent hydrogen, or polar bonds between polymer and metal (oxide)
2. Mechanical or hydrodynamic disbondment as a result of forces caused by accumulation of water and osmotic pressure

For chemical disbondment to take place it is not necessary that there be any sites of poorly bonded coating. This is not the case for mechanical disbonding, where water is supposed to condense at existing sites of bad adhesion. Water volume at the interface may subsequently increase due to osmosis. As the water volume increases under the coating, hydrodynamic stresses develop. These stresses eventually result in an increase of the nonadherent surface area.

## Osmosis

Osmotic pressure may result from one or more of the following conditions:

1. Presence of soluble salts as contaminants at the original metal surface.
2. Inhomogeneities in the metal surface such as precipitates, grain boundaries, or particles from blasting pretreatment.

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3. Surface roughness due to abrasion. Once corrosion has started at the interface, the corrosion products produced can be responsible for the increase in osmotic pressure.

## Blistering

Various phenomena may be responsible for the formation of blisters and the start of underfilm corrosion. These include the presence of voids, wet adhesion problems, swelling of the coating during water uptake, gas inclusions, impurity ions in the coating, poor general adhesion properties, and defects in the coating.

When a coating is exposed to an aqueous solution, water vapor molecules and some oxygen diffuse into the film and end up at the substrate interface. Eventually a thin film of water may develop at sites of poor adhesion or at sites where wet adhesion problems arise. A corrosion reaction can start with the presence of an aqueous electrolyte with an electrochemical double layer, oxygen and the metal. This reaction will cause the formation of macroscopic blisters. Depending on the specific materials and circumstances, the blisters may grow out because of the hydrodynamic pressure, in combination with one of the chemical propagation mechanisms such as cathodic delamination or anodic undermining.

### *Cathodic Delamination*

Loss of adhesion of the paint film adjacent to defects on a coated metal to which cathodic protection is applied is known as cathodic delamination. It derives its name from the fact that the driving force is the cathodic reaction taking place at the interface. As a result of the high pH values resulting from the cathodic reactions, delamination occurs. In the case of cathodic overprotection, blistering, due to the evolution of hydrogen gas, can take place.

### *Anodic Undermining*

This is a class of corrosion reactions underneath an organic coating in which loss of adhesion is caused by anodic dissolution of the substrate metal or its oxide in contrast to cathodic delamination. In this case the metal is anodic at the blister edges. Anodic undermining usually is initiated at a corrosion-sensitive site underneath the coating such as an enclosed particle, or a section of the metal with potentially increased activity caused by scratches. These sites become active once corrodents have penetrated to the metal surfaces. The corrosion rates start out low, but as corrosion products are formed osmotic pressure develops, which stimulates blister growth. Once formed, the blister will grow due to a type of anodic crevice corrosion at the edge of the blister.

In general, coated aluminum tends to be susceptible to anodic undermining, while coated steel is more susceptible to cathodic delamination.

## Filiform Corrosion

Filiform corrosion is a threadlike undermining of the coating and is sometimes referred to as worm track corrosion. It generally occurs in humid chloride-containing environments and is common under organic coatings on steel, aluminum, magnesium, and galvanized steel. The majority of problems occur on coated aluminum and represent a special form of anodic undermining.

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Filiform corrosion takes place when the following conditions are present:

1. The coating has defects.
2. The coating is permeable to water.
3. High relative humidity, specifically in the range 80–95%.
4. Contaminants are present on or in the coating or at the coating–substrate interface.

## Early Rusting

When a latex paint is applied to a cold steel substrate under high-moisture conditions, a measles-like, rusty appearance may develop immediately when the coating is touch dry. This corrosion takes place when the following conditions are met:

1. The air humidity is high.
2. The substrate temperature is low.
3. A thin (up to 40 μm) latex coating has been applied.

## Flash Rusting

Flash rusting is the appearance of brown rust stains on a blasted steel surface immediately after application of a water-based primer. Contaminants remaining on the metal surface after blast cleaning are responsible for this corrosion. The grit on the surface provides crevices or local galvanic cells that activate the corrosion process as soon as the surface is wetted by the water-based primer.

## Stages of Corrosion

To prevent excessive corrosion, good inspection procedures and preventive maintenance practices are required. Proper design considerations are also necessary as well as selection of the proper coating system. Regular inspections of coatings should be conducted. Since corrosion of substrates under coatings takes place in stages, early detection will permit correction of the problem, thereby preventing ultimate failure.

### *First Stages of Corrosion*

The first stages of corrosion are indicated by rust spotting or the appearance of a few small blisters. Rust spotting is the very earliest stage of corrosion and in many cases is left unattended. Standards have been established for evaluating the degree of rust spotting and may be found in ASTM D-610-68 or "Steel Structures Painting Council Vis-2." One rust spot in 1 square foot may provide a 9+ rating, but three or four rust spots drop the rating to 8. If the rust spots go unattended, a mechanism for further corrosion is provided.

Blistering is another form of early corrosion. Frequently, blistering occurs without external evidence of rusting or corrosion. The mechanism of blistering is attributed to osmotic attack or a dilution of the coating film at the interface with the steel under the influence of moisture. Water and gases pass through the film and dissolve ionic material from either the film or the substrate, causing an osmotic pressure greater than that of the external face of the coating. This produces a solution concentration gradient, with water building up at these sites until the film eventually blisters. Visual blistering standards are found in ASTM D-714-56.

Electrochemical reactions also assist in the formation of blisters. Water diffuses through a coating also by an electro-endesmotic gradient. Once corrosion has started,

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moisture is pulled through the coating by an electrical potential gradient between the corroding areas and the protected areas that are in electrical contact. Therefore, osmosis starts the blistering, and once corrosion begins, electro-endesmotic reactions accelerate the corrosion process. The addition of heat and acidic chemicals increases the rate of breakdown. Temperatures of 150 to 200°F (66 to 93°C) accelerate the chemical reaction. Under these conditions steel will literally dissolve in a chemical environment. Moisture is always present and often condenses on the surface behind the blister. This condensation offers a solute for gaseous penetrants to dissolve. When the environment is acidic, the pH of the water behind the blister can be as low as 1.0 to 2.0, subjecting the steel to severe attack.

### *Second Stage of Corrosion*

After the initial one or two rust spots have been observed, or after a few blisters are found, a general rusting in the form of multiple rust spots develops. This rusting is predominantly $Fe_2O_3$, a red rust. In atmospheres lacking sufficient oxygen, such as in sulfur dioxide scrubbers, a black FeO rust develops. Once the unit has been shut down and more oxygen becomes available, the FeO will eventually convert to $Fe_2O_3$.

### *Third Stage of Corrosion*

This advanced stage of corrosion is the total disbondment of the coating from the substrate, exposing the substrate directly to the corrodents. Corrosion can occur at an uninhibited rate since the coating is no longer protecting the steel.

### *Fourth Stage of Corrosion*

Attack of the metal substrate after the removal of the coating is not usually of a uniform nature, but rather that of a localized attack, resulting in pitting.

### *Fifth Stage of Corrosion*

Deep pits formed in the substrate during the fourth stage of attack may eventually penetrate completely to cause holes. Within the corrosion cell, pitting has occurred to such a degree that undercutting, flaking, and delamination of the substrate take place. As the small hole develops, the electrolyte has access to the reverse side and corrosion now takes place on both sides of the substrate.

### *Final Stage of Corrosion*

Corrosion is now taking place at its most rapid and aggressive rate. Large, gaping holes are formed, causing severe structural damage.

## Composition of Coatings

The most commonly used organic coating is paint. When applied for corrosion protection, paints are referred to as coatings. Paints consist of binders, pigments, fillers, additives, and solvents.

### *Binder*

The binder forms the continuous polymeric phase in which all of the other ingredients are incorporated. Its density and composition determine the permeability, chemical resistance,

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and ultraviolet resistance of the coating. The protective film is formed through physical curing, chemical curing, or a combination of these.

### *Pigments*

Pigments are added to the coating for two reasons: to provide color and to improve the corrosion resistance of the coating. The improvement in corrosion resistance may be accomplished by one or more of the following:

1. Anticorrosion pigments dissolve slowly in the coating and provide protection by covering corrosion-sensitive sites under the coating, or by sacrificially corroding themselves, thereby protecting the substrate metal, or by passivating the surface.
2. Blocking pigments absorb at the active metal surface, reducing the active area for corrosion, and form a transport barrier for ionic species to and from the substrate.
3. Galvanic pigments are nonnoble metal particles (relative to the substrate). These particles when exposed corrode preferentially, while at the original metal surface only the cathodic reaction occurs.
4. Passivating pigments stabilize the oxide film on the exposed metal substrate. Chromates with limited water solubility are generally used.

### *Fillers*

Fillers are used to increase the volume of the coating. They are also used to improve such properties as impact, abrasion resistance, and water permeability.

### *Additives*

Additives are made up of numerous materials that are added in small amounts to enhance certain specific properties. They consist of thickeners, antifungal agents, dispersing agents, antifoam agents, anticoalescence agents, UV absorbers, and fire-retarding agents.

### *Solvents*

Solvents have two different roles to perform in a coating. Prior to application, the solvent has to function to reduce viscosity of the binder and other components to permit their homogeneous mixing. The reduced viscosity also enables the coating to be applied in a thin, smooth, continuous film. Prior to application, the liquid mixture should be a solution or stable dispersion or emulsion of binder, pigments, and additives in the solvent. After the paint has been applied, a major attractive force between the components is necessary for the formation of a continuous film. There should be no interaction between the solvent and other components, so that the solvent is free to evaporate from the curing film.

Two-component epoxy coatings do not require the use of a solvent. These coatings have a low viscosity. The two components are mixed, usually at elevated temperatures, to reduce the viscosity as much as possible.

## Complex Coating Systems

Because of poor adhesion, the corrosion protection supplied by organic coatings is not always satisfactory. To compensate for this, conversion layers are applied to the substrate metal. These layers provide ions, which become part of the protective coating after (electro)chemical reaction of the substrate with a reactive medium. Common conversion layers are phosphate layers on steel and zinc, chromate layers on zinc and aluminum, and anodized layers on aluminum,

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the latter without an organic topcoat. Anodizing is an electrochemical treatment of a metal (mainly aluminum) while the metal itself is the anode. This produces a reasonably thick oxide layer, which is passive.

Pretreatment layers are used for a variety of reasons:

1. To provide a uniform grease-free surface
2. To obtain electrically insulating barrier layers
3. To improve the adherence of the organic layer
4. To provide active corrosion inhibition by passivating the metallic substrate or by reducing the rate of oxygen reduction reaction.

There are two types of resin systems, thermoplastic and thermosetting. Thermoplastic solvent-deposited coatings do not undergo any chemical change from the time of application until the attainment of final properties as a protective film. Thermosetting resins differ in that a chemical change takes place after application and solvent evaporation. The coating is said to cure as the chemical reaction is taking place. This curing can take place at room temperature or, in the case of baked coatings, at elevated temperatures. The reaction is irreversible and unlike with thermoplastic coatings, high temperatures or exposure to solvents does not cause the coating to melt or soften. The more commonly used industrial paints are discussed.

### *Vinyls (Thermoplastic)*

These are polyvinyls dissolved in aromatics, ketones, or ester solvents.

1. Resistance: insoluble in oils, greases, aliphatic hydrocarbons, and alcohols; resistant to water and aqueous salt solutions; at room temperature resistant to inorganic acids and alkalies; fire resistant
2. Temperature resistance: 180°F (82°C) dry; 140°F (60°C) wet
3. Limitations: dissolved by ketones, aromatics, and ester solvents
4. Applications: used on surfaces exposed to potable water and on sanitary equipment

### *Chlorinated Rubbers (Thermoplastic)*

These are resins dissolved in hydrocarbon solvents.

1. Resistance: chemically resistant to acids and alkalies; low permeability to water vapor; abrasion resistant; fire resistant
2. Temperature resistance: 200°F (93°C) dry; 120°F (49°C) wet
3. Limitations: degraded by ultraviolet light; attacked by hydrocarbons
4. Applications: used on structures exposed to water and marine atmospheres (swimming pools, etc.); excellent adherence to concrete and masonry

### *Epoxy (Thermoset)*

These are a series of various epoxy paints, all of which are of the thermoset variety.

### *Epoxy (Thermoset)*

This is a polyamine plus epoxy resin (amine epoxy).

1. Resistance: resistant to acids, acid salts, alkalies, and organic solvents
2. Temperature resistance: 225°F (107°C) dry; 190°F (88°C) wet

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3. Limitations: harder and less flexible than other epoxies; less tolerant of moisture during application
4. Applications: widest range of chemical and solvent resistance of epoxies; used for piping and vessels

*Epoxy (Thermoset)*

This is polyamide plus epoxy resin.

1. Resistance: partially resistant to acids, acid salts, alkalies, and organic solvents; resistant to moisture
2. Temperature resistance: 150°F (66°C) dry; 225°F (107°C) wet
3. Limitations: chemical resistance inferior to that of the polyamine epoxies
4. Applications: used on wet surfaces or underwater, as in tidal zone areas of pilings, oil rigs, etc.

*Epoxy (Thermoset)*

This is aliphatic polyamine plus partially prepolymerized epoxy.

1. Resistance: partially resistant to acids, acid salts, and organic solvents
2. Temperature resistance: 225°F (107°C) dry; 150°F (66°C) wet
3. Limitations: film formed has greater permeability than the other amine epoxies
4. Applications: used for protection against mild atmospheric corrosion

*Epoxy (Thermoset)*

Esters of epoxies and fatty acids are modified (epoxy ester).

1. Resistance: resistant to weathering; attacked by alkalies
2. Temperature resistance: 225°F (107°C) dry; 150°F (66°C) wet
3. Limitations: chemical resistance generally poor
4. Applications: used where properties of a high-quality oil base paint are required

*Epoxy (Thermoset)*

This is a cool tar plus epoxy resin (amine or polyamide cured).

1. Resistance: excellent resistance to fresh water, salt water, and inorganic acids
2. Temperature resistance: 225°F (107°C) dry; 150°F (66°C ) wet
3. Limitations: attacked by organic solvents
4. Application: used on steel for immersion or below-grade service

*Oil Base*

This comprises coating formulations with vehicles (alkyd), epoxy (urethane), combined with drying oils.

1. Resistance: resistant to weathering
2. Temperature resistance: 225°F (107°C) dry; 150°F (66°C) wet
3. Limitations: chemical resistance generally poor
4. Applications: used on wood exterior surfaces because of its penetrating power

*Urethanes*

This is a moisture-cured isocyanate prepolymer reacting with atmospheric moisture.

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1. Resistance: abrasion resistant; if cross-linked, resistant to chemicals and solvents
2. Temperature resistance: 250°F (121°C) dry; 150°F (66°C) wet
3. Limitations: may yellow under ultraviolet light; poor chemical resistance
4. Applications: used on furniture and floors

### *Urethanes*

These are catalyzed aliphatic or aromatic isocyanate reacted with polyesters, epoxy, or acrylic polyhydroxyls.

1. Resistance: good chemical resistance; similar to polyamide epoxy
2. Temperature resistance: 225°F (107°C) dry; 150°F (66°C) wet
3. Limitations: not recommended for exposure to or immersion in strong acids or alkalies
4. Applications: used as a decorative coating of tank cars and steel in highly corrosive atmospheres

### *Silicones*

Consider the high-temperature type.

1. Resistance: water repellent
2. Temperature resistance: 1200°F (649°C) dry and wet
3. Requires baking for good cure; not chemically resistant
4. Applications: water solvent formulations used on limestone, cement, and nonsilaceous materials; solvent formulations used on bricks and noncalcaceous masonry

### *Water Base*

These are aqueous emulsions of polyvinyl acetate, acrylic, or styrene-butadiene latex.

1. Resistance: poor chemical resistance; resistant to weather
2. Temperature resistance: 150°F (66°C) dry and wet
3. Limitations: not suitable for immersion service
4. Applications: used in general decorative applications, primarily on wood

### *Polyesters*

These are organic acids condensed with polybasic alcohols. Styrene is a reactive diluent.

1. Resistance: excellent resistance to acids and aliphatic solvents; good resistance to weathering
2. Temperature resistance: 180°F (82°C) dry and wet
3. Limitations: not suitable for use with alkalies and most aromatic solvents, since they swell and soften these coatings
4. Applications: lining materials for tanks and chemical process equipment

### *Coal Tar*

This is a distilled coking by-product in aromatic solvent.

1. Resistance: excellent resistance to moisture; good resistance to weak acids, weak alkalies, petroleum oils, and salts
2. Temperature resistance: 100°F (38°C) dry and wet

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3. Limitations: ultraviolet light and weathering will degrade
4. Applications: used on submerged or buried steel and concrete

*Asphalt*

These are solids from crude oil refining in aliphatic solvents.

1. Resistance: good resistance to weak acids, alkalies, and salts
2. Temperature resistance: 230°F (110°C) dry and wet
3. Applications: used in above-ground weathering environments and chemical fume atmospheres

*Zinc Rich*

This is metallic zinc in a vehicle of organic or inorganic type.

1. Resistance: highly resistant to galvanic and pitting-type corrosion
2. Temperature resistance: 700°F (371°C) dry and wet
3. Limitations: must have top coat in severe environments or when pH is below 6 or above 10.5
4. Applications: jet fuel storage tanks; petroleum products

See Refs. 1, 2, 8, 16–20.

## COBALT ALLOYS

Cobalt alloys are primarily used for hard-face applications such as in valve seats. The purpose of hard facing is to improve resistance to abrasion, friction, galling, and/or impact. The cobalt hard-face alloys usually contain 30–60% cobalt with additives of carbon, nickel, chromium, tungsten, and/or molybdenum. Application is made by either welding or thermal spray processes. Their corrosion resistance is approximately that of the 300 series stainless steels. A typical alloy is Stellite.

See Ref. 4.

## COLD WATER PITTING

Cold water pitting is the electrochemical pitting of copper tubes and fittings in domestic water systems that transport groundwaters containing free carbon dioxide in conjunction with dissolved oxygen. The action may be accelerated by the presence of chlorides and sulfates in the water.

## COLUMBIUM

In 1801 an English chemist, C. Hatchett, found a new element. Since he found the element in a black stone discovered near Connecticut, he named it columbium after the country of origin, Columbia, a synonym for America.

A Swedish chemist, Ekeberg, discovered tantalum only one year later, in 1802. He gave it the name tantalum because of the tantalizing difficulty he had dissolving the oxide of the new metal in acids.

The discoveries of niobium and tantalum were almost simultaneous; however, the similarity of their chemical properties caused great confusion for the early scientists who tried to establish their separate identities. The confusion was compounded by some scientists' use of two different names for the same discovery—columbium and niobium.

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It was not until 1865 that Mangnac separated niobium and tantalum by using the difference in solubilities of their double fluorides of potassium. In 1905 Dr. W. von Bolton introduced both tantalum and niobium to industry.

The dual nomenclature of niobium and columbium caused confusion and controversy. Niobium was preferred in Europe, and columbium was preferred in the United States. Finally, at the Fifteenth International Union of Chemistry Congress in Amsterdam in 1949, the name niobium was chosen as the recognized international name.

For more details see "Niobium."

## COMPOSITE LAMINATES

Composite laminates are two composite materials joined to form a dual laminate, one material being on the exterior and the other on the interior. Typical combinations include ABS and polyester, bisphenol and isophthalic fibrous glass systems, vinyl ester and polyester, epoxy and polyester, glass and reinforced polyester, polypropylene-lined reinforced polyester, and PVC and polyester composite.

When applying a composite laminate, it is necessary to evaluate each member of the composite as to its compatibility with the corrosive environment.

See also "Composites."

## COMPOSITES

For the purpose of corrosion-resisting materials, a composite is defined as a mixture of two or more materials that are distinct in composition and form, all being present in significant quantities (e.g., greater than 5 volume percent). By this definition, conventional alloyed steel would not be considered a composite since the alloying ingredients are present in quantities of much less than 1% by weight or volume, and most often less than 0.1%.

The object of composite materials is to achieve properties in composite form that exceed those of their individual components alone. In forming composites at times it is necessary to accept a trade-off. For example, combining a strong but brittle ceramic fiber in a ductile and weaker metal matrix results in a composite whose strength lies somewhere between the strength of the ceramic fiber and that of the metal matrix, but which is not as brittle as the ceramic alone.

The possibilities of forming composites are quite extensive. The duplex stainless steels, which contain approximately equal amounts of ferrite and austenite, are examples of metallic composites (see "Duplex Stainless Steels").

Glass fiber–reinforced polyesters are considered the first engineered composites. In addition to glass fiber, other types of fibers used to produce composites include boron, carbon, silicon carbide, and aramid fibers. For more detailed information on composites, refer to the following topics in this book:

Composite Laminates
Duplex Stainless Steels
Thermoset Reinforcing Materials

See Ref. 21.

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## CONCENTRATION CELLS

These are the cause of pitting and crevice corrosion. The primary factors causing pitting are electrical contact between dissimilar materials or areas of the same metal where oxygen or conductive salts in water differ. Such a coupling is sufficient to cause a difference of potential, causing an electric current to flow through the water, or across moist steel, from the metallic anode to a nearby cathode. The cathode may be mill scale or any other portion of the metal surface that is cathodic to the more active metal areas. Mill scale is cathodic to steel and is one of the more common causes of pitting. If the cathodic area is relatively large compared with the anodic area, the damage is spread out and usually negligible. When the anode area is relatively small, the metal loss is concentrated and may be serious.

Concentration cells are capable of causing severe corrosion, leading to pitting, when differences in dissolved oxygen concentrations occur. That portion of the metal that is in contact with water relatively low in dissolved oxygen concentration is anodic to adjoining areas with water higher in dissolved oxygen concentration. This lack of oxygen may be caused by exhaustion of dissolved oxygen in a crevice. The low-oxygen area is always anodic. This type of cell is responsible for corrosion at crevices that are formed at the interface of two coupled pipes, or at threaded connections, since the oxygen concentration is lower within the crevice or at the threads than elsewhere. It also is responsible for pitting damage under rust or at the water line (air–water interface). These differential aeration cells are responsible for initiating pits in stainless steel, aluminum, nickel, and other so-called passive metals when they are exposed to aqueous environments such as seawater.

See Ref. 22.

## CONVERSION COATINGS

Conversion coatings are coatings formed on metal either naturally by reaction with the environment or artificially using chemical or electrochemical treatment. The films or coatings formed by these treatments serve two purposes. They not only improve the corrosion resistance of the metal, but also increase the adhesive bonding of paint coatings.

Typical examples of this type of coating include anodizing of aluminum, magnesium, and titanium alloys; phosphate coatings on iron and steel, aluminum, and zinc; chromate coatings on zinc, aluminum, and cadmium; oxide bluing of iron and steel; oxide coatings on cadmium, iron, steel, copper, and zinc alloys; and pack cementation to form diffusion coatings on various metals.

See Refs. 1 and 2.

## COPOLYMER

A copolymer is a polymer produced from two or more types of different monomers.

## COPPER AND COPPER ALLOYS

Since before the dawn of history, when primitive people first discovered the red metal, copper has been serving mankind. The craftsmen who built the Great Pyramid for the Egyptian pharaoh Cheops used copper pipe to convey water to the royal bath. A remnant

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**Table C.18** Chemical Composition of Coppers: Maximum[a] Composition (%)

| Copper UNS no. | Cu | Ag min. | P | As | Sb | Te | Other |
|---|---|---|---|---|---|---|---|
| C10200 | 99.95 | | | | | | |
| C10300 | 99.95 | | 0.001–0.005 | | | | |
| C10400 | 99.95 | 0.027 | | | | | |
| C10800 | 99.95 | | 0.005–0.012 | | | | |
| C11000 | 99.90 | | | | | | |
| C11300 | 99.90 | 0.027 | | | | | |
| C12000 | 99.90 | | 0.004–0.012 | | | | |
| C12200 | 99.90 | | 0.015–0.040 | | | | |
| Cl 2500 | 99.88 | | | 0.012 | 0.003 | 0.025 | 0.050 Ni, 0.003 Bi, 0.004 Pb |
| C13000 | 99.88 | 0.085 | | 0.012 | 0.003 | 0.025 | 0.050 Ni, 0.003 Bi, 0.004 Pb |
| C14200 | 99.40 | | 0.015–0.040 | 0.15–0.50 | | | |

[a]Except for Ag and when shown as a range.
*Source:* Ref. 3.

of this pipe was unearthed some years ago, still in usable condition, a testimonial to copper's durability and resistance to corrosion. Today, nearly 5000 years after Cheops, copper is still used to convey water and is a prime material for this purpose.

To be classified as a copper, the alloy must contain a minimum of 99.3% copper. Elements such as silver, arsenic, lead, phosphorus, antimony, tellurium, nickel, cadmium, sulfur, zirconium, manganese, boron, and bismuth may be present singly or in any combination. Since copper is a noble metal, it finds many applications in corrosive environments. Table C.18 gives the chemical compositions of some of the coppers used in corrosion applications.

Copper itself is inherently corrosion resistant. It is noble to hydrogen in the emf series and thermodynamically stable with no tendency to corrode in water and in nonoxidizing acids free of dissolved oxygen. With copper and its alloys the predominant cathode reaction is the reduction of oxygen to form hydroxide ions. Therefore, oxygen or other oxidizing agents are necessary for corrosion to take place. In oxidizing acids or in aerated solutions of ions that form copper complexes (e.g., CN, $MH_A$), corrosion can be severe. Copper is also subject to attack by turbulently flowing solutions, even though the metal may be resistant to the solution in a stagnant condition. Most of the corrosion products that form on copper and copper alloys produce adherent, relatively impervious films with low solubility that provide the corrosion protection.

Copper finds many applications in the handling of seawater and/or fresh water. The corrosion resistance of copper, when in contact with fresh water or seawater, is dependent on the surface oxide film that forms. In order for corrosion to continue, oxygen must diffuse through this film. High-velocity water will disturb this film, while carbonic acid or organic acids, which are present in some fresh waters and soils, will dissolve the film. Either situation leads to an appreciably high corrosion rate. If the water velocity is limited to 4–5 ft/s, the film will not be disturbed.

Sodium and potassium hydroxide solutions can be handled at room temperature by copper in all concentrations. Copper is not corroded by perfectly dry ammonia, but it

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may be rapidly corroded by moist ammonia and ammonium hydroxide solutions. Alkaline salts, such as sodium carbonate, sodium phosphate, or sodium silicate, act like hydroxides but are less corrosive.

When exposed to the atmosphere over a long period of time, the protective film that forms is initially dark in color, gradually turning green. This corrosion product is known as patina. Since the coloration is given by copper hydroxide products, the length of time required to form this coloration is dependent on the atmosphere. In marine atmospheres the compound is a mixture of copper hydroxide and chloride and in urban or industrial atmospheres a mixture of copper hydroxide and sulfate.

Pure copper is immune to stress corrosion cracking. However, alloys of copper containing more than 15% zinc are particularly subject to this type of corrosion.

The coppers are resistant to urban, marine, and industrial atmospheres. For this reason copper is used in many architectural applications such as building fronts, downspouts, flashing, gutters, roofing, and screening. In addition to corrosion resistance, their good thermal conductivity properties make the coppers ideal for use in solar panels and related tubing and piping used in solar energy conversion. These same properties plus their resistance to engine coolants make the coppers suitable for use as radiators.

Large amounts of copper are used in the beverage industry, particularly in the brewing and distilling operations.

In general, the coppers are resistant to

1. Seawater
2. Fresh waters, hot or cold
3. De-aererated, hot or cold, dilute sulfuric acid, phosphoric acid, acetic acid, and other nonoxidizing acids
4. Atmospheric exposure

The coppers are not resistant to

1. Oxidizing acids such as nitric and hot concentrated sulfuric acid, and aerated nonoxidizing acids (including carbonic acid).
2. Ammonium hydroxide (plus oxygen). A complex ion, $Cu(NH_3)_4^{2+}$, forms. Substituted ammonia compounds (amines) are also corrosive.
3. High-velocity aerated waters and aqueous solutions.
4. Oxidizing heavy metal salts (ferric chloride, ferric sulfate, etc.).
5. Hydrogen sulfide and some sulfur compounds.

The compatibility of copper with selected corrodents is shown in Table C.19.

Copper has excellent electrical and thermal conductivity properties, is malleable, and is machinable, but has low mechanical properties. The mechanical and physical properties are given in Table C.20. To obtain strength, the metal must be cold worked or alloyed. As a result, there are hundreds of copper alloys. The Copper Development Association, together with the American Society of Testing and Materials and the Society of Automotive Engineers, has developed a five-digit system to identify these alloys. This system is part of the unified numbering system for metals and alloys. The numbers C10000 through C79999 denote the wrought alloys, whereas the cast copper and copper alloys are numbered C80000 through C99999.

See Refs. 23, 24.

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**Table C.19** Compatibility of Copper, Aluminum Bronze, and Red Brass with Selected Corrodents[a]

| | Maximum temperature (°F/°C) | | |
|---|---|---|---|
| Chemical | Copper | Aluminum bronze | Red brass |
| Acetaldehyde | x | x | x |
| Acetamide | | 60/16 | |
| Acetic acid 10% | 100/38 | | x |
| Acetic acid 50% | x | x | x |
| Acetic acid 80% | x | x | x |
| Acetic acid, glacial | x | x | x |
| Acetic anhydride | 80/27 | 90/32 | x |
| Acetone | 140/60 | 90/32 | 220/104 |
| Acetyl chloride | x | 60/16 | x |
| Acrylonitrile | 80/27 | 90/32 | 210/99 |
| Adipic acid | 80/27 | | |
| Allyl alcohol | 90/32 | 90/32 | 90/32 |
| Alum | 90/32 | 60/16 | 80/27 |
| Aluminum acetate | 60/16 | | |
| Aluminum chloride, aqueous | x | x | x |
| Aluminum chloride, dry | 60/16 | | |
| Aluminum fluoride | x | 90/32 | |
| Aluminum hydroxide | 90/32 | x | 80/27 |
| Aluminum nitrate | | x | x |
| Aluminum oxychloride | | | |
| Aluminum sulfate | 80/27 | x | x |
| Ammonia gas | x | 90/32 | x |
| Ammonium bifluoride | x | | x |
| Ammonium carbonate | x | | x |
| Ammonium chloride 10% | x | x | |
| Ammonium chloride 50% | x | x | |
| Ammonium chloride, sat. | x | x | x |
| Ammonium fluoride 10% | x | | x |
| Ammonium fluoride 25% | x | x | x |
| Ammonium hydroxide 25% | x | x | x |
| Ammonium hydroxide, sat. | x | x | x |
| Ammonium nitrate | x | x | x |
| Ammonium persulfate | 90/32 | x | x |
| Ammonium phosphate | x | 90/32 | x |
| Ammonium sulfate 10–40% | x | x | x |
| Ammonium sulfide | x | x | x |
| Ammonium sulfite | x | | x |
| Amyl acetate | 90/32 | x | 400/204 |
| Amyl alcohol | 80/27 | 90/32 | 90/32 |
| Amyl chloride | 80/27 | 90/32 | 80/27 |
| Aniline | x | 90/32 | x |
| Antimony trichloride | 80/27 | x | x |
| Aqua regia 3:1 | x | x | x |
| Barium carbonate | 80/27 | 90/32 | 90/32 |
| Barium chloride | 80/27 | 80/27 | 80/27 |
| Barium hydroxide | 80/27 | x | 80/27 |
| Barium sulfate | 80/27 | 60/16 | 210/99 |
| Barium sulfide | x | x | x |
| Benzaldehyde | 80/27 | 90/32 | 210/99 |

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**Table C.19** Compatibility of Copper, Aluminum Bronze, and Red Brass with Selected Corrodents[a] (Continued)

| | Maximum temperature (°F/°C) | | |
|---|---|---|---|
| Chemical | Copper | Aluminum bronze | Red brass |
| Benzene | 100/38 | 80/27 | 210/99 |
| Benzene sulfonic acid 10% | | | 90/32 |
| Benzoic acid 10% | 80/27 | 90/32 | 210/99 |
| Benzyl alcohol | 80/27 | 90/32 | 210/99 |
| Benzyl chloride | x | | x |
| Borax | 80/27 | 90/32 | 80/27 |
| Boric acid | 100/38 | 90/32 | x |
| Bromine gas, dry | 60/16 | x | |
| Bromine gas, moist | x | x | |
| Bromine liquid | | x | |
| Butadiene | 80/27 | | 80/27 |
| Butyl acetate | 80/27 | | 300/149 |
| Butyl alcohol | 80/27 | 90/32 | 90/32 |
| Butyl phthalate | 80/27 | | 210/99 |
| Butyric acid | 60/16 | 90/32 | 80/27 |
| Calcium bisulfite | 80/27 | x | x |
| Calcium carbonate | 80/27 | x | 80/27 |
| Calcium chlorate | x | x | x |
| Calcium chloride | 210/99 | x | 80/27 |
| Calcium hydroxide 10% | 210/99 | 80/27 | |
| Calcium hydroxide. sat. | 210/99 | 60/16 | 210/99 |
| Calcium hypochlorite | x | x | x |
| Calcium nitrate | | x | x |
| Calcium sulfate | 80/27 | x | 80/27 |
| Caprylic acid | x | | x |
| Carbon bisulfide | 80/27 | | x |
| Carbon dioxide, dry | 90/32 | 90/32 | 570/299 |
| Carbon dioxide, wet | 90/32 | 90/32 | x |
| Carbon disulfide | 80/27 | | x |
| Carbon monoxide | | 60/16 | 570/299 |
| Carbon tetrachloride | 210/99 | 90/32 | 180/82 |
| Carbonic acid | 80/27 | x | 210/99 |
| Cellosolve | 80/27 | 60/16 | 210/99 |
| Chloracetic acid, 50% water | x | | |
| Chloracetic acid | x | 80/27 | x |
| Chlorine gas, dry | 210/99 | 90/32 | 570/299 |
| Chlorine gas, wet | x | x | x |
| Chlorine, liquid | | | |
| Chlorobenzene | 90/32 | 60/16 | 210/99 |
| Chloroform | 80/27 | 90/32 | 80/27 |
| Chlorosulfonic acid | x | x | x |
| Chromic acid 10% | x | x | x |
| Chromic acid, 50% | x | x | x |
| Citric acid 15% | 210/99 | 90/32 | x |
| Citric acid, concentrated | x | x | x |
| Copper acetate | 90/32 | x | x |
| Copper carbonate | 90/32 | | |
| Copper chloride | x | x | x |

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**Table C.19** Compatibility of Copper, Aluminum Bronze, and Red Brass with Selected Corrodents[a] (Continued)

| | Maximum temperature (°F/°C) | | |
|---|---|---|---|
| Chemical | Copper | Aluminum bronze | Red brass |
| Copper cyanide | x | x | x |
| Copper sulfate | x | x | x |
| Cupric chloride 5% | x | | |
| Cupric chloride 50% | | | |
| Cyclohexane | 80/27 | 80/27 | 80/27 |
| Cyclohexanol | 80/27 | | 80/27 |
| Dichloroethane | | | 210/99 |
| Ethylene glycol | 100/38 | 80/27 | 80/27 |
| Ferric chloride | 80/27 | x | x |
| Ferric chloride 50% in water | x | x | x |
| Ferric nitrate 10–50% | x | x | x |
| Ferrous chloride | | x | x |
| Ferrous nitrate | | | |
| Fluorine gas, dry | x | x | x |
| Fluorine gas, moist | x | | |
| Hydrobromic acid, dilute | x | x | x |
| Hydrobromic acid 20% | x | x | x |
| Hydrobromic acid 50% | x | x | x |
| Hydrochloric acid 20% | x | x | x |
| Hydrochloric acid 38% | x | x | x |
| Hydrocyanic acid 10% | x | x | x |
| Hydrofluoric acid 30% | x | x | x |
| Hydrofluoric acid 70% | x | x | x |
| Hydrofluoric acid 100% | x | x | x |
| Hypochlorous acid | x | | x |
| Iodine solution 10% | | | |
| Ketones, general | | 90/32 | 100/38 |
| Lactic acid 25% | | x | 90/32 |
| Lactic acid, concentrated | 90/32 | 90/32 | 90/32 |
| Magnesium chloride | 300/149 | 90/32 | x |
| Malic acid | x | | |
| Manganese chloride | x | | |
| Methyl chloride | 90/32 | x | 210/99 |
| Methyl ethyl ketone | 80/27 | 60/16 | 210/99 |
| Methyl isobutyl ketone | 90/32 | | 210/99 |
| Muriatic acid | x | | |
| Nitric acid 5% | x | x | x |
| Nitric acid 20% | x | x | x |
| Nitric acid 70% | x | x | x |
| Nitric acid, anhydrous | x | x | x |
| Nitrous acid, concentrated | 80/27 | x | |
| Oleum | | x | x |
| Perchloric acid 10% | | | x |
| Perchloric acid 70% | | | x |
| Phenol | x | x | 570/299 |
| Phosphoric acid 50–80% | x | x | x |
| Picric acid | x | x | x |
| Potassium bromide 30% | 80/27 | | |

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**Table C.19** Compatibility of Copper, Aluminum Bronze, and Red Brass with Selected Corrodents[a] (Continued)

| Chemical | Maximum temperature (°F/°C) | | |
|---|---|---|---|
| | Copper | Aluminum bronze | Red brass |
| Salicylic acid | 90/32 | | 210/99 |
| Silver bromide 10% | x | | |
| Sodium carbonate | 120/49 | 60/16 | 90/32 |
| Sodium chloride to 30% | 210/99 | 60/16 | 210/99 |
| Sodium hydroxide 10% | 210/99 | 60/16 | 210/99 |
| Sodium hydroxide 50% | x | x | x |
| Sodium hydroxide, concentrated | x | x | x |
| Sodium hypochlorite 20% | x | x | 80/27 |
| Sodium hypochlorite, concentrated | x | x | x |
| Sodium sulfide to 50% | x | x | x |
| Stannic chloride | x | x | x |
| Stannous chloride | x | x | x |
| Sulfuric acid 10% | x | x | 200/93 |
| Sulfuric acid 50% | x | x | x |
| Sulfuric acid 70% | x | x | x |
| Sulfuric acid 90% | x | x | x |
| Sulfuric acid 98% | x | x | x |
| Sulfuric acid 100% | x | x | x |
| Sulfuric acid, fuming | x | x | x |
| Sulfurous acid | x | x | 90/32 |
| Toluene | 210/99 | 90/32 | 210/99 |
| Trichloroacetic acid | 80/27 | x | 80/27 |
| Zinc chloride | x | x | x |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable. When compatible, corrosion rate is <20 mpy.
*Source:* PA Schweitzer. *Corrosion Resistance Tables,* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

**Table C.20** Mechanical and Physical Properties of Copper

| Property | Annealed | Hard-drawn |
|---|---|---|
| Modulus of elasticity $\times 10^6$, psi | 17 | 17 |
| Tensile strength $\times 10^3$ psi | 33 | 45 |
| Yield strength 0.2% offset $\times 10^3$, psi | 10 | 40 |
| Elongation in 2 in., % | 45 | 10 |
| Hardness, Rockwell | F-45 | B-40 |
| Density, lb/in.$^3$ | 0.323 | 0.323 |
| Specific gravity | 8.91 | 8.91 |
| Specific heat, Btu/hr °F | 0.092 | 0.092 |
| Thermal conductivity at 68°F Btu/hr ft$^2$ °F | 2364 | 2364 |
| Coefficient of thermal expansion at 77–572°F in/in. °F $\times 10^{-6}$ | 9.8 | 9.8 |

## High-Copper Alloys

Wrought high-copper alloys contain a minimum of 96% copper. Table C.21 lists the chemical compositions of some of the high-copper alloys. High-copper alloys are used primarily for electrical and electronic applications.

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**Table C.21** High-Copper Alloys: Maximum[a] Composition (%)

| UNS no. | Cu | Fe | Ni | Co | Be | Pb | P | Zn | Sn | Si | Al |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C1700 | Balance | [b] | [b] | [b] | 1.6–1.79 | — | — | — | — | 0.20 | 0.20 |
| C17200 | Balance | [b] | [b] | [b] | 1.8–2.00 | — | — | — | — | 0.20 | 0.20 |
| C17300 | Balance | [b] | [b] | [b] | 1.8–2.00 | 0.20–0.60 | — | — | — | 0.20 | 0.20 |
| C1800[c] | Balance | 0.10 | 2.5 | — | — | — | — | — | 0.4 | 0.7 | — |
| C19200 | 96.7 min. | 0.8–1.2 | — | — | — | — | 0.01–0.04 | — | — | — | — |
| C19400 | 97.0 min. | 2.1–2.6 | — | — | — | 0.03 | 0.015–0.15 | 0.05–0.20 | — | — | — |

[a]Unless shown as a range or minimum.
[b]M + Co: 0.20 min.; Ni + Fe + Co: 0.60 max.
[c]Also available in cast form as copper alloy UNS C81540.
*Source:* Ref. 25.

The corrosion resistance of the high-copper alloys is approximately the same as that of the coppers. These alloys are used in corrosion service when mechanical strength is needed as well as corrosion resistance. Alloy C19400 is basically copper that has about 2.4% iron added to improve corrosion resistance. It is used in seam-welded condenser tubing in desalting services.

## Copper-Aluminum Alloys

These are alloys commonly referred to as aluminum bronzes. They are available in both wrought and cast forms. The ability of copper to withstand the corrosive effects of salt and brackish water is well known. Copper artifacts recovered from sunken ships have been identifiable and in many cases usable after hundreds of years under the sea. During the early 1900s aluminum was added to copper as an alloying ingredient. It was originally added to give strength to copper while maintaining the corrosion resistance of the base metal. As it developed, the aluminum bronzes were more resistant to direct chemical attack because aluminum oxide plus copper oxide were formed. The two oxides are complementary and often give the alloy superior corrosion resistance. Table C.22 lists the alloys generally used for corrosion resistance.

**Table C.22** Wrought Copper-Aluminum Alloys: Maximum[a] Composition (%)

| UNS no. | Cu | Al | Fe | Ni | Mn | Si | Sn | Zn | Other |
|---|---|---|---|---|---|---|---|---|---|
| C60800 | 92.5–94.8 | 5.0–6.5 | 0.010 | — | — | — | — | — | 0.02–0.25 As, 0.10 Pb |
| C61000 | 90.0–93.0 | 6.0–8.5 | 0.50 | — | — | 0.10 | — | 0.20 | 0.02 Pb |
| C61300 | 88.6–92.0 | 6.0–8.5 | 2.0–3.0 | 0.15 | 0.10 | 0.10 | 0.20–0.50 | 0.05 | 0.01 Pb |
| C61400 | 88.0–92.5 | 6.0–8.0 | 1.5–3.5 | — | 0.10 | — | — | 0.20 | 0.01 Pb |
| C61500 | 89.0–90.5 | 7.7–8.3 | — | 1.8–2.2 | — | — | — | — | 0.015 Pb |
| C61800 | 86.9–91.0 | 8.5–11.0 | 0.5–1.5 | — | — | 0.10 | — | 0.02 | 0.02 Pb |
| C62300 | 82.2–89.5 | 8.5–11.0 | 2.0–4.0 | 1.0 | 0.50 | 0.25 | 0.60 | — | — |
| C63000 | 78.0–85.0 | 9.0–11.0 | 2.0–4.0 | 4.0–5.5 | 1.5 | 0.25 | 0.20 | 0.30 | — |
| C63200 | 75.9–84.5 | 8.5–9.5 | 3.0–5.0 | 4.0–5.5 | 3.5 | 0.10 | — | — | 0.02 Pb |

[a]Unless shown as a range.
*Source:* Ref. 25

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Aluminum bronzes have progressed from simple copper-aluminum alloys to more complex alloys with the addition of iron, nickel, silicon, manganese, tin, and other elements.

Aluminum bronzes are resistant to nonoxidizing mineral acids such as phosphoric and sulfuric. The presence of an oxidizing agent controls their resistance.

These alloys are resistant to many organic acids, such as acetic, citric, formic, and lactic. The possibility of copper pickup by the finished product may limit their use. Such a pickup may discolor the product even though it is very low. Refer to Table C.19 for the compatibility of aluminum bronze with selected corrodents.

Dealloying is rarely seen in all alpha, single-phase alloys such as UNS C60800, C61300, or C61400. When dealloying does occur, it is in conditions of low pH and high temperature.

Alloy C61300 is used to fabricate vessels to handle acetic acid because its good corrosion resistance, strength, and heat conductivity make it a good choice for acetic acid processing. Alkalies such as sodium and potassium hydroxides can also be handled by aluminum bronze alloys.

Aluminum bronzes are also used as condenser tube sheets in both fossil fuel and nuclear power plants to handle fresh, brackish, and seawaters for cooling, particularly alloys C61300, C61400, and C63000.

## Copper-Nickel Alloys

These are referred to as cupronickels. The copper nickels are single-phase alloys, with nickel as the principal alloying ingredient. The alloys most important for corrosion resistance are those containing 10% and 30% nickel. Table C.23 lists these alloys. Iron, manganese, silicon, and niobium may be added. Iron improves the impingement resistance of these alloys if it is in solid solution. Iron present in small microprecipitates can be detrimental to corrosion resistance. To aid weldability, niobium is added.

Of the several commercial copper-nickel alloys available, alloy C70600 offers the best combination of properties for marine application and has the broadest application in seawater service. Alloy 706 has been used aboard ships for seawater distribution and shipboard fire protection. It is also used in many desalting plants. Exposed to seawater, alloy 706 forms a thin but tightly adhering oxide film on its surface. To the extent that this film forms, copper-nickel does in fact "corrode" in marine environments. However, the copper-nickel oxide film is firmly bonded to the underlying metal and is nearly insoluble in seawater. It therefore protects the alloy against further attack once it is formed. Initial corrosion rates may be in the range of less than 1.0 to about 2.5 mpy. In the absence of turbulence, as would be the case in a properly designed piping system, the copper-nickel's corrosion rate will decrease with time, eventually dropping to as low as 0.05 mpy after several years of service.

**Table C.23** Chemical Composition of Wrought Cupronickels (%)

| UNS no. | Cu | Ni | Fe | Mn | Other |
|---|---|---|---|---|---|
| C70600 | Balance | 9.0–11.0 | 1.0–1.8 | 1.0 max. | Pb 0.05 max., Zn 1.0 max. |
| C71500 | Balance | 29.0–33.0 | 0.40–0.7 | 1.0 max. | Pb 0.05 max., Zn 1.0 max. |
| C71900 | Balance | 29.0–32.0 | 0.25 max. | 0.5–1.0 | Cr 2.6–3.2, Zr 0.08–0.2, Ti 0.02–0.08 |

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**Table C.24** Mechanical and Physical Properties of 90–10 Copper-Nickel Alloy 706

| | |
|---|---|
| Modulus of elasticity $\times 10^6$, psi | 18 |
| Tensile strength $\times 10^3$ psi | |
| 4½ in. O.D. | 40 |
| 5½ in. O.D. | 38 |
| Yield strength at 0.5% extension under load $\times 10^3$ psi | |
| 4½ in. O.D. | 15 |
| 5½ in. O.D. | 13 |
| Elongation in 2 in., % | 25 |
| Density, lb/in.$^3$ | 0.323 |
| Specific heat, Btu/lb °F | 0.09 |
| Thermal conductivity, Btu/h/ft/at ft.$^2$/°F | 26 |
| Coefficient of thermal expansion at 68–572°F. in/in. °F $\times 10^{-6}$ | 9.5 |

Another important advantage of the oxide film developed on alloy 706 is that it is an extremely poor medium for the adherence and growth of marine life forms. Algae and bromades, the two most common forms of marine biofouling, simply will not grow on alloy 706. Alloy 706 piping therefore remains clean and smooth, neither corroding appreciably nor becoming encrusted with growth. Refer to Table C.24 for the mechanical and physical properties of alloy 706.

Alloy C71500 finds use in many of the same applications as alloy C70600. Sulfides as low as 0.007 ppm in seawater can induce pitting in both alloys, and both alloys are highly susceptible to accelerated corrosion as the sulfide concentration exceeds 0.01 ppm.

Alloy C71900 is a cupronickel to which chromium has been added. It was developed for naval use. The chromium addition strengthens the alloy by spinodal decomposition. This increases the yield strength from 20.5 ksi for C71500 to 45 ksi for C71900. This alloy has improved resistance to impingement. There is, however, some sacrifice in general corrosion resistance, pitting, and crevice corrosion under stagnant or low-velocity conditions.

The copper-nickels are highly resistant to stress corrosion cracking. Of all the copper alloys, they are the most resistant to stress corrosion cracking in ammonia and ammoniacal environments. Although not used in these environments because of cost, they are resistant to some nonoxidizing acids, alkalies, neutral salts, and organics.

## Copper-Tin Alloys

These alloys are known as tin bronzes or phosphor bronzes. Although tin is the principal alloying ingredient, phosphorus is always present in small amounts, usually less than 0.5%, because of its use as an oxidizer.

These alloys are probably the oldest alloys known, having been the bronzes of the Bronze Age. Even today many of the artifacts produced during that age are still in existence. Items such as statues, vases, bells, and swords have survived hundreds of years of exposure to a wide variety of environments, testifying to the corrosion resistance of these materials.

Alloys that contain more than 5% tin are especially resistant to impingement attack. In general, the tin bronzes are noted for their high strength. Their main application is in water service for such items as valves, valve components, pump casings, and similar items. Because of their corrosion resistance in stagnant waters, they also find wide application as components of fire protection systems.

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## Copper-Zinc Alloys (Brasses)

Brasses contain zinc as their principal alloying ingredient. Other alloying additions are lead, tin, and aluminum. Lead is added to improve machinability and does not improve the corrosion resistance. The addition of approximately 1% tin increases the dealloying resistance of the alloys. Aluminum is added to stabilize the protective surface film. Alloys containing in excess of 15% zinc are susceptible to dealloying in environments such as acids, both organic and inorganic, dilute and concentrated alkalies, neutral solutions of chlorides and sulfates, and mild oxidizing agents.

This is a type of corrosion in which the brass dissolves as an alloy and the copper constituent redeposits from the solution onto the surface of the brass as a metal in porous form. The zinc constituent may be deposited in place of an insoluble compound or carried away from the brass as a soluble salt. The corrosion can take place uniformly or be local. Uniform corrosion is more apt to take place in acid environments while local corrosion is more apt to take place in alkaline, neutral, or slightly acid environments. The addition of tin or arsenic will inhibit this form of corrosion.

Conditions of the environment that favor dezincification are high-temperature, stagnant solutions, especially acid, and porous inorganic scale formation. Other factors that stimulate the process are increasing zinc concentrations and the presence of both cuprous and chloride ions.

As the dealloying proceeds, a porous layer of pure or almost pure copper is left behind. This reaction layer is of poor mechanical strength. The dezincification process on copper-zinc alloys is therefore very detrimental. These alloys are also subject to stress corrosion cracking. Moist ammonia in the presence of air will cause this form of corrosion. The quantity of ammonia present need not be great, as long as the other factors are present.

The relative resistance of the brasses to stress corrosion cracking is as given in the table.

| |
|---|
| *Low resistance* |
| Brasses containing >15% zinc |
| Brasses containing >15% zinc and small amounts of lead, tin, or aluminum |
| *Intermediate resistance* |
| Brasses containing <15% zinc |
| Aluminum bronzes |
| Nickel-silvers |
| Phosphor bronzes |
| *Good resistance* |
| Silicon bronzes |
| Phosphorized copper |
| *High resistance* |
| Commercially pure copper |
| Cupronickels |

If the metal is cold formed, residual stresses may be present that can also cause stress corrosion cracking. By heating the metal to a temperature high enough to permit recrystallization, the stresses will be removed. It is also possible to provide a stress-relieving anneal at a lower temperature without substantially changing the mechanical properties of the cold-worked metal.

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As stated earlier, the addition of small amounts of tin improves the dezincification resistance of these alloys. The brasses most commonly used for corrosion-resistant applications are

| Copper Alloy UNS No. |
|---|
| C27000 |
| C28000 |
| C44300 |
| C44400 |
| C44500 |
| C46400 |
| C46500 |
| C46600 |
| C46700 |
| C68700 |

Copper alloys UNS C44300 through C44500 are known as admiralty brasses. They are resistant to dealloying as a result of the presence of tin in the alloy.

Admiralty brass finds application mainly in the handling of seawater and/or fresh water, particularly in condensers. These brasses are also resistant to hydrogen sulfide and therefore find application in petroleum refineries.

The high-zinc brasses, such as C27000, C28000, C44300, and C46400, resist sulfides better than do the low-zinc brasses. Dry hydrogen sulfide is well resisted.

Alloys containing 15% or less of zinc resist dealloying and are generally more corrosion resistant than the high-zinc–bearing alloys. These alloys are resistant to many acids, alkalies, and salt solutions that cause dealloying in the high-zinc brasses. Dissolved air, oxidizing materials such as chlorine and ferric salts, compounds that form soluble copper complexes (e.g., ammonia) and compounds that react directly with copper (e.g., sulfur and mercury) are corrosive to the low-zinc brasses. These alloys are more resistant to stress corrosion cracking than the high-zinc–containing alloys.

Red brass (C23000) is a typical alloy in this group, containing 15% zinc and 85% copper. It has the basic corrosion resistance of copper but with greater tensile strength. Refer to Table C.19 for the compatibility of red brass with selected corrodents. The mechanical and physical properties of red brass are shown in Table C.25.

The leaded brasses (C31200 through C38500) have improved machinability as a result of the addition of lead.

**Table C.25** Mechanical and Physical Properties of Red Brass

| | |
|---|---|
| Modulus of elasticity $\times 10^6$, psi | 17 |
| Tensile strength $\times 10^3$, psi | 40 |
| Yield strength 0.2% offset $\times 10^3$ psi | 15 |
| Elongation in 2 in., % | 50 |
| Hardness, Brinell | 50 |
| Density, lb/in.$^3$ | 0.316 |
| Specific gravity | 8.75 |
| Specific heat, Btu/lb °F | 0.09 |
| Thermal conductivity at 32–212°F Btu/ft$^2$/h/ °F/in. | 1100 |
| Coefficient of thermal expansion at 31–212°F in/in. °F $\times 10^{-6}$ | 9.8 |

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## CORROSION ALLOWANCE

The required wall thickness of a pressure vessel or storage tank is determined by the physical and mechanical properties of the specific metal or alloy being used and the operating conditions of temperature and pressure. Calculations provide the minimum required thickness to which a safety factor is added. The corrosion allowance is an extra thickness of metal above that needed for mechanical strength. The extra thickness, which is determined by the corrosion rate of the metal or alloy, is added to the design thickness to compensate for the anticipated lifetime corrosion loss. In general, the corrosion allowance for vessels, heat exchangers, and tanks should provide for 20 years of corrosion. For piping 10 years of corrosion allowance should be required, based on the easier replaceability of piping.

A minimum of 3 mm ($\frac{1}{8}$ in.) corrosion allowance should be provided for carbon steel and low-alloy vessels, heat exchangers, and tanks, unless the service is considered noncorrosive.

For high alloys a nominal corrosion allowance of 1.5 mm ($\frac{1}{16}$ in.) may be specified. This would apply to alloy plate, the clad layer of clad plate, and the overlay of overlayed plate.

Some service may require different corrosion allowances for different sections of the same vessel. For example, the lower course and bottom of an oil storage tank may have a 3 mm ($\frac{1}{8}$ in.) corrosion allowance for water corrosion, while the upper courses, which are not exposed to water corrosion, may have only a 1.5 mm ($\frac{1}{16}$ in.) or even zero corrosion allowance.

In some instances an external corrosion allowance may be considered. Such circumstances would include buried piping or external insulation. Soils can be corrosive to buried piping and cause failure from the outside. When insulation is applied to a vessel, there is the possibility of corrosion taking place under the insulation. To guard against premature failure in these instances, a corrosion allowance may be applied.

## CORROSION COUPONS

See "Corrosion Testing."

## CORROSION FATIGUE

Corrosion fatigue is the cracking of a metal or alloy under the combined action of a corrosive environment and repeated or fluctuating stress. As in stress corrosion cracking (SCC), successive or alternate exposure to stress and corrosion does not lead to corrosion fatigue.

Metals and alloys fail by cracking when subjected to cyclic or repetitive stress even in the absence of a corrosive medium. This is known as fatigue failure. The greater the applied stress, the fewer the number of cycles required and the shorter the time to failure. In steels and other ferrous metals, no failure occurs for an infinite number of cycles at or below a stress level called the endurance limit or the fatigue limit. In a corrosive medium, failure occurs at any applied stress if the number of cycles is sufficiently large. Corrosive fatigue may therefore be defined as the reduction in fatigue life of a metal in a corrosive environment. Unlike SCC, corrosion fatigue is equally prevalent in pure metals and their alloys, and is not restricted to specific environments. Any environment causing general

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attack in a metal or alloy is capable of causing corrosion fatigue. For steels the minimum corrosion rate required is approximately 1 mpy.

Corrosion fatigue increases almost proportionately with the increase of general aggressiveness of the corrodent. Consequently, an increase in temperature, a lowering of the pH, or an increase in the concentration of the corrodent leads to aggravation of corrosion fatigue.

Corrosion fatigue can be reduced or eliminated by

1. Lowering of the stress
2. Controlling the environment
3. Use of coatings
4. Cathodic protection
5. Shot peening

See Refs. 10, 26, and 27.

## CORROSION INHIBITORS

Corrosion of metallic surfaces can be reduced or controlled by the addition of chemical compounds to the corrodent. This form of corrosion control is called inhibition, and the compounds added are known as inhibitors. These inhibitors will reduce the rate of either anodic oxidation or cathodic reduction or both processes. The inhibitors themselves form a protective film on the surface of the metal. It has been postulated that the inhibitors are absorbed into the metal surface either by physical (electrostatic) adsorption or chemisorption.

Physical adsorption is the result of electrostatic attractive forces between the organic ions and the electrically charged metal surface. Chemisorption is the transfer of, or sharing of, the inhibitor molecule's charge to the metal surface, forming a coordinate bond. The adsorbed inhibitor reduces the corrosion rate of the metal surface either by retarding the anodic dissolution reaction of the metal or by cathodic evolution of hydrogen or both. Inhibitors can be used at pH values from acid to near neutral to alkaline.

Inhibitors can be classified in many different ways, according to

1. Their chemical nature (organic or inorganic substances)
2. Their characteristics (oxidizing or nonoxidizing compounds)
3. Their technical field of application (pickling, descaling, acid cleaning, cooling water systems, and the like)

The most common and widely known use of inhibitors is their application in automobile cooling systems and boiler feedwaters.

### Inhibitor Evaluation

Since there may be more than one inhibitor suitable for a specific application, it is necessary to have a means of comparing their performance. This can be done by determining the inhibitor efficiency according to the correlation

$$I_{\text{eff}} = \frac{R_0 - R_i}{R_0} \times 100$$

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where

$I_{\text{eff}}$ = efficiency of inhibitor, %
$R_0$ = corrosion rate of metal without inhibitor present
$R_i$ = corrosion rate of metal with inhibitor present

$R_0$ and $R_i$ can be determined by any of the standard corrosion-testing techniques. The corrosion rate can be measured in any units, such as weight loss (mpy), as long as consistent units are used for all tests.

## Classification of Inhibitors

Inhibitors can be classified in several ways, as indicated previously. We will classify and discuss inhibitors under the headings

1. Passivation inhibitors
2. Organic inhibitors
3. Precipitation inhibitors

### *Passivation Inhibitors*

Passivation inhibitors are chemical oxidizing materials such as chromate ($Cr_2O_4^{2-}$) and nitrite ($NO_2^-$) or substances such as $Na_3PO_4$ or $NaBrO_7$. These materials favor the adsorption on the metal surface of dissolved oxygen.

This type of inhibitor is the most effective and consequently widely used. Chromatics are the least expensive inhibitors for use in water systems and are widely used in the recirculation—cooling—systems of internal combustion engines, rectifiers, and cooling towers. Sodium chromate in concentrations of 0.04 to 0.1% is used for this purpose. At higher temperatures or in fresh water that has a chloride concentration above 10 ppm, higher concentrations are required. If necessary, sodium hydroxide is added to adjust the pH to a range of 7.5 to 9.5. If the concentration of chromate falls below a concentration of 0.016%, corrosion will be accelerated. Therefore, it is essential that periodic colorimetric analysis be conducted to prevent this from occurring.

Recent environmental regulations have been imposed on the use of chromates. They are toxic and on prolonged contact with the skin can cause a rash. It is usually required that the $Cr^{+6}$ ion be converted to $Cr^{+3}$ before discharge. The $Cr^{+3}$ ion is water soluble and toxic. The $Cr^{+3}$ sludge is classified as a hazardous waste and must be constantly monitored. Because of the cost of the conversion of the chromate ions, the constant monitoring required, and the disposal of the hazardous wastes, the economics of the use of these inhibitors are not as attractive as they formerly were.

Since most antifreeze solutions contain methanol or ethylene glycol, the chromates cannot be used in this application since the chromates have a tendency to react with organic compounds. In these applications borax ($Na_2B_4O_7 \cdot 10H_2O$), to which have been added sulfonated oils to produce an oily coating, and mercaptobenzothiazole are used. The latter material is a specific inhibitor for the corrosion of copper.

Nitrites are also used in antifreeze-type cooling water systems since they have little tendency to react with alcohols or ethylene glvcol. Since they are gradually decomposed by bacteria, they are not recommended for use in cooling tower waters. Nitrites are the corrosion inhibitors of the internal surfaces of pipelines used to transport petroleum products or gasoline, which is accomplished by continuously injecting a 5–30% sodium nitrite solution into the line.

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At lower temperatures, such as in underground storage tanks, gasoline can be corrosive to steel as dissolved water is released. This water, in contact with the large quantities of oxygen dissolved in the gasoline, corrodes the steel and forms large quantities of rust. The sodium nitrite enters the water phase and effectively inhibits corrosion.

The nitrites are also used to inhibit corrosion by cutting oil-water emulsions used in the machining of metals.

Passivation inhibitors can actually cause pitting and accelerate corrosion when concentrations fall below minimum limits. For this reason it is essential that constant monitoring of the inhibitor concentration be performed.

### *Organic Inhibitors*

These materials build up a protective film of adsorbed molecules on the metal surface, which provides a barrier to the dissolution of the metal in the electrolyte. Since the metal surface covered is proportional to the inhibitor concentrates, the concentration of the inhibitor in the medium is critical. For any specific inhibitor in any given medium there is an optimal concentration. For example, a concentration of 0.05% sodium benzoate, or 0.2% sodium cinnamate, is effective in water that has a pH of 7.5 and contains 17 ppm sodium chloride or 0.5% by weight of ethyl octanol.

The corrosion due to ethylene glycol cooling water systems can be controlled by the use of ethanolamine as an inhibitor.

### *Precipitation Inhibitors*

These are compounds that cause the formation of precipitates on the surface of the metal, thereby providing a protective film. Hard water, which is high in calcium and magnesium, is less corrosive than soft water because of the tendency of the salts in hard water to precipitate on the surface of the metal and form a protective film.

If the water pH is adjusted in the range of 5 to 6, a concentration of 10 to 100 ppm of sodium pyrophosphate will cause a precipitate of calcium or magnesium orthophosphatc to form on the metal surface, providing a protective film. The inhibition can be improved by the addition of zinc salts.

## Inhibition of Acid Solution

The inhibition of corrosion in acid solutions can be accomplished by the use of a variety of organic compounds. Among those used for this purpose are triple-bonded hydrocarbons; acetylenic alcohols; sulfoxides and mercaptans; aliphatic, aromatic, and heterocyclic compounds containing nitrogen; and many other families of simple organic compounds of condensation products formed by the reaction between two different species such as amines and aldehydes.

Incorrect choice or use of organic inhibitors in acid solutions can lead to corrosion stimulation and/or hydrogen penetration into the metal. In general, stimulation of corrosion is not related to the type and structure of the organic molecule. Stimulation of acid corrosion of iron has been found with mercaptans, sulfoxides, azole and treazole deratives, nitrites, and quinoline. This adverse action depends on the type of acid. For example, bis(4-dimethylaminophenyl) antipyrilcarbinol and its derivatives at a $10^{-4}$ M concentration inhibited attack of steel in hydrochloric acid solutions but stimulated attack in sulfuric acid solutions. Much work has been done studying the inhibiting and

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stimulating phenomena of organic compounds on ferrous as well as nonferrous metals. Organic inhibitors have a critical concentration value below which inhibition decreases and stimulation begins. Therefore, it is essential that when organic inhibitors are used, constant monitoring of the solution should take place to ensure that the inhibitor concentration does not fall below the critical value.

### Inhibition of Near-Neutral Solutions

Because of differences in the mechanisms of the corrosion process between acid and near-neutral solutions, the inhibitors used in acid solutions usually have little or no inhibition effect in near-neutral solutions. In acid solutions the inhibitor action is due to adsorption on oxide-free metal surfaces. In these media the main cathodic process is hydrogen evolution.

In almost neutral solutions the corrosion process of metals results in the formation of sparingly soluble surface products such as oxides, hydroxides, or salts. The cathodic partial reaction is oxygen reduction.

Inorganic or organic compounds as well as chelating agents are used as inhibitors in near-neutral aqueous solutions. Inorganic inhibitors can be classified according to their mechanism of action:

1. Formation and maintenance of protective films can be accomplished by the addition of inorganic anions such as polyphosphates, phosphates, silicates, and borates.
2. Oxidizing inhibitors such as chromates and nitrites cause self-passivation of the metallic material. It is essential that the concentration of these inhibitors be maintained above a "safe" level. If not, severe corrosion can occur as a result of pitting or localized attack caused by the oxidizer.
3. Precipitation of carbonates on the metal surfaces, forming a protective film. This usually occurs due to the presence of $Ca^{2+}$ and $Mg^{2+}$ ions usually present in industrial waters.
4. Modification of surface film protective properties is accomplished by the addition of $Ni^{2+}$, $Co^{2+}$, $Zn^{2+}$, or $Fe^{2+}$.

The sodium salts of organic acids such as benzoate, salicylate, cinnamate, tartrate, and azelate can be used as alternatives to the inorganic inhibitors, particularly in ferrous solutions. When using these particular compounds in solutions containing certain anions such as chlorides or sulfates, the inhibitor concentration necessary for effective protection will depend on the concentration of the aggressive anions. Therefore, the critical pH value for inhibition must be considered rather than the critical concentration. Other formulations for organic inhibition of near-neutral solutions are given in Table C.26.

**Table C.26** Organic Inhibitors for Use in Near-Neutral Solutions

| Inhibitor | Type of metal protected |
|---|---|
| Organic phosphorus-containing compounds, salts of aminomethylenephosphonic acid, hydroxyethylenediphosphonic acid. phosphenocarboxylic acid, polyacrylate, polymethacrylate | Ferrous |
| Borate or nitrocinnimate anions (dissolving oxygen in solution required) | Zinc, zinc alloys |
| Acetate or benzoate anions | Aluminum |
| Heterocylic compounds such as benzotriazole and its derivatives, 2-mercaptobenzothiazole, 2-mercaptobenzimidazole, | Copper and copper-based alloys |

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**Table C.27** Chelating Agents Used as Corrosion Inhibitors in Near-Neutral Solution

| Chelating agent | Type of metal protected |
|---|---|
| Alkyl-catechol derivatives. sarcosine derivatives, carboxymethylated fatty amines, and mercaptocarboxylic acids | Steel in industrial cooling systems |
| Azo compounds, cupferron, and rubeanic acid | Aluminum alloys |
| Azole derivatives and alkyl esters of thioglycolic acid | Zinc and galvinized steel |
| Oximes and quinoline derivatives | Copper |
| Cresol phthalexon and thymol phthalexon derivatives | Titamium in sulfuric acid solutions |

Chelating agents of the surface-active variety also act as efficient corrosion inhibitors when insoluble surface chelates are formed. Various surface-acting chelating agents recommended for corrosion inhibition of different metals are given in Table C.27.

## Inhibition of Alkaline Solutions

All metals whose hydroxides are amphoteric and metals covered by protective oxides that are broken in the presence of alkalies are subject to caustic attack. Localized attack may also occur as a result of pitting and crevice formation.

Organic substances such as tannions, gelatin, saponin, and agar-agar are often used as inhibitors for the protection of aluminum, zinc, copper, and iron. Other materials that have been found to be effective are thiourea, substituted phenols and naphthols, beta-diketones, 8-hydroxyquinoline, and quinalizarin.

## Temporary Protection with Inhibitors

Occasions arise when temporary protection of metallic surfaces against atmospheric corrosion is required. Typical instances are in the case of finished metallic materials or of machinery parts during transportation and/or storage prior to use. When ready to be used, the surface treatment or protective layer can be easily removed.

It is also possible to provide protection by controlling the aggressive environment either by eliminating the moisture and the aggressive gases or by introducing a vapor phase inhibitor. This latter procedure can only be accompliished in a closed environment such as a sealed container, a museum showcase, or a similar enclosure.

Organic substances used as contact inhibitors or vapor inhibitors are compounds belonging to the following classes:

1. Aliphatic, cycloaliphatic, aromatic, and heterocyclic amines
2. Amine salts with carbonic, carbamic, acetic, benzoic, nitrous, and chromic acids
3. Organic esters
4. Nitro derivatives
5. Acetylenic alcohols

## Summary

Corrosion inhibitors are usually able to prevent general or uniform corrosion. However, they are very limited in their ability to prevent localized corrosion such as pitting, crevice corrosion, galvanic corrosion, dezincification, or stress corrosion cracking. Additional research is being undertaken in the use of inhibitors to prevent these types of corrosion.

See Refs. 10, 28, and 29.

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## CORROSION MEASUREMENT

See "Monitoring Corrosion" and "Corrosion Testing."

## CORROSION MECHANISMS

Most of the commonly used metals are unstable in the atmosphere. These unstable metals are produced by reducing ores artificially; therefore, they tend to return to their original state or to similar metallic compounds when exposed to the atmosphere. Exceptions to this are gold and platinum, which are already in their metal state.

Corrosion, in its simplest definition, is the process of a material returning to its thermodynamic state. For most materials this means the formation of the oxides or sulfides which they started out as when they were taken from the earth before being refined into useful engineering materials.

Most corrosion processes are electrochemical in nature, consisting of two or more electrode reactions: the oxidation of a metal (anode partial reaction) and the reduction of an oxidizing agent (cathodic partial reaction). The study of electrochemical thermodynamics and electrochemical kinetics is necessary to understand corrosion reactions. For example, the corrosion of zinc in an acid medium proceeds according to the overall reaction

$$\mathrm{Zn} + 2\mathrm{H}^{+} \rightarrow \mathrm{Zn}^{2+} + \mathrm{H}_2 \tag{1}$$

This breaks down into the anodic partial reaction

$$\mathrm{Zn} \rightarrow \mathrm{Zn}^{2+} + 2e \tag{2}$$

and the cathodic partial reaction

$$2\mathrm{H}^{+} + 2e \rightarrow \mathrm{H}_2 \tag{3}$$

The corrosion rate depends on the electrode kinetics of both partial reactions. If all of the electrochemical parameters of the anodic and cathodic partial reactions are known, in principle the rate may be predicted.

According to Faraday's Law, a linear relationship exists between the metal dissolution rate at any potential $V_M$, and the partial anodic current density for metal dissolution $i_{aM}$:

$$V_M = \frac{i_{aM}}{nF} \tag{4}$$

where $n$ is the charge number (dimensionless), which indicates the number of electrons exchanged in the dissolution reaction, and $F$ is the Faraday constant ($F$ = 96,485 C/mol). In the absence of external polarization, a metal in contact with an oxidizing electrolytic environment spontaneously acquires a certain potential, called the corrosion potential, $E_{\mathrm{corr}}$. The partial anodic current density at the corrosion potential is equal to the corrosion current density $i_{\mathrm{corr}}$.

Equation (4) then becomes

$$V_{\mathrm{corr}} = \frac{i_{\mathrm{corr}}}{nF} \tag{5}$$

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The corrosion potential lies between the equilibrium potentials of the anodic and cathodic reactions.

The equilibrium potential of the partial reaction is predicted by electrochemical thermodynamics. The overall stoichiometry of any chemical reaction can be expressed by

$$0 = \sum V_i B_i \tag{6}$$

where $B$ designates the reactants and products. The stoichiometric coefficients $V_i$ of the products are positive and those of the reactants negative. The free enthalpy of reaction $\Delta G$ is

$$\Delta G = \sum V_i m_i \tag{7}$$

where $\boldsymbol{\mu}_i$ is the chemical potential of the participating species. If reaction (6) is conducted in an electrochemical cell, the corresponding equilibrium potential $E_{\text{rev}}$ is given by

$$\Delta G = -nFE_{\text{rev}} \tag{8}$$

Under standard conditions (all activities equal to 1),

$$\Delta G^\circ = -nFE^\circ \tag{9}$$

where $G^\circ$ represents the standard free enthalpy and $E^\circ$ represents the standard potential of the reaction.

Electrode reactions are commonly written in the form

$$\sum V_{\text{ox}i} \bullet B_{\text{ox}i} + n\text{e} = \sum V_{\text{red}i} \bullet B_{\text{red}i} \tag{10}$$

where $V_{\text{ox}i}$ represents the stoichiometric coefficient of the "oxidized" species, $B_{\text{ox}i}$, appearing on the left side of the equality sign with the free electrons, and $V_{\text{red}i}$ indicates the stoichiometric coefficient of the reduced species, $B_{\text{red}i}$ appearing on the right side of the equality sign, opposite the electrons. Equation (10) corresponds to a partial reduction reaction, and the stoichiometric coefficients $V_{\text{ox}i}$ and $V_{\text{red}i}$ are both positive.

By setting the standard chemical potential of the solvated proton and of the molecular hydrogen equal to zero—$\mu^\circ_{\text{H}^+} = 0$, $\mu^\circ_{\text{H}_2} = 0$, —it is possible to define the standard potential of the partial reduction reaction (10) with respect to the standard hydrogen electrode. The standard potential of an electrode reaction that corresponds to the overall reaction

$$\sum V_{\text{ox}i} B_{\text{ox}i} + \frac{n}{2}\text{H}_{2(P\text{H}_2 = 1\ \text{bar})} = \sum V_{\text{red}i} B_{\text{red}i} + n\text{H}^+_{(a\text{H}^+ = 1)} \tag{11}$$

Table C.28 indicates the standard potential of selected electrode ractions.

For a given reaction to take place, there must be a negative free energy change as calculated from equation

$$\Delta G = -nFE \tag{12}$$

For this to occur, the cell potential must be positive. The cell potential is taken as the difference between two half-cell reactions, the one at the cathode minus the one at the anode.

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**Table C.28** Standard Potentials of Electrode Actions at 25°C

| Electrode | E°/V |
|---|---|
| $Li^+ + e = Li$ | –3.045 |
| $Mg^{2+} + 2e = Mg$ | –2.34 |
| $Al^{3+} + 3e = Al$ | –1.67 |
| $Ti^{2+} + 2e = Ti$ | –1.63 |
| $Cr^{2+} + 2e = Cr$ | –0.90 |
| $Zn^{2+} + 2e = Zn$ | –0.76 |
| $Cr^{3+} + 3e = Cr$ | –0.74 |
| $Fe^{2+} + 2e = Fe$ | –0.44 |
| $Ni^{2+} + 2e = Ni$ | –0.257 |
| $Pb^{2+} + 2e = Pb$ | –0.126 |
| $2H^+ + 2e = H_2$ | 0 |
| $Cu^{2+} + 2e = Cu$ | 0.34 |
| $O_2 + 2H_2O + 4e = 4OH$ | 0.401 |
| $Fe^{3+} + e = Fe^{2+}$ | 0.771 |
| $Ag^+ + e = Ag$ | 0.799 |
| $Pt^{2+} + 2e = Pt$ | 1.2 |
| $O_2 + 4H^+ + 4e = 2H_2O$ | 1.229 |
| $Au^{3+} + 3e = Au$ | 1.52 |

If we place pure iron in hydrochloric acid, the chemical reaction can be expressed as

$$Fe + 2HCl \rightarrow FeCl_2 + H_2 \uparrow \tag{13}$$

On the electrochemical side we have

$$Fe + 2H^+ = 2Cl^{2-} \rightarrow Fe^{2+} = Cl^{2-} + H_2 \uparrow \tag{14}$$

The cell potential is calculated to be

$$E = \text{cathode half-cell minus anode half-cell}$$

$$E = E(H^+/H_2) - E(Fe/Fe^{2+})$$

$$E = 0 - (-0.440) = +0.44$$

Since the cell is positive, the reaction can take place. The larger this potential difference, the greater the driving force of the reaction. Other factors will determine whether or not corrosion does take place and if so at what rate. For corrosion to take place, there must be a current flow and a completed circuit, which is then governed by Ohm's Law ($I = E/R$). The cell potential calculated here represents the peak value for the case of two independent reactions. If the resistance were infinite, the cell potential would remain as calculated but there would be no corrosion. If the resistance of the circuit were zero, the potentials of the half-cells would approach each other while the rate of corrosion would be infinite.

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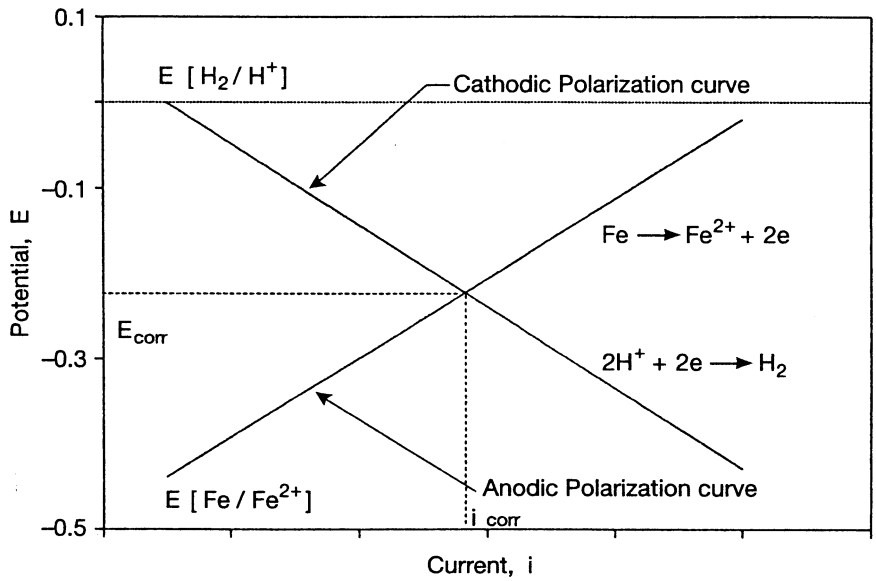



**Figure C.9** Polarization of iron in acid.

At an intermediate resistance in the circuit, some current begins to flow and the potentials of the half-cells move slightly toward each other. This change in potential is called polarization. The resistance in the circuit is dependent on various factors, including the resistivity of the media, surface films, and the metal itself. Figure C.9 shows the relationship between the polarization reactions at the two half-cells. The intersection of the two polarization curves closely approximates the corrosion current and the combined cell potentials for the freely corroding situation.

The corrosion density can be calculated by determining the surface area once the corrosion current is determined. The corrosion rate in terms of metal loss per unit time can be determined using Faraday's laws.

In addition to estimating corrosion rates, the extent of polarization can help predict the type and severity of corrosion. As polarization increases, corrosion decreases. Understanding the influence of environmental changes on polarization can aid in controlling corrosion. For example, in the iron–hydrochloric acid example, hydrogen gas formation at the cathode can actually slow the reaction by blocking access of hydrogen ions to the cathode site, thereby increasing circuit resistance, resulting in cathodic polarization, lowering the current flow and corrosion rate. If the hydrogen is removed by bubbling oxygen through the solution, which combines with the hydrogen to form water, the corrosion rate will increase significantly.

There are three basic causes of polarization: concentration, activation, and potential drop. Concentration polarization is the effect resulting from the excess of a species that impedes the corrosion process (as in the previous hydrogen illustration) or from the depletion of a species critical to the corrosion process.

Activation polarization is the result of a rate-controlling step within the corrosion reaction. In the $H^+/H_2$ conversion reaction the first step of the process,

$$2H^+ + 2e \rightarrow 2H$$

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proceeds rapidly, whereas the second step,

$$2H \rightarrow H_2$$

takes place more slowly and can become a rate-controlling factor.

Potential drop is the change in voltage associated with effects of the environment and the circuit between the anode and cathode sites. Included are the effects of surface films, corrosion products, resistivity of the media, etc.

Other factors affecting corrosion include temperature, relative velocities between the metal and the media, surface finish, grain orientation, stresses, and time.

Since corrosion is an electrochemical reaction and reaction rates increase with increasing temperature, it is logical that corrosion rates will also increase with increasing temperature.

In some instances increasing the velocity of the corrodent over the surface of the metal will increase the corrosion rate when concentration polarization occurs. However, with passive metals, increasing the velocity can actually result in lower corrosion rates, since the increased velocity shifts the cathodic polarization curve so that it no longer intersects the anodic polarization curve in the active corrosion region.

Rough surfaces or tight crevices can promote the formation of concentration cells. Surface cleanliness is also a factor since deposits or films can act as initiation sites. Biological growths can behave as deposits or change the underlying surface chemistry to promote corrosion.

Variations within the metal surface on a microscopic level can influence the corrosion process. Microstructural differences such as secondary phases or grain orientation will affect the manner in which the corrosion process will take place. The grain size of the material plays an important role in determining how rapidly the material's properties deteriorate when the grain boundaries are attacked by corrosive environments.

Stress is a requirement for stress corrosion cracking or corrosion fatigue, but can also influence the rate of general corrosion.

The severity of corrosion is affected by time. Corrosion rates are expressed as a factor of time. Some corrosion rates are rapid and violent, while most are slow and almost imperceptible on a day-to-day basis.

Potential-pH diagrams (Pourbaix diagrams) represent graphically the stability of a metal and its corrosion products as a function of the potential and pH of an aqueous solution. The pH is shown on the horizontal axis and the potential on the vertical axis. Pourbaix diagrams are widely used in corrosion because they easily permit identification of the predominant species at equilibrium for a given potential and pH. However, being based on thermodynamic data, they provide no information on the rate of possible corrosion reactions.

In order to trace such a diagram, the concentration of the dissolved material must be fixed. Figure C.10 shows a simplified Pourbaix diagram for zinc. The numbers indicate the $H_2CO_3$ content in the moisture film, for example, $10^{-2}$ and $10^{-4}$ mol/L. The diagram takes into account the formation of zinc hydroxide, of $Zn^{2+}$, and of the zincate ions $HZnO_2^-$ and $ZnO_2^{2-}$. At high potentials $ZnO_2$ may possibly be formed, but because the corresponding thermodynamic data are uncertain, they are not presented in the diagram. The broken lines indicate the domain of thermodynamic stability of water.

See Refs. 23 and 30.

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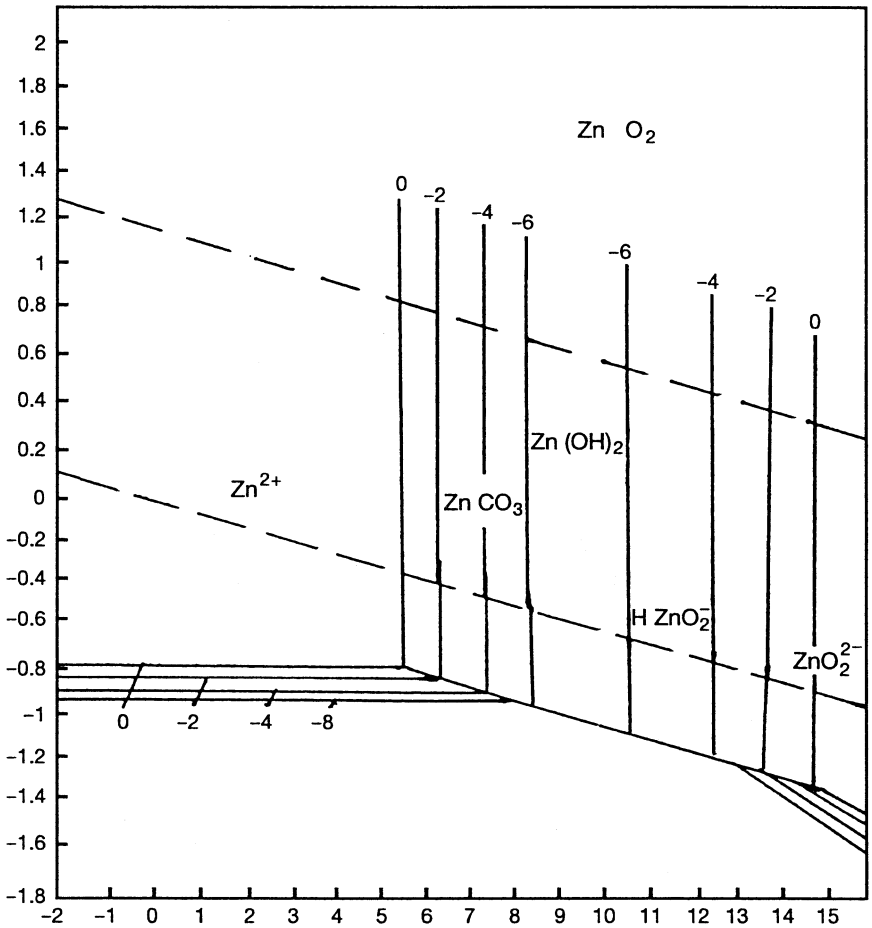



**Figure C.10** Potential-pH diagram for the system Zn-$CO_2$-$H_2O$ at 77°F/21°C.

## CORROSION MONITORING

See "Monitoring Corrosion."

## CORROSION TESTING

When a corrosion test is designed and conducted properly, reliable corrosion data may be obtained. There are a number of testing techniques that may be employed. The simplest of these involve the determination of a change in weight or dimension and observation of the corroded surface. Other, more complex methods involve the measurement of hydrogen diffusion or electrical resistance or determining electrochemical characteristics.

### Weight Change

Corrosion testing utilizing weight change involves the use of corrosion coupons. Coupons can be made in any size or shape. They are carefully weighed and measured before

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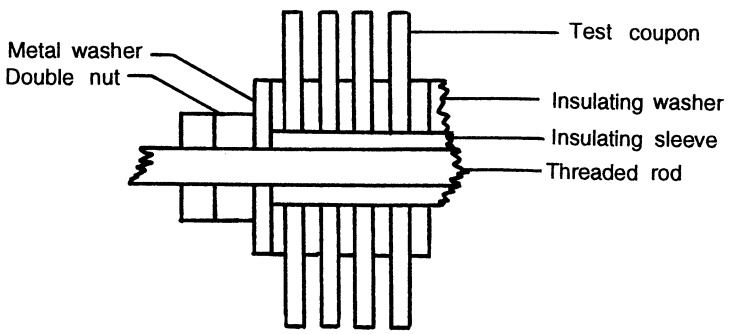



**Figure C.11** Corrosion coupons insulated from each other and the coupon rack.

assembly on a test rack. They may be mounted in different configurations to study different types of corrosion mechanisms, such as galvanic attack, crevice corrosion, and stress corrosion. By mounting different materials of construction on the same test rack it is possible to evaluate the difference in resistance to corrosion of various materials. When assembling the coupons on the test rack it is necessary that they be insulated both from the test rack itself and from each other. This is to avoid galvanic corrosion taking place between the test pieces. See Fig. C.11.

When the test is completed the test rack is disassembled and the coupons are cleaned, weighed, and measured. The formula for calculating the uniform corrosion rate is

$$\text{mpy} = \frac{534W}{DAT}$$

where

$W$ = weight loss, mg
$D$ = density of specimen, g/cm$^3$
$A$ = area of specimen, in.$^2$
$T$ = exposure time, h

The low cost, the ability to evaluate several materials at one time, and closer resemblance to actual conditions of the equipment are the main advantages to using corrosion coupons. The time involved in preparing and evaluating the coupons to determine the corrosion rates after sufficient exposure time, and the limited locations for placing the test coupons, are the primary disadvantages. The use of test coupons does not permit the engineer to evaluate the results of changing process conditions, which can also be a disadvantage.

Whenever possible, actual field conditions should be used to determine which metal is going to provide the best service. Coupons should be exposed to all conditions to which the metal will be subjected. Different locations in the process may have different corrosive effects. For example, the effects in the vapor space may vary from those in the liquid phase or in the condensing area. Because of this it is necessary to install test racks in each of the various locations.

If field testing is not possible, then laboratory tests should be planned to duplicate as closely as possible actual field conditions. Remember that very small changes in the

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environment can produce large changes in the corrosion rates of metals. Test apparatus must be used that will simulate the different conditions that will be faced in the actual equipment. For example, condensate is often more corrosive than the bulk of the liquid; also heat transfer surfaces can exhibit different corrosive effects from other surfaces.

Manufacturers of metals and new products usually have fairly large amounts of data available. These data are a good guide as to which materials should be considered, but testing should still be conducted to ensure that the material will be satisfactory for the specific application.

It is important that the proper data be recorded. This will vary depending on the purpose of the test. The following are guidelines as to what data should be recorded.

1. For corrosive media, the overall concentration and variation in concentration during the test; also any contaminants that may be present
2. For test metals, the trade name, chemical composition, product type (plate, sheet, rod, etc.), metallurgical condition (cold rolled, hot rolled, quenched and tempered, solution heat treated, stabilized, cast, etc.), and the size and shape of the coupon
3. Volume of test solution, for laboratory tests
4. The temperature: average, variation, and whether it was a heat transfer test
5. For aeration, the technique or conditions for the laboratory test, process exposed to atmosphere for field test
6. The apparatus and test rack type
7. The test time
8. The exposure location
9. The cleaning technique
10. The weight loss
11. The type and nature of localized corrosion: stress corrosion cracking, intergranular corrosion, pitting (maximum and average depth), crevice corrosion, etc.
12. The agitation: velocity for field tests, and technique for laboratory tests
13. The corrosion rate ( which, if localized corrosion is present, may be rnisleading)

## Dimension Change

Changes in dimensions can be measured using ultrasonic measuring techniques, microscopic examination, or eddy current. The most straightforward is the ultrasonic measurement of parts.

1. *Ultrasonic thickness measurement.* This technique can be used to measure thickness either while the part is in service or after it has been removed from service. The thickness of the part is measured before testing starts, and thereafter at regular time intervals. After each measurement the thickness is plotted against time as shown in Fig. C.12. The difference between thickness measurements can be divided by the time interval to obtain the corrosion rate. This information is particularly useful in determining the remaining service life of a vessel.

   Assume that the pressure vessel represented in Fig. C.12 had a corrosion allowance of 0.125 inches. During the initial plant start-up (*A*) the corrosion rate was 15 mpy based on the ultrasonic measurement. The corrosion rate during the second year (*B*) equals 5 mpy. The overall rate equals 10 mpy. The process changed

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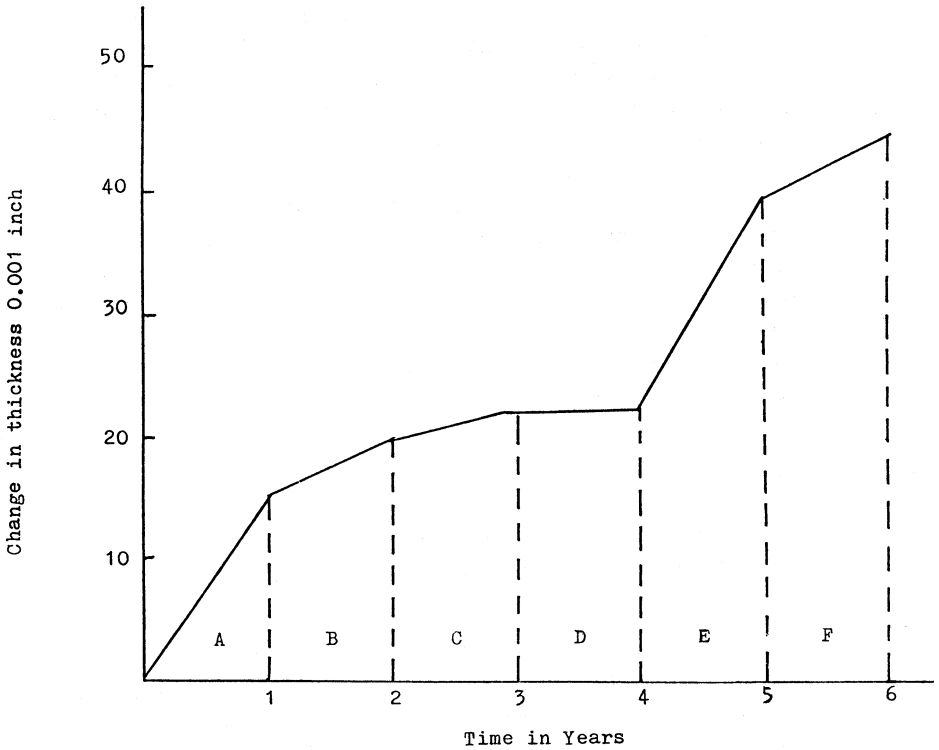



**Figure C.12** Change in wall thickness plotted against time.

during the third year (*C*), with a corrosion rate equal to 2 mpy, making for an average corrosion rate of 7 mpy. During the fourth year (*D*) the plant was shut down. A new process was introduced in the fifth year (*E*) with an average corrosion rate equal to 18 mpy. The overall corrosion rate equals 8 mpy. The vessel continues in service during the sixth year with a corrosion rate equaling 6 mpy. Of the original corrosion allowance of 0.125 inches, there is now 0.080 inch remaining, or an expected life of 13 years based on the overall corrosion rate or 16 years based on the last year's corrosion rate.

This measurement technique is not accurate enough for most laboratory testing, but it is the most accurate technique that can be used to measure the thickness of parts while in service. It also has the advantage of being able to detect changes in corrosion rates when there are process changes, or if inhibitors are added. If there is a possibility of nonuniform corrosion, an instrument with a cathode ray tube should be used, since digital instruments can give misleading readings.

2. *Microscopic examination.* When testing for high-temperature corrosion or dealloying (dezincification), it is usually necessary to examine a polished cross-section to determine how much unaffected metal remains. In these types of corrosion, considerable damage can take place because of inward diffusion of a corrodent such as oxygen or sulfur or because of the removal of some of the elements from the solid alloy. A change in external dimensions or a loss of weight is not an indication of the amount of damage that may have taken place. To determine accurately how much metal is

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left, it is necessary to prepare a cross-section of corroded metal for a metallographic examination and determine microscopically how much metal is left.

3. *Eddy current.* An eddy current instrument and a probe are used to measure the wall thickness of nonferromagnetic tubes. In this manner tubes in a heat exchanger may be inspected for corrosion while still in place. The instrument must first be calibrated on a tube of known thickness of the same metal as the tube to be inspected.

   Changes in thickness can be measured with an accuracy of ±2% . It is also possible to test for nonuniform corrosion.

## Electrochemical Techniques

The three most often used electrochemical techniques are zero-resistance ammeters, polarization curves, and linear polarization resistance curves.

1. *Zero-resistance ammeter.* A zero-resistance ammeter is a potentiostat that has been programmed to zero potential difference between the reference electrode and the test electrode. The current lead to the counterelectrode is connected to the reference electrode. This permits measurement of the amount and direction of the current that flows between the two electrodes that are electrically short-circuited. Corrosion rates of the anode cannot be calculated directly from the galvanic current because it is only a measure of how much faster the anode is corroding than the cathode.
2. *Polarization curves.* This is primarily a laboratory technique to study corrosion, particularly pitting. A variety of methods and equipment are available to conduct these studies. The following types are generally used:

   Potentiostatic
   Potential held constant
   Galvanostatic
   Current held constant
   Potentiodynamic
   a. Potential changed constantly at a specified rate
   b. Potential changed in steps and held constant at each step
   Galvanodynamic
   a. Current changed continuously at a specified rate
   b. Current changed in steps and held constant at each step

   As with all electrochemical techniques, they can only be used with sufficiently conductive media and when the area of the wetted electrode is known. Because of the high polarization potentials required, the estimation of corrosion rates is less precise than with linear polarization resistance methods.
3. *Linear polarization resistance*. The linear polarization technique permits measurement of the corrosion rate of a metal at any instant. In order to be utilized, the electrodes must be exposed to an electrolyte that has a continuous path between them. Laboratory or field testing can be conducted using either manual or automatic linear polarization equipment.

## Hydrogen Diffusion

Some corrosive reactions produce atomic hydrogen at the cathode, which can diffuse through steel and most other metals if it does not combine to form hydrogen molecules.

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When sulfides are present, the atomic hydrogen produced by the corrosion reaction readily diffuses through steel. If hydrogen diffusion is detected, corrosion is taking place. Hydrogen diffusion can be measured using either a hydrogen probe (pressure measurement) or a hydrogen monitoring system (electrochemical).

### Electrical Resistance

As the products of corrosion build up, small changes in electrical resistance occur. Low corrosion rates can be measured in this manner by not removing the products of corrosion. Probes are available with test elements made from all of the common alloys used to fabricate process equipment. Temperature changes can result in erroneous readings, since resistance changes with temperature. Although there have been modifications in probe design, it is still not possible to measure small changes in corrosion rate with a single reading unless you are absolutely sure that the temperature remained constant.

Corrosion is measured by first taking a reading on the test and check element. The probe is then inserted into the test environment and allowed to come to the test temperature. Another reading is then taken on the test and check element. Corrosion is allowed to take place for a few hours, after which a new set of readings is taken. The corrosion rate is calculated using the equation

$$\text{Corrosion rate (mpy)} = \frac{\text{CR} \times \text{PM} \times 0.365}{\text{CT}}$$

where

CR = current reading minus the previous reading. If the reading is negative, the results are not related to corrosion. They are due to either the temperature of a conductive film or the test element.

PM = probe multiplier supplied by the manufacturer

CT = change of time, in days

The overall corrosion rate (rate over the total exposed time) and the corrosion rate between readings should both be calculated to determine whether the corrosion rate is changing with time.

See Refs. 31 and 32.

## CORROSION TESTING FOR ENVIRONMENTALLY ASSISTED CRACKING (EAC)

There is no single testing technique that will take into account all the factors that come into play for a particular material and environment for the evaluation of EAC. The testing program undertaken will take into account as many of the factors as possible. This may require

1. Different alternative configurations of the same specimen
2. More than one type of test specimen
3. Several test techniques with the same specimen

It is also important that the laboratory and field or in-plant test data he correlated with service experience. There are three basic general types of tests that can be performed. They are constant load/deflection techniques, slow-strain-rate tests, and fracture mechanics tests.

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### Constant Load/Deflection Tests

Types of tests in this category include

1. Tension tests per ASTM G-49
2. Bent beam per ASTM G-38
3. C-ring tests per ASTM G-38
4. U-bend tests per ASTM G-30

Each type of test provides data relating to the specific type of stress or strain to which the specimen will be subjected under constant load.

### Slow-Strain-Rate Tests

This test replaces the constant load with a slow extension of the sample until failure. A detailed description of this test method is given in ASTM G-129 . The advantage of SSR testing is that it produces a result in a relatively short period of time. The primary benefit of SSR testing is that it permits the evaluation of the effect of alloy composition heat treatment and/or environmental changes such as aeration, concentration, and inhibition.

### Fracture Mechanics Tests

These tests are conducted to determine the effects of metallurgical or environmental changes on EAC when the specimen contains a sharp crack. There are several fracture mechanics techniques that can be used to evaluate EAC. Regardless of which technique is used, the specimen is usually one of constant load or deflection.

When a constant-load specimen is employed, a load is applied to a fracture mechanics specimen using a directly applied dead weight or through a pulley or lever system to magnify the dead weight load.

Alternatively, constant-deflection specimens may be used. In this situation either constant-tension or double-cantilever beam specimens are loaded to an initial level of crack tip stress intensity by deflection of the arms of the specimen. The deflection is obtained either by tightening a bolt arrangement that deflects the arms of the specimen or by inserting a wedge into the specimen. The initial stress intensity must be above the threshold stress for EAC that permits cracking to start. Once started, the stress intensity decreases as the crack proceeds through the specimen.

See Ref. 33.

## CORROSION UNDER INSULATION

Insulation is applied to vessels and piping as a means of conserving heat or of providing personnel protection from hot surfaces. As a result, the selection of a particular insulating material is normally based on installed cost versus energy saved. However, there arc other costs associated with insulation that are generally overlooked, namely the cost of corrosion and maintenance.

Corrosion that takes place under the insulation can be caused by the insulation itself or by improper application. If after a period it is necessary to remove sections of insulation to make repairs on the equipment, these costs and the cost of repairing the insulation should be considered during the selection process.

Thermal insulation, when exposed to water, can hold a reservoir of available moisture which together with the permeability of air causes severe attack, up to 200 to

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300 mpy. This is particularly true on warm steel surfaces. Severe corrosion may occur on cold surfaces where structural members abut the insulated vessel or pipe, permitting rime ice to form. Depending upon the specific containment, insulation can cause stress corrosion cracking of high-strength copper alloys and external stress corrosion cracking of type 300 series stainless steels. Chlorides or alkaline containments will rapidly attack aluminum. The use of an appropriate coating system, such as a catalyzed epoxy-phenolic and modified silicone, will help to prevent such corrosion in the event of ingress of water. Zinc and chloride-free coatings should be used for stainless steels.

## Types of Corrosion Under Insulation

There are three types of corrosion that can take place under insulation:

1. Alkaline or acidic corrosion
2. Chloride corrosion
3. Galvanic corrosion

Alkaline or acidic corrosion takes place as a result of either acid or alkali being present in contact with moisture in the insulating material. When these materials are applied to hot surfaces at temperatures above 250°F (121°C), the water is driven off, but it may condense at the edge of the insulation, dissolving any alkaline or acidic materials present. This results in corrosion of aluminum with certain alkaline waters.

Some insulating cements, before drying, contain alkaline chemicals and water. During the drying operation these alkaline chemicals will attack such metals as stainless steel, copper, brass, and aluminum. If the vessel being insulated is constructed of one of these metals, it may be subject to corrosion. Under normal circumstances steel would not be affected during the time required for the cement to dry.

Foam insulations containing fire-retardant chemicals, such as brominated or chlorinated compounds, can produce acidic solutions. This has been found to be true with polyurethane and phenolic foams.

Steps can be taken to prevent this type of corrosion. When external corrosion of the jacket is a problem, a good all-weather plastic jacket should be considered. If a metal jacket is to be used, a moisture barrier should be installed on the inside of the insulation. It goes without saying that all joints must be tightly sealed to prevent external water from entering the insulation.

Care should be taken in selection of the insulating material. Insulating cements are best mixed with clean potable water. The use of distilled water will increase the aggressiveness of the attack.

Chloride corrosion results when the insulating material contains leachable chlorides, temperatures are above 140°F (60°C), and the substrate surface is a 300 series stainless steel. The attack will usually be a typical stress corrosion cracking. Corrosion is propagated when water enters the insulation and diffuses inward toward the hot surface, eventually finding a "dry" spot. Adjacent to this dry spot will be found an area in which the pores of the insulation are filled with a saturated salt solution in which chlorides may be present. As the vessel wall cools down, this saturated area "moves" into the metal wall. When the wall is reheated it will be temporarily in contact with the saturated salt solution and any chlorides present. This will initiate stress corrosion cracking.

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The most efficient means of preventing chloride corrosion under insulation is to use the proper insulating materials. Insulation that meets ASTM C-795 or MIL-I-24244 specifications can safely be used over 300 series stainless steels. Care must be taken, however, to prevent chlorides in the atmosphere from impregnating the insulation.

As with acidic or alkaline corrosion, care must be taken when installing the outer insulation jacket and barrier, making sure that all joints are properly sealed.

Galvanic corrosion under insulation occurs when wet insulation that has an electrolyte salt present allows a current to flow between dissimilar metals such as the insulated metal surface and the outer metal jacket or other metallic accessories. This can result in corroding of the metal jacket or of the vessel, depending on which is the less noble metal.

Galvanic corrosion can be prevented by using a cellular insulation and applying a synthetic rubber or plastic jacket over the insulation. Hypalon performs well in this application.

### Summary

Corrosion under insulation can be prevented by taking into account

Insulation selection
Equipment design
Weather barriers

The type of insulation to be used will be dependent on the application, keeping in mind the types of corrosion that can occur. Equipment design also enters into the picture. Adequate insulation supports should be provided and additional protection should be considered where leakage or mechanical damage is possible. Additional flashing should also be installed where spills or hosing down is prevalent.

Weather barriers are a must because all corrosion under insulation requires moisture of some kind. Therefore, it becomes a necessity to make sure that all joints are properly sealed and that an adequate weather barrier is installed.

## CRACK-INDUCING AGENTS

Crack-inducing agents can be either active or passive. Most crack-inducing agents require the presence of an electrolyte to become active. Passive agents, though present, cause no harm. For example, hydrogen sulfide requires the presence of liquid water or some other electrolyte to become an active agent. On the other hand, ammonia does not require the presence of an electrolyte to attack copper.

### Hydrogen Sulfide

Wet hydrogen sulfide can cause several forms of hydrogen cracking, including sulfide stress corrosion cracking (SSCC) hydrogen-induced cracking (HIC), and stress-oriented hydrogen-induced cracking (SOHIC). SSCC occurs in many steels and alloys. HIC occurs in "dirty" steels. It is not necessary for stress to be present for this cracking to initiate. SOHIC is a stress-assisted form of HIC. It usually occurs in the heat-affected zones of restrained welds, where residual stresses probably assist the cracking operation.

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Wet hydrogen sulfide corrosion is the beginning of the hydrogen cracking. As the sulfide ion combines with iron to form iron sulfide, hydrogen is released as a corrosion by-product. The sulfide ion being a cathodic poison encourages two phenomena:

1. The nascent hydrogen tends to dissolve into the metal rather than combining with another hydrogen atom to form hydrogen gas.
2. Under normal circumstances this type of corrosion is rapidly slowed by the formation of a polarizing layer of hydrogen gas at the anode. However, the sulfide ion prevents such polarization. As a result, large amounts of nascent hydrogen are produced, as corrosion continues, until a thick film of dense iron sulfide forms, stopping further corrosion.

### *Sulfide Stress Cracking*

Sulfide stress cracking is a form of hydrogen stress cracking. It can develop in areas of excessive metal hardness. The low- to medium-strength carbon steels are most resistant to SSCC. Microalloyed carbon steels should not be used in welded construction subject to SCC since they have a tendency to produce excessively hard weld heat-affected zones. Such heat-affected zones are difficult to temper by postweld heat treatment. It is difficult to generate weld metal or heat-affected zone hardnesses to cause SSCC in low- to medium-strength carbon steels. When welding ordinary carbon steels, preheat and proper welding procedures will provide the necessary control to prevent excessive hardness. Postweld heat treatment is usually not necessary unless other crack-inducing agents (such as amines) or other cathodic poisons (such as cyanide) are also present. In these situations reduction of resident stresses is necessary to reduce the susceptibility to stress cracking.

### *Hydrogen-Induced Cracking*

Hydrogen-induced cracking is not technically a form of stress corrosion cracking, but it is related. HIC occurs primarily in steel plates containing excessive amounts of nonmetallic inclusions (primarily manganese sulfides) which have been flattened by the rolling process. Hydrogen-induced cracking is essentially a crack initiation mechanism. Nascent hydrogen diffuses into the steel as a result of hydrogen sulfide corroding the surface of the steel. Catalyst sites are established by nonmetallic inclusions, causing the diffusing nascent hydrogen to recombine into hydrogen gas. Pressure builds up adjacent to the inclusions as a result of the accumulating hydrogen gas, causing the inclusion matrix to split, initiating an HIC crack. A split can develop parallel to the surfaces of the steel plate when multiple initiation sites are present and the plate is relatively thin, less than ½ inch. On relatively thick plates staggered internal HIC cracks can link up and in extreme cases can cause through-thickness cracks.

Hydrogen-induced cracking lakes place in the temperature range of 32 to 130°F (0 to 55°C). HIC damage proceeds slowly above 130°F (55°C).

### *Stress-Oriented Hydrogen-Induced Cracking*

Stress-oriented hydrogen-induced cracking (SOHIC) usually occurs in heat-affected zones associated with the residual stresses of welds. The mechanics involves two components:

1. HIC cracks form in a stacked manner, producing a crack plane perpendicular to the surface of the plane. The cracks are generally short but closely spaced.

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2. By shearing the ligaments between the stacked HIC cracks, a through-thickness crack develops. These cracks can be minimized by postweld heat treatment and normalizing.

### Mercury

Intergranular cracking of copper alloys, as well as intergranular cracking and pitting corrosion of aluminum, can be caused by liquid mercury. This effect is known as liquid metal embrittlement.

### Zinc

Liquid metal embrittlement in iron and aluminum alloys can be caused by zinc. For this reason galvanized carbon steel should not be used at temperatures exceeding 390°F (200°C). Intergranular penetration of the steel substrate by zinc from the galvanized coating is possible. At temperatures exceeding 1380°F (750°C) molten zinc will rapidly attack the grain boundaries of austenitic stainless steel at a rate of inches per second.

The following conditions can cause failures:

1. Welding or cutting stainless steel components that have been coated with a zinc-rich product such as zinc paint
2. Welding a galvanized steel part to an austenitic steel component without first removing the galvanizing adjacent to the weld preparation

Higher alloys such as alloy 20Cb-3 and alloy 276 are not as susceptible as the conventional austenitic stainless steels.

### Cyanides

Cyanides by themselves do not cause stress corrosion cracking. However, in combination with wet hydrogen sulfide they can increase the rate of sulfide stress corrosion cracking of carbon and low-alloy steels. The hydrogen sulfide need only be present at concentration greater than 20 ppm.

Cyanides can also accelerate the rate of wet hydrogen sulfide corrosion. Sulfide films are usually stable and limit corrosion, but the presence of cyanides converts the iron sulfide scale deposits into soluble salt complexes. This subjects the underlying carbon steel to rapid corrosion.

### Chlorides

Chlorides are capable of causing stress corrosion cracking of austenitic stainless steels, provided the exposed surface is in tension. Residual tensile stresses can be the result of welding or of cold work. Such stresses can be relieved by solution annealing, postweld heat treatment, stress relief heat treatment, and shot peening, which ensures that the exposed surface is in compression.

Austenitic stainless steels may be exposed to external chloride stress corrosion cracking as well as internal exposure from the process. External chloride attack can be the result of exposure to wet chlorides in atmospheric marine environments or to chlorides deposited externally by wind, dust, or water.

### Caustics

Caustics can cause stress corrosion cracking of carbon steel and low-alloy steels. Under severe conditions caustics can also cause cracking of stainless steels and nickel-based

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alloys. For moderate temperatures and concentrations, carbon steel is the recommended material of construction. It is advisable to stress relieve or postweld heat treat carbon steel equipment to be used in caustic service.

### Carbonates and Bicarbonates

Carbon steel is subject to stress corrosion cracking when combinations of carbonates and bicarbonates (either singly or in combination) exceed 1 weight percent. Postweld heat treatment does not prevent cracking since cracking generally occurs in the parent metal. A better choice is to upgrade to duplex or austenitic stainless steels, or for low-pressure applications to use a nonmetallic material. Coatings are not recommended.

### Amines

Amines can cause alkaline stress corrosion cracking in carbon steel. If the amine concentration exceeds 2 weight percent, all carbon steel components should be postweld heat treated regardless of service temperature. If the amine is fresh and uncontaminated, the heat treating may be eliminated. Some amines are rich in hydrogen sulfide and can cause various types of hydrogen-related cracking.

### Ammonia

Copper and copper alloys are subject to stress cracking in the presence of anhydrous liquid ammonia if there is less than 0.1 weight percent of water present.

See Refs. 10 and 34–37.

## CREVICE CORROSION

Crevice corrosion is a localized type of corrosion occurring within or adjacent to narrow gaps or openings formed by metal-to-metal or metal-to-nonmetal contact. It results from local differences in oxygen concentrations, associated deposits on the metal surface, gaskets, lap joints, or crevices under bolts or around rivet heads, where small amounts of liquid can collect and become stagnant.

The material responsible for the formation of the crevice need not be metallic. Wood, plastics, rubber, glass, concrete, asbestos, wax, and living organisms have been reported to cause crevice corrosion. Once the attack begins within the crevice, its progress is very rapid. It is frequently more intense in chloride environments.

Prevention can be accomplished by proper design and operating procedures. Nonabsorbant gasketing material should be used at flanged joints. Fully penetrated butt-welded joints are preferable to lap joints. If lap joints are used, the laps should be filled with fillet welding or a suitable caulking compound designed to prevent crevice corrosion.

See Refs. 10 and 38.

## CRITICAL CREVICE CORROSION TEMPERATURE

The critical crevice corrosion temperature of an alloy is that temperature at which crevice corrosion is first observed when immersed in a ferric chloride solution. Listed below are the critical crevice corrosion temperatures of several alloys in 10% ferric chloride solution.

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| Alloy | Temperature (°F/°C) |
|---|---|
| Type 316 | 27/–3 |
| Alloy 825 | 27/–3 |
| Type 317 | 36/2 |
| Alloy 904L | 59/15 |
| Alloy 220S | 68/20 |
| E-Brite | 70/21 |
| Alloy G | 86/30 |
| Alloy 625 | 100/38 |
| AL-6XN | 100/38 |
| Alloy 276 | 130/55 |

## CRITICAL PITTING TEMPERATURE

The critical pitting temperature of an alloy is the temperature of a solution at which pitting is first observed. These temperatures are usually determined in ferric chloride (10% $FeCl_3$–$6H_2O$) and in an acidic mixture of chlorides and sulfates.

## CYCOLOY

Cycology is G. E. Plastics' trademark for their polycarhonate/acrylonitrile-butadiene-styrene thermoplastic alloy. It is available in several blends. The alloy can be formulated to maintain its impact and ductility below –40°F (–40°C). See Table C.29 for the range of physical and mechanical properties based on the specific formulation.

**Table C.29** Range of Physical and Mechanical Properties of Cycoloy Based on the Specific Formulation

| Property | Value | Units |
|---|---|---|
| Specific gravity | 1.12–1.8 | |
| Water absorption, 24 h at 73°F (23°C) | 0.07–0.20 | % |
| Tensile strength, type 1 | | |
| 0.125 in. (3.2 mm) yield | 6.5–9.1 | psi $\times 10^3$ |
| break | 7.25 | psi $\times 10^3$ |
| Tensile elongation, type 1 | | |
| 0.125 in. (3.2 mm) yield | 4.0–5.0 | % |
| break | | % |
| Tensile modulus, type 1 | | |
| 0.125 in. (3.2 mm) | 2.8–3.9 | psi $\times 10^5$ |
| Flexural strength | | |
| 0.125 in. (3.2 mm) yield | 11.2–14.8 | psi |
| break | 12–13.2 | psi |
| Flexural modulus | | |
| 0. 125 in. (3.2 mm) | 3.0–4.0 | psi |
| 0.250 in. (6.4 mm) | 3.85 | psi |
| Hardness. Rockwell R | 115 | |

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# D

## DEALLOYING

See "Dezincification."

## DECARBURIZATION

See "Hydrogen Damage."

## DEPOSIT ATTACK

See "Poultice Corrosion."

## DEPOSIT CORROSION

See "Poultice Corrosion."

## DEW POINT CORROSION

Dew point corrosion is a form of attack that occurs when the temperature of the metal surface is below the dew point of the atmosphere. This can occur outdoors during the night when the surface temperature may decrease by radiant heat transfer between the metal structure and the sky. It is also possible to have dew formation in the early morning when the temperature of the air increases faster than the temperature of the metal surface. Dew may also form when metal products are brought into warm storage after cold transport.

Dew point corrosion can also take place in the low-temperature sections of fossil fuel power plant combustion equipment as a result of acidic flue gas vapors that condense and cause corrosion damage.

## DEZINCIFICATION (DEALLOYING)

When one element of a solid alloy is removed by corrosion, the process is known as selective leaching, dealloying, or dezincification. The most common example is the removal of zinc from brass alloys that contain more than 15% zinc. When the zinc corrodes preferentially, a porous residue of copper and corrosion products remains. The corroded part often retains its original shape and may appear undamaged except for surface tarnish. However, its tensile strength and particularly its ductility are seriously reduced.



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Dezincification of brasses takes place in either localized areas on the metal surface, called plug type, or uniformly over the surface, called layer type. Low-zinc alloys favor plug-type attack while layer-type attack is more prevalent in high-zinc alloys. The nature of the environment seems to have a great effect in determining the type of attack. Uniform attack takes place in slightly acidic water, low in salt content and at room temperature. Plug-type attack is favored in neutral and alkaline water, high in salt content and above room temperature. Crevice conditions under a deposit or scale tend to aggravate the situation.

A plug of dezincified brass may flow out, leaving a hole, while a water pipe having layer-type dezincification may split open.

Conditions that favor selective leaching are

1. High temperatures
2. Stagnant solutions, especially if acidic
3. Porous inorganic scale formation

Brasses that contain 15% or less zinc are usually immune. Dezincification can be suppressed by alloying additions of tin, aluminum, arsenic, or phosphorus.

Corrective measures that may be taken include

1. Use a more resistant alloy. This is the most practical approach. Red brass, with less than 15% zinc, is almost immune. Cupronickels provide a better substitute in severely corrosive atmospheres.
2. Periodic removal of scales and deposits from the inside surface of pipelines.
3. Removal of stagnation of corrosives, particularly acidic.
4. Use of cathodic protection.

Other alloy systems are also susceptible to this form of corrosion. Refer to Table D.1. Selective leaching of aluminum takes place in aluminum bronze exposed to hydrofluoric acid or acid-containing chlorides. Copper-aluminum alloys containing more than 8% aluminum are particularly susceptible. Selective leaching of tin in tin bronzes in hot brine or steam and of silicon from silicon bronzes in high-temperature steam are other examples.

Selective leaching of iron from gray iron is termed graphitic corrosion. Iron will leach out selectively from gray iron pipe buried in soil. Graphite corrosion does not occur in ductile iron or malleable iron.

See Refs. 1–3.

## DIFFERENTIAL AERATION CELL

See "Oxygen Concentration Cell."

## DISSIMILAR METAL CORROSION

See "Galvanic Corrosion."

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**Table D.1** Combinations of Alloys and Environments for Selective Leaching

| Alloy | Environment | Element removed |
|---|---|---|
| Aluminum | Hydrofluoric acid, acid chloride solutions | Aluminum |
| Bronzes, brasses | Many waters | Zinc |
| Cupronickels | High heat flux and low water velocity (in refinery condenser tubes) | Nickel |
| Gray iron | Soils, many waters | Iron |
| Gold alloys | Nitric, chromic, and sulfuric acids, human saliva | Copper or silver |
| High-nickel alloys | Molten salts | Chromium, iron, molybdenum, tungsten |
| Iron-chromium alloys | High-temperature oxidizing atmospheres | Chromium |
| Medium and high-carbon steels | Oxidizing atmospheres, hydrogen at high temperatures | Carbon |
| Monel | Hydrogen and other acids | Copper in some acids, nickel in others |
| Nickel-molybdenum alloys | Oxygen at high temperatures | Molybdenum |
| Silicon bronzes | High-temperature steam, acidic solution | Silicon |
| Tin bronzes | Hot brine, steam | Tin |

## DUCTILE (NODULAR) IRON

Ductile iron not only retains all of the attractive qualities of gray iron, such as machinability and corrosion resistance, but also provides additional strength, toughness, and ductility. Ductile iron differs from gray iron in that its graphite form is spheroidal, or nodular, instead of the flake form found in gray iron. Due to its nodular graphite form, ductile iron has approximately twice the strength of gray iron as determined by tensile, beam, ring bending, and bursting tests. Its tensile and impact strength and elongation are many times greater compared with gray iron.

The corrosion resistance of ductile iron is essentially the same as that of gray iron. It exhibits good resistance to alkaline solutions, such as sodium hydroxide and molten caustic soda. It is also resistant to alkaline salt solutions, such as cyanides, carbonates, sulfides, and silicates. Acids and oxidizing salts rapidly attack ductile iron.

See Refs. 4 and 5.

## DUPLEX STAINLESS STEELS

The duplex stainless steels are those alloys whose microstructures are a mixture of austenite and ferrite. These alloys were developed to improve the corrosion resistance of the austenitic stainlesses, particularly in the areas of chloride stress corrosion cracking and maintenance of corrosion resistance after welding. The original duplex stainlesses developed did not meet all of the criteria desired. Consequently, additional research was undertaken.

Duplex stainless steels have been available since the 1930s. The first-generation duplex stainless steels, such as type 329 (S32900), have a good general corrosion resistance because of their high chromium and molybdenum contents. When welded, however, these

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grades lose the optimal balance of austenite and ferrite, and consequently corrosion resistance and toughness are reduced. While these properties can be restored by a postweld heat treatment, most of the applications of the first-generation duplexes use fully annealed material without further welding. Since these materials do not meet all of the criteria of duplex stainless steels, they have been included with the austenitic stainless steels.

In the l970s, this problem was made manageable through the use of nitrogen as an alloy addition. The introduction of argon-oxygen decarburization (AOD) technology permitted the precise and economical control of nitrogen in stainless steel. Although nitrogen was first used because it was an inexpensive austenite former, replacing some nickel, it was quickly found that it had other benefits. These include improved tensile properties and pitting and crevice corrosion resistance.

The original duplex stainless steels did not have nitrogen added specifically as an alloying ingredient. By adding 0.15–0.25% nitrogen, the chromium partitioning between the two phases is reduced, resulting in the pitting and crevice corrosion resistance of the austenite being improved. This nitrogen addition also improves the weldability of the stainless steel without losing any of its corrosion resistance.

Nitrogen also causes austenite to form from ferrite at a higher temperature, allowing for restoration of an acceptable balance of austenite and ferrite after a rapid thermal cycle in the heat-affected zone (HAZ) after welding. This nitrogen enables the use of duplex grades in the as-welded condition and has created the second generation of duplex stainless steels.

The duplex grades characteristically contain molybdenum and have a structure of approximately 50% ferrite and 50% austenite because of the excess of ferrite-forming elements such as chromium and molybdenum. The duplex structure, combined with molybdenum, gives them improved resistance to chloride-induced corrosion (pitting, crevice corrosion, and stress corrosion cracking), in aqueous environments particularly.

However, the presence of ferrite is not an unmixed blessing. Ferrite may be attacked selectively in reducing acids, sometimes aggravated by a galvanic influence of the austenite phase, while the sigma phase produced by thermal transformation (as by heat of welding) is susceptible to attack by strong oxidizing acids. The duplex structure is subject to 885°F (475°C) embrittlement and has poor NDIT properties. Except for temper embrittlement these problems can be minimized through corrosion testing and impact testing.

The high chromium and molybdenum contents of the duplex stainless steels are particularly important in providing resistance in oxidizing environments and are also responsible for the exceptionally good pitting and crevice corrosion resistance, especially in chloride environments. In general, these stainless steels have greater pitting resistance than type 316, and several have an even greater resistance than alloy 904L. The critical crevice corrosion temperature of selected duplex stainless steels in 10% $FeCl_3$ $6H_2O$ having a pH of 1 are shown below.

| UNS number | Temperature (°F/°C) |
|---|---|
| S32900 | 41/5 |
| S31200 | 41/5 |
| S31260 | 50/10 |
| S32950 | 60/15 |
| S31803 | 63.5/17.5 |
| S32250 | 72.5/22.5 |

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The resistance to crevice corrosion of the duplexes is superior to the resistance of the 300 series austenitics. They also provide an appreciably greater resistance to stress corrosion cracking. Like 20Cb3, the duplexes are resistant to chloride stress corrosion cracking in chloride-containing process streams and cooling water. However, under very severe conditions, such as boiling magnesium chloride, the duplexes will crack, as will alloy 20Cb3.

To achieve the desired microstructure, the nickel content of the duplexes is below that of the austenitics. Because the nickel content is a factor for providing corrosion resistance in reducing environments, the duplexes show less resistance in these environments than do the austenitics. However, the high chromium and molybdenum contents partially offset this loss, and consequently they can be used in some reducing environments, particularly dilute and cooler solutions. Although their corrosion resistance is good, the boundary between acceptable and poor performance is sharper than with austenitic materials. As a result, they should not be used under conditions that operate close to the limits of their acceptability.

## Alloy 2205 (31803)

Alloy 2205 exhibits an excellent combination of both strength and corrosion resistance. The chemical composition is shown in Table D.2.

The approximate 50/50 ferrite-austenite structure provides excellent chloride pitting and stress corrosion cracking resistance. The high chromium and molybdenum contents coupled with the nitrogen addition, provide general corrosion pitting and crevice corrosion resistance superior to those of types 316L and 317L.

Compared with type 316 stainless steel, alloy 2205 demonstrates superior erosion-corrosion resistance. It is not subject to intergranular corrosion in the welded condition.

Alloy 2205 resists oxidizing mineral acids and most organic acids in addition to reducing acids, chloride environments, and hydrogen sulfide.

The following corrosion rates have been reported for alloy 2205:

| Solution | Corrosion rate (mpy) |
|---|---|
| 1% hydrochloric acid, boiling | 0.1 |
| 10% sulfuric acid, 150°F/66°C | 1.2 |
| 10% sulfuric acid, boiling | 206 |
| 30% phosphoric acid, boiling | 1.6 |
| 85% phosphoric acid, 150°F/66°C | 0.4 |
| 65% nitric acid, boiling | 2.1 |
| 10% acetic acid, boiling | 0.1 |
| 20% acetic acid, boiling | 0.1 |
| 20% formic acid, boiling | 1.3 |
| 45% formic acid, boiling | 4.9 |
| 3% sodium chloride, boiling | 0.1 |

Alloy 2205 will be attacked by hydrochloric and hydrofluoric acids. Applications are found primarily in oil and gas field piping applications, condensers, reboilers, and heat exchangers. Its mechanical and physical properties are shown in Table D.3.

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**Table D.2** Chemical Composition of Alloy 2205 Stainless Steel

| Chemical | Weight percent |
|---|---|
| Carbon | 0.03 max. |
| Manganese | 2.00 max. |
| Phosphorus | 0.03 max. |
| Sulfur | 0.02 max. |
| Silicon | 1.00 max. |
| Chromium | 21.00–23.00 |
| Nickel | 4.50–6.50 |
| Molybdenum | 2.50–3.50 |
| Nitrogen | 0.14–0.20 |
| Iron | Balance |

**Table D.3** Mechanical and Physical Properties of Alloy 2205 Duplex Stainless Steel

| | |
|---|---|
| Modulus of elasticity $\times 10^6$, psi | 29.0 |
| Tensile strength $\times 10^3$, psi | 90 |
| Yield strength 0.2% offset $\times 10^3$, psi | 65 |
| Elongation in 2 in., % | 25 |
| Hardness, Rockwell | C30.5 |
| Density, lb/in.$^3$ | 0.283 |
| Specific gravity | 7.83 |
| Thermal conductivity at 70°F (20°C), Btu/h °F | 10 |
| Thermal expansion coefficient at 68–212°F in./in. °F $\times 10^{-6}$ | 7.5 |

## 7-Mo Plus (S32950)

7-Mo Plus stainless steel is a trademark of Carpenter Technology. It is a duplex alloy with approximately 45% austenite distributed within a ferrite matrix. Alloy S32950 displays good resistance to chloride stress corrosion cracking, pitting corrosion, and general corrosion in many severe environments. The chemical composition is shown in Table D.4.

**Table D.4** Chemical Composition of Type 7-Mo Plus Stainless Steel

| Chemical | Weight percent |
|---|---|
| Carbon | 0.03 max. |
| Manganese | 2.00 max. |
| Phosphorus | 0.035 max. |
| Sulfur | 0.010 max. |
| Silicon | 0.60 max. |
| Chromium | 26.00–29.00 |
| Nickel | 3.50–5.20 |
| Molybdenum | 1.00–2.50 |
| Nitrogen | 0.15–0.35 |
| Iron | Balance |

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This alloy is subject to 885°F (475°C) embrittlement when exposed for extended period of times between 700°F and 1000°F (371–538°C).

The general corrosion resistance of 7-Mo Plus stainless is superior to that of stainless steels such as type 304 and type 316 in many environments. Because of its high chromium content, it has good corrosion resistance in strong oxidizing media such as nitric acid. Molybdenum extends the corrosion resistance into the less oxidizing environments. Chromium and molybdenum impart a high level of resistance to pitting and crevice corrosion. It has a PREN of 40.

Alloy S32950 exhibits excellent resistance to nitric acid, phosphoric acid, organic acids, alkalies, seawater, and chloride stress corrosion cracking. It is not suitable for service in hydrochloric or hydrofluoric acids or some salts. Refer to Table D.5 for the mechanical and physical properties of 7-Mo Plus stainless steel.

## Zeron 100 (S32760)

Zeron 100 is a trademark of Weir Materials Limited of Manchester, England. Table D.6 details the chemical composition of Zeron 100, which is tightly controlled by Weir Materials, while the chemical composition of S32760 is a broad compositional range.

Zeron 100 is a highly alloyed duplex stainless steel for use in aggressive environments. In general, its properties include high resistance to pitting and crevice corrosion, resistance to stress corrosion cracking in both chloride and sour environments, resistance to erosion-corrosion and corrosion fatigue.

Zeron 100 is highly resistant to corrosion in a wide range of organic and inorganic acids. Its excellent resistance to many nonoxidizing acids is the result of the copper content.

**Table D.5** Mechanical and Physical Properties of Type 7-Mo Plus[a] Stainless Steel

| | |
|---|---|
| Modulus of elasticity $\times 10^6$, psi | 29.0 |
| Tensile strength $\times 10^3$ psi | 90 |
| Yield strength 0.2% offset $\times 10^3$, psi | 70 |
| Elongation in 2 in., % | 20 |
| Hardness. Rockwell | C30.5 |
| Density, lb/in.$^3$ | 0.280 |
| Specific gravity | 7.74 |
| Specific heat (75–212°F), Btu/lb °F | 0.114 |
| Thermal conductivity, Btu/h °F | |
| at 70°F (20°C) | 8.8 |
| at 1500°F (815°C) | 12.5 |
| Thermal expansion coefficient in./in. °F $\times 10^{-6}$ | |
| at 75–400°F | 6.39 |
| at 75–600°F | 6.94 |
| at 75–800°F | 7.49 |
| at 75–1000°F | 7.38 |
| Charpy V-notch impact at 75°F (20/°C), ft-lb | 101 |

[a]Registered trademark of Carpenter Technology Corp.

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**Table D.6** Chemical Composition of Zeron 100 (S32760) Stainless Steel

| Chemical | Weight percent |
|---|---|
| Carbon | 0.03 max. |
| Manganese | 1.00 max. |
| Phosphorus | 0.03 max. |
| Sulfur | 0.01 max. |
| Silicon | 1.00 max. |
| Chromium | 24.0–26.0 |
| Nickel | 6.0–8.0 |
| Molybdenum | 3.0–4.0 |
| Copper | 0.5–1.0 |
| Nitrogen | 0.2–0.3 |
| Tungsten | 0.5–1.0 |
| Iron | Balance |

A high resistance to pitting and crevice corrosion is also exhibited by Zeron 100. It has a PREN of 48.2. Intergranular corrosion is not a problem since the alloy is produced to a low carbon specification and water quenched from solution annealing, which prevents the formation of any harmful precipitates and eliminates the risk of intergranular corrosion.

Resistance is also exhibited to stress corrosion cracking in chloride environments and process environments containing hydrogen sulfide and carbon dioxide.

## Ferralium 255 (S32550)

The chemical composition of Ferralium 255 is shown in Table D.7. This is a duplex alloy with austenitic distributed within a ferrite matrix. Ferralium 255 exhibits good general corrosion resistance to a variety of media, with a high level of resistance to chloride pitting and stress corrosion cracking. The following corrosion rates for Ferralium 255 have been reported:

| Solution | Corrosion rate (mpy) |
|---|---|
| 1% hydrochloric acid, boiling | 0.1 |
| 10% sulfuric acid, 150°F (66°C) | 0.2 |
| 10% sulfuric acid, boiling | 40 |
| 30% phosphoric acid, boiling | 0.2 |
| 85% phosphoric acid, 150°F (66°C) | 0.1 |
| 65% nitric acid, boiling | 5 |
| 10% acetic acid, boiling | 0.2 |
| 20% formic acid, boiling | 0.4 |
| 3% sodium chloride, boiling | 0.4 |

This alloy has a maximum service temperature of 500°F (260°C).
See Refs. 7–10.

This alloy has a maximum service temperature of 500°F (260°C).

See Refs. 6–9.

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**Table D.7** Chemical Composition of Ferralium 255 (S32550) Stainless Steel

| Chemical | Weight percent |
|---|---|
| Carbon | 0.04 |
| Manganese | 1.50 |
| Phosphorus | 0.04 |
| Sulfur | 0.03 |
| Silicon | 1.00 |
| Chromium | 24.0–27.0 |
| Nickel | 4.5–6.5 |
| Molybdenum | 2.9–3.9 |
| Copper | 1.5–2.5 |
| Nitrogen | 0.1–0.25 |
| Iron | Balance |

## DURALUMIN

Duralumin is a heat-treatable aluminum-copper alloy developed in Germany in 1919. It is produced in the United States as alloy 2017, containing approximately 4% copper and usually lesser amounts of magnesium, manganese, and on occasion silicon. Recently lithium has also been added.

See Ref. 10.

## DURIRON

See "High-Silicon Iron."

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# E

## E-GLASS

This is a boroaluminosilicate glass used for reinforcing thermosetting resins. See "Thermoset Reinforcing Materials."

## ELASTOMER CROSS REFERENCE

| Generic name | Designation | Manufacturers'[a] common or trade names |
|---|---|---|
| Natural rubber | NR | 26–31 |
| Isoprene | IR | |
| Polychloroprene | CR | 26–31, neoprene (1), Bayprene (2) |
| Butadiene-styrene | SBR | 26–30, Buna-S, GR-S |
| Butadiene-acrylonitrile | NBR | 16, 26–31, nitrile rubber, Buna-N, Perbunan (2), Nytek (21) |
| Butyl rubber | IIR | Gr-l, 26–30, Kalar (19) |
| Chlorobutyl rubber | CiiR | 26–30 |
| Carboxylic-acrylonitrile-butadiene | NBR | 16, 26–31 |
| Chlorosulfonated polyethylene | CSM | 26–28, 30, 31, Hypalon (1) |
| Polybutadiene | BR | 26–28, 30, 31, Buna-85, Buna-DB (2) |
| Ethylene-acrylic | EA | 13, 28 Vamac (1) |
| Acrylate-butadiene | ABR | 13, 28 |
| Acrylic ester–acrylic halide | ACM | 13, 28 |
| Ethylene-propylene | EPDM | 26–31 |
| | EPT | Nordel (1), Royalene EPDM (8), Dutral (9) |
| Styrene-butadiene styrene | SBS | Kraton G (3) |
| Styrene-ethylene-butylene-styrene | SEBS | Kraton G (3) |
| Polysulfide | ST | 27, 28, 30, Thiokol (4) |
| | FA | BIak-Stretchy (14), Blak-Tufy (14), Gra-Tufy (14) |
| Urethane | AU | 16, 27, 30, 38, 31, Adiprene (I), Baytec (2), Futrathane (11), Conathane (16), Texion (2), Urane (23), Pellethane (22), pure CMC (14) |
| Polyamides | Nylon | Nylon (1), Rilsan (12), Vydyne (18), Plaskin (25) |
| Polyester | PE | Hytrel (1), Kodar (20) |



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| Generic name | Designation | Manufacturers'[a] common or trade names |
|---|---|---|
| Thermoplastic elastomers | TPE | Duracryn (1), Flexsorb (17), Geolast (18), Kodapak (20), Santoprene (18). Zurcon (24) |
| Silicone | SI | 27–29, 32, Cohrplastic (15), Green Sil (14). Parshield (13), Baysilone (2), Blue-Sil (14) |
| Fluorosilicone | FSI | Parshield (13) |
| Vinylidene fluoride | HFP | Kynar (7). Foraflon (5) |
| Fluoroelastomers | FKM | 24, 26, 28–31, Viton (1), Fluorel (6), Technoflon (9) |
| Ethylene-tetrafluoroethylene | ETFE | Tefzel (1), Halon ET (9) |
| Ethylene-chlorotrifluoroethylene | ECTFE | Halar (9) |
| Perfluoroelastomers | FPM | Kalrez (1). Chemraz (10). Kel-F (6) |

[a]List of manufacturers:
1. E. I. du Pont; 2. Mobay Corp.; 3. Shell Chemical Co.; 4. Morton Thiokol Inc.; 5. Atochem Inc.; 6. 3-M Corp; 7. Pennwalt Corporation; 8. Uniroyal; 9. Ausimont; 10. Greene, Tweed & Co., Inc.; 11. Futura Coatings Inc.; 12. Attochem Inc.; 13. Parker Seal Group; 14. The Perma-Flex Mold Co.; 15. CHR Industries; 16. Conap Inc.; 17. Polymer Corp.; 18. Monsanto Co.; 19. Hardman Inc.; 20. Eastman Chemical Products Inc.; 21. Edmont Div. of Becton, Dickinsen & Co.; 22. Dow Chemical USA; 23. Krebs Engineers; 24. W. S. Shamban & Co.; 25. Allied Signal; 26. General Rubber Co.; 27. Hecht Rubber Co.; 28. Minor Rubber Co.; 29. Newco Holz Rubber Co.; 30. Alvan Rubber Co.; 31. Burke Rubber Co.; 32. Unaflex.

## ELASTOMERS

Also see "Permeation," "Adsorption," and "Polymers." An elastomer is generally considered to be any material, either natural or synthetic, that is elastic or resilient and in general resembles natural rubber in feeling and appearance. A more detailed technical definition is provided by ASTM, which states

> An elastomer is a polymeric material which at room temperature can be stretched to at least twice its original length and upon immediate release of the stress will return quickly to its original length.

These materials are sometimes referred to as rubbers.

Natural rubber is a polymerized hydrocarbon whose commercial synthesis proved to he difficult. Synthetic rubbers now produced are similar but not identical to natural rubber. Natural rubber has the hydrocarbon butadiene as the simplest unit. Butadiene, $CH_2 = CH - CH = CH_2$, has two unsaturated linkages and is easily polymerized. It is produced commercially by cracking petroleum and also from ethyl alcohol. Natural rubber is a polymer of methyl butadiene (isoprene):

$$CH_2 = \underset{\displaystyle |}{\overset{\displaystyle CH_3}{C}} - C = CH_2$$

When butadiene or its derivatives become polymerized, the units link together to form long chains that each contain over 1000 units. In early attempts to develop a synthetic rubber it was found that simple butadiene does not yield a good grade of rubber, apparently because the chains are too smooth and do not interlock sufficiently strongly. Better results are obtained by introducing side groups into the chain

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either by modifying butadiene or by making a copolymer of butadiene and some other compound.

As development work continued in the production of synthetic rubbers, other compounds were used as the parent material in place of butadiene. Two of them were isobutylene and ethylene.

Elastomers are primarily composed of large molecules that tend to form spiral threads, similar to coiled springs, that are attached to each other at frequent intervals. These coils tend to stretch or compress when a small stress is applied but exert an increasing resistance to the application of additional stress. This phemonemon is illustrated by the reaction of rubber to the application of additional stress.

In the raw state elastomers tend to be soft and sticky when hot, and hard and brittle when cold. Compounding increases the utility of rubber and synthetic elastomers. Vulcanization extends the temperature range within which they are flexible and elastic. In addition to vulcanizing agents, ingredients are added to make elastomers stronger, tougher, or harder, to make them age better, to color them, and in general to improve specific properties to meet specific application needs. The following examples illustrate some of the important properties that are required of elastomers and the typical services that require these properties:

Resistance to abrasive wear: automobile tire treads, conveyor belt covers, soles and heels, cables, hose covers

Resistance to tearing: tire treads, footwear, hot water bags, hose covers, belt covers, O-rings

Resistance to flexing: auto tires, transmission belts, V-belts, mountings, footwear

Resistance to high temperature: auto tires, belts conveying hot materials, steam hose, steam packing, O-rings

Resistance to cold: airplane parts, automotive parts, auto tires, refrigeration hose, O-rings.

Minimum heat buildup: auto tires, transmission belts, V-belts, mountings

High resilience: sponge rubber, mountings, elastic bands, thread, sandblast hose, jar rings, O-rings

High rigidity: packing, soles and heels, valve cups, suction hose, battery boxes

Long life: fire hose, transmission belts, tubing

Electrical resistivity: electrician's tape. switchboard mats, electrician's gloves, wire insulation

Electrical conductivity: hospital flooring, nonstatic hose, matting

Impermeability to gases: balloons, life rafts, gasoline hose, special diaphragms

Resistance to ozone: ignition distributor gaskets, ignition cables, windshield wipers

Resistance to sunlight: wearing apparel, hose covers, bathing caps, windshield wipers

Resistance to chemicals: tank linings, hose for chemicals

Resistance to oils: oil-suction hose, paint hose, creamery hose, packing house hose, special belts, tank linings, special footwear

Stickiness: cements, electrician's tape, adhesive tapes, pressure sensitive tapes

Low specific gravity: airplane parts, forestry hose, balloons

Lack of odor or taste: milk tubing, brewery and winery hose, nipples, jar rings

Acceptance of color pigments: ponchos, life rafts, welding hose

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Table E.1 provides a comparison of the important properties of the most common elastomers. Specific values of each property will be found in the section dealing with each elastomer. Tensile strength and elongation as applied to elastomers are defined by the American Society for Testing and Materials as follows:

**Table E.1** Comparative Properties of Elastomers[a]

| Property | Natural rubber (NR) | Isoprene (IR) | Neoprene (CR) | Butadiene-styrene (Bune S) | Nitrile-NBR (Buna N) | Butyl (IIR) | Chlorobutyl (CIIR) | Hypalon (CSM) | Polybutadiene (BR) | Ethylene-acrylic (EA) | Acrylate-butadiene (ABR) | Acrylic ester–acrylic halide (ACM) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abrasion resistance | E | E | G | G | G | G | G | G | E | E | G | FG |
| Acid resistance | P | P | GE | P | F | G | P | E | G | PG | G | P |
| Chemical resistance | | | | | | | | | | | | |
| Aliphatic hydrocarbons | P | P | G | P | E | P | E | G | P | G | E | E |
| Aromatic hydrocarbons | P | P | F | P | G | P | P | F | P | F | P | P |
| Oxygenated (ketones, etc.) | G | G | P | G | P | G | P | P | G | P | P | P |
| Oil and gasoline | P | P | FG | P | E | P | E | G | P | G | E | E |
| Animal and vegetable oils | PG | PG | G | PG | E | E | G | G | PG | G | G | G |
| Resistance to | | | | | | | | | | | | |
| Water absorption | E | E | G | GE | FG | G | G | GE | G | G | G | G |
| Ozone | P | P | GE | P | P | E | E | E | P | E | E | E |
| Sunlight aging | P | P | E | P | P | G | G | E | P | E | E | G |
| Heat aging | P | G | G | F | G | G | G | E | G | G | E | G |
| Flame | P | P | G | P | P | P | P | G | P | P | P | P |
| Electrical properties | G | G | F | E | F | E | PF | G | E | FG | G | PF |
| Impermiability | G | G | G | GE | G | E | G | E | G | G | G | G |
| Compression set resistance | E | E | F | G | GE | P | F | G | G | G | G | FG |
| Tear resistance | GE | GE | FG | P | FG | GE | G | G | G | G | G | G |
| Tensile strength | E | E | G | G | GE | G | G | GE | G | G | G | G |
| Water/steam resistance | E | E | F | E | FG | E | PF | G | E | G | G | PF |
| Weather resistance | P | P | E | P | F | E | F | E | G | G | E | F |
| Adhesion to metals | E | E | E | E | E | G | G | E | E | G | G | G |
| Adhesion to fabrics | E | E | E | E | G | G | G | E | E | G | G | G |
| Rebound | | | | | | | | | | | | |
| Cold | E | E | E | G | G | P | F | G | E | P | G | F |
| Hot | E | E | E | G | G | G | F | G | E | F | G | F |

[a]E = excellent; G = good; F = fair; P = poor; PF = poor to fair; PG = poor to good; GE = good to excellent.

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Tensile strength is the force per unit of the original cross-sectional area which is applied at the time of the rupture of the specimen.

Elongation or strain is the extension between benchmarks produced by a tensile force applied to a specimen and is expressed as a percentage of the original distance between the marks. Ultimate elongation is the elongation at the time of rupture.

| Ethylene-propylene (EPDM) | Styrene-butadiene-styrene (SBS) | Styrene-ethylene-butylene-styrene (SEBS) | Polysulfide (ST) | Polysulfide (FA) | Urethane (AU) | Polyamides | Polyester (PE) | Thermoplastic (TPE) | Silicone (SI) | Fluorosilicone (FSI) | Vinylidene fluoride (HFP) | Fluoroelastomers (FKM) | Ethylene-tetrafluoroethylene (ETFE) | Ethylene-chlorotrifluoroethylene (ECTFE) | Perfluoroelastomers (FPM) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GE | G | GE | PF | PF | E | E | E | G | P | P | G | G | G | E | G |
| G | E | E | F | G | P | FG | F | G | FG | FG | E | E | E | E | E |
| P | P | P | E | E | E | G | E | P | G | E | G | E | E | E | E |
| P | P | P | E | E | P | G | G | P | P | FG | G | E | E | G | E |
| GE | P | P | G | G | P | G | F | P | P | PF | G | P | E | G | FG |
| P | F | FG | E | E | E | G | G | FG | P | G | E | E | E | E | E |
| G | P | G | | | E | FG | G | G | G | G | G | E | E | E | E |
| GE | E | E | G | | G | G | G | E | G | G | G | GE | G | E | G |
| E | P | E | E | E | E | E | E | E | E | E | E | E | E | E | E |
| E | P | G | E | E | P | P | G | G | E | E | E | GE | E | E | E |
| E | G | E | P | G | F | G | E | G | E | E | E | E | E | E | E |
| P | P | PG | P | P | P | F | G | P | F | G | E | G | G | | E |
| G | F | E | G | G | FG | G | FG | F | E | E | F | G | G | E | G |
| G | G | G | E | E | G | FG | G | P | P | G | G | E | G | G | E |
| GE | G | G | P | P | F | G | F | G | GE | GE | GE | GE | | | G |
| GE | G | G | P | P | GE | G | E | G | P | P | F | F | G | | P |
| GE | G | G | F | G | E | G | E | G | P | F | GE | GE | G | G | G |
| E | FG | FG | E | G | P | G | FG | G | F | F | FG | G | G | | G |
| E | F | G | E | E | G | E | G | E | E | E | E | E | E | E | E |
| GE | G | G | E | E | G | E | G | G | G | GE | G | GE | P | | |
| G | G | G | G | G | G | E | G | G | E | E | | GE | F | | |
| G | G | G | P | P | E | G | G | G | G | G | | G | | | |
| G | G | G | P | P | E | G | E | G | G | G | | E | | | |

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The procedure for conducting tensile tests is standardized and described in ASTM D412. Dumbbell-shaped specimens 4 or 5 inches long are die-cut from flat sheets and marked in the narrow section with benchmarks 1 or 2 in. apart. The ends of a specimen are placed in the grips of a vertical testing machine. The lower grip is power driven at 20 in./min and stretches the specimen until it breaks. As the distance between benchmarks widens, measurements arc taken between their centers to determine elongation.

Tension tests are frequently conducted before and after an exposure test to determine the relative resistance of a group of compounds to deterioration by such things as oil, sunlight, weathering, ozone, heat, oxygen, and chemicals. Even a small amount of deterioration results in appreciable changes in tension properties.

Hardness, as applied to elastomeric products, is defined as relative resistance of the surface to indentation by a Shore A durometer. In this device the indenter point projects upward from the flat bottom of the case, held in the zero position by a spring. When pressed against a sample, the indenter point is pushed back into the case against the spring: This motion is translated through a rack-and-pinion mechanism into movement of the pointer on the durometer dial. Hardness numbers from a durometer scale for typical products are as follows:

| | |
|---|---|
| Faucet washer, flooring, typewriter platen | $90 \pm 5$ |
| Shoe sole | $80 \pm 5$ |
| Solid tire, heel | $70 \pm 5$ |
| Tire tread, hose cover, conveyor belt cover | $60 \pm 5$ |
| Inner tube, bathing cap | $50 \pm 5$ |
| Rubber band | $40 \pm 5$ |

Erasers and printing rolls usually have hardness values below 30.

Compression set is permanent deformation that remains in the elastomer after a compression force has been removed. The area of the elastomer that has compression set is not only permanently deformed but also less resilient than normal. The possibility of compression set occurring increases with increasing temperature, compression force, and length of time that the force is applied. Each type of elastomer has a different resistance to compression set. As with any material, each elastomer also has a limiting temperature range within which it may be used. Table E.2 shows the allowable operating temperature range of each of the common elastomers.

## Causes of Failure

Elastomeric materials can fail as the result of chemical action and/or mechanical damage. Chemical deterioration occurs as the result of a chemical reaction between the elastomer and the medium or by the absorption of the medium into the elastomer. This attack results in the swelling of the elastomer and a reduction in its tensile strength.

The degree of deterioration is a function of the temperature and concentration of the corrodent. In general, the higher the temperature and the higher the concentration of the corrodent, the greater will be the chemical attack. Elastomers, unlike metals, absorb varying quantities of the material they are in contact with, especially organic liquids. This can result in swelling, cracking, and penetration to the substrate in an elastomer-lined vessel. Swelling can cause softening of the elastomer and in a lined vessel introduce high stresses and failure of the bond. If an elastomeric lining has high absorption, permeation

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**Table E.2** Operating Temperature Range of Common Elastomers

| | Temperature range | | | |
|---|---|---|---|---|
| | °F | | °C | |
| Elastomer | Min | Max | Min | Max |
| NR, natural rubber | –59 | 175 | –50 | 80 |
| IR, isoprene rubber | –59 | 175 | –50 | 80 |
| CR, neoprene rubber | –13 | 203 | –25 | 95 |
| SBR, Buna-S | –66 | 175 | –56 | 80 |
| NBR, nitrile rubber, Buna-N | –40 | 250 | –40 | 105 |
| IIR, butyl rubber | –30 | 300 | –34 | 149 |
| CIIR, chlorobutyl rubber | –30 | 300 | –34 | 149 |
| CSM, Hypalon | –20 | 250 | –30 | 105 |
| BR, polybutadiene rubber | –150 | 200 | –101 | 93 |
| EA, ethylene-acrylic rubber | –40 | 340 | –40 | 170 |
| ABR, acrylate-butadiene rubber | –40 | 340 | –40 | 170 |
| EPDM, ethylene-propylene | –65 | 300 | –54 | 149 |
| SBS, styrene-butadiene-styrene | | 150 | | 65 |
| SEBS, styrene-ethylene butylene-styrene | –102 | 220 | –75 | 105 |
| ST, polysulfide | –50 | 212 | –45 | 100 |
| FA, polysulfide | –30 | 250 | –35 | 121 |
| AU, polyurethane | –65 | 250 | –54 | 121 |
| Polyamides | –40 | 300 | –40 | 149 |
| PE, polyesters | –40 | 302 | –40 | 150 |
| TPE, thermoplastic elastomers | –40 | 277 | –40 | 136 |
| SI, silicone | –60 | 450 | –51 | 232 |
| FSI. fluorosilicone | –100 | 375 | –73 | 190 |
| HEP, vinylidene fluoride | –40 | 450 | –40 | 232 |
| FKM, fluoroelastomers | –10 | 400 | –18 | 204 |
| ETFE, ethylene tetrafluoroethylene elastomer | –370 | 300 | –223 | 149 |
| ECTFE, ethylene chlorotrifluoroethylene elastomer | –105 | 340 | –76 | 171 |
| FPM, perfluoroelastomers | –58 | 600 | –50 | 316 |

will probably result. Some elastomers, such as the fluorocarbons, are easily permeated but have little absorption. An approximation of the expected permeation and/or absorption of an elastomer can be based on the absorption of water.

Permeation is a factor closely related to absorption but is a function of other physical effects, such as diffusion and temperature. All materials are somewhat permeable to chemical molecules, but the permeability rate of elastomers tends to be an order of magnitude greater than that in metals. This permeation has been a factor in elastomer-lined vessels where corrodents have permeated the rubber and formed bubbles between the rubber lining and the steel substrate. Permeation and absorption can result in

1. Bond failure and blistering. These are caused by an accumulation of fluids at the bond when the substrate is less permeable than the lining or from the formation of corrosion or reaction products if the substrate is attacked by the corrodent.
2. Failure of the substrate due to corrosive attack.

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3. Loss of contents through lining and substrate as the result of eventual failure of the substrate.

Thickness of lining is a factor affecting permeation. For general corrosion resistance, thicknesses of 0.010–0.020 in. are usually satisfactory, depending upon the combination of elastomeric material and specific corrodent When mechanical factors such as thinning due to cold flow, mechanical abuse, and permeation rates are a consideration, thicker linings may be required.

Increasing the lining thickness will normally decrease permeation by the square of the thickness. Although this would appear to be the approach to follow to control permeation, there are disadvantages. First, as the thickness increases, the thermal stresses on the boundary increase, which can result in bond failure. Temperature changes and large differences in coefficients of thermal expansion are the most common causes of bond failure. Thickness and modulus of elasticity of the elastomer are two of the factors that would influence these stresses. Second, as the thickness of the lining increases, installation becomes more difficult, with a resulting increase in labor costs.

The rate of permeation is also affected by temperature and temperature gradient in the lining. Lowering these will reduce the rate of permeation. Lined vessels that are used under ambient conditions, such as storage tanks, provide the best service.

In unbonded linings it is important that the space between the liner and the support member be vented to the atmosphere not only to allow the escape of minute quantities of permeant vapors but also to prevent the expansion of entrapped air from collapsing the liner.

Although elastomers can be damaged by mechanical means alone, this is not usually the case. When in good physical condition, an elastomer will exhibit abrasion resistance superior to that of metal. The actual size, shape, and hardness of the particles and their velocity are the determining factors in how well a particular rubber resists mechanical damage from the medium. Hard, sharp objects, including those foreign to the normal medium, may cut or gouge the elastomer. Most mechanical damage occurs as a result of chemical deterioration of the elastomer. When the elastomer is in a deteriorated condition, the material is weakened, and consequently it is more susceptible to mechanical damage from flowing or agitated media.

Elastomers in outdoor use can be subject to degradation as a result of the action of ozone, oxygen, and sunlight. These three weathering agents can greatly affect the properties and appearance of a large number of elastomeric materials. Surface cracking, discoloration of colored stocks, serious loss of tensile strength and elongation, and other rubberlike properties are the result of this attack.

## Selecting an Elastomer

Many factors must be taken into account when selecting an elastomer for a specific application. First and foremost is the compatibility of the elastomer with the medium at the temperature and concentration to which it will he exposed.

It should also be remembered that each of the materials can be formulated to improve certain of its properties. However, the improvement in one property may have an adverse effect on another property, such as corrosion resistance. Consequently, specifications of an elastomer should include the specific properties required for the application, such as resilience, hysteresis, static or dynamic shear and compression modulus, flex

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fatigue and cracking, creep resistance to oils and chemicals, permeability, and brittle point, all in the temperature range to be encountered in service. This must also be accompanied by a complete listing of the concentrations of all media to be encountered. Providing this information will permit a competent manufacturer to supply an elastomer that will give years of satisfactory service. Because of the ability to change the formulation of many of these elastomers, the wisest policy is to permit a competent manufacturer to make the selection of the elastomer to satisfy the application. In addition to being able to change the formulation of each elastomer, it is also a common practice to blend two or more elastomers to produce a compound having specific properties. By so doing the advantageous properties of each elastomer can be made use of.

Fabrics are very often used as reinforcing members in conjunction with elastomers. Cotton, because of its ease of processing, availability in a wide range of weaves, and high adhesive strength, is the most widely used. It is also priced relatively low in comparison with synthetic fibers. The disadvantages of cotton are its poor heat resistance and the need for bulk in order to obtain the proper strength.

When operating temperatures of reinforced elastomeric products are in the range of 200–250°F (93–120°C), DuPont's Dacron polyester fiber is used to provide good service life. In addition to better heat-resisting qualities than cotton, Dacron has strength comparable to that of cotton with considerably less bulk. On the negative side, Dacron is more difficult to process than cotton, has lower adhesive strength, and is initially more expensive. Table E.3 provides the corrosion resistance of selected elastomers and selected corrodents.

## Applications

Elastomeric or rubber materials find a wide range of applications. One of the major areas of application is that of linings for vessels. Both natural and synthetic materials are used for this purpose. These linings have provided many years of service in the protection of steel vessels from corrosion. They are sheet applied and bonded to a steel substrate.

These materials are also used extensively as membranes in acid brick–lined vessels to protect the steel shell from corrosive attack. The acid brick lining in turn protects the elastomer from abrasion and excessive temperature. Another major use is as an impermeable lining for settling ponds and basins. These materials are employed to prevent pond contaminants from seeping into the soil and causing pollution of groundwater and contamination of the soil.

Natural rubber and most of the synthetic elastomers are unsaturated compounds that oxidize and deteriorate rapidly when exposed to air in thin films. These materials can be saturated by reacting with chlorine under the proper conditions, producing compounds that are clear, odorless, nontoxic, and noninflammable. They may be dissolved and blended with varnishes to impart high resistance to moisture and to the action of alkalies. This makes these products particularly useful in paints for concrete, where the combination of moisture and alkali causes the disintegration of ordinary paints and varnishes. These materials also resist mildew and are used to impart flame resistance and waterproofing properties to canvas. Application of these paints to steel will provide a high degree of protection against corrosion.

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**Table E.3** Corrosion Resistance of Selected Elastomers

| | Butyl | | Hypalon | | EPDM | | EPT | | Viton A | | Kalrez | | Natural rubber | | Neoprene | | Buna N | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chemical | °F | °C | °F | °C | °F | °C | °F | °C | °F | °C | °F | °C | °F | °C | °F | °C | °F | °C |
| Acetaldehyde | 80 | 27 | 60 | 16 | 200 | 93 | 210 | 99 | x | x | x | x | x | x | 200 | 93 | x | x |
| Acetamide | | | x | x | 200 | 93 | 200 | 93 | 210 | 99 | x | x | x | x | 200 | 93 | 180 | 82 |
| Acetic acid 10% | 150 | 66 | 200 | 93 | 140 | 60 | x | x | 190 | 88 | 200 | 93 | 150 | 66 | 160 | 71 | 200 | 93 |
| Acetic acid 50% | 110 | 43 | 200 | 93 | 140 | 60 | x | x | 180 | 82 | 200 | 93 | x | x | 160 | 71 | 200 | 93 |
| Acetic acid 80% | 110 | 43 | 200 | 93 | 140 | 60 | x | x | 180 | 82 | 90 | 32 | x | x | 160 | 71 | 210 | 99 |
| Acetic acid, glacial | 90 | 32 | x | x | 140 | 60 | x | x | x | x | 80 | 27 | x | x | x | x | 100 | 38 |
| Acetic anhydride | 150 | 66 | 200 | 93 | x | x | x | x | x | x | 210 | 99 | x | x | 90 | 32 | 200 | 93 |
| Acetone | 160 | 71 | x | x | 300 | 148 | x | x | x | x | 210 | 99 | x | x | x | x | x | x |
| Acetyl chloride | | | x | x | x | x | x | x | 190 | 88 | 210 | 99 | x | x | x | x | x | x |
| Acrylic acid | | | | | | | | | x | x | 210 | 99 | x | x | x | x | x | x |
| Acrylonitrile | x | x | 140 | 60 | 140 | 60 | 100 | 38 | x | x | 110 | 43 | 90 | 32 | 160 | 71 | x | x |
| Adipic acid | x | x | 140 | 60 | 200 | 93 | 140 | 60 | 180 | 82 | 210 | 99 | 80 | 27 | 160 | 71 | 180 | 82 |
| Allyl alcohol | 190 | 88 | 200 | 93 | 300 | 148 | 80 | 27 | 190 | 88 | | | 80 | 27 | 120 | 49 | 180 | 82 |
| Allyl chloride | x | x | | | x | x | x | x | 100 | 38 | | | x | x | x | x | x | x |
| Alum | 190 | 88 | 200 | 93 | 200 | 93 | 140 | 60 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Aluminum acetate | | | x | x | 200 | 93 | 180 | 82 | 180 | 82 | 210 | 99 | | | x | x | 200 | 93 |
| Aluminum chloride, aqueous | 150 | 66 | 250 | 121 | 210 | 99 | 180 | 82 | 190 | 88 | 210 | 99 | 140 | 60 | 200 | 93 | 200 | 93 |
| Aluminum chloride, dry | | | | | | | | | | | 190 | 88 | | | | | | |
| Aluminum fluoride | 180 | 82 | 200 | 93 | 210 | 99 | 180 | 82 | 180 | 82 | 210 | 99 | 150 | 66 | 200 | 93 | 190 | 88 |
| Aluminum hydroxide | 100 | 38 | 250 | 121 | 210 | 99 | 140 | 60 | 190 | 88 | 210 | 99 | | | 180 | 82 | 180 | 82 |
| Aluminum nitrate | 190 | 88 | 250 | 121 | 210 | 99 | 180 | 82 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Aluminum oxychloride | | | | | | | | | x | x | | | | | | | | |
| Aluminum sulfate | 190 | 88 | 200 | 93 | 210 | 99 | 210 | 99 | 190 | 88 | 210 | 99 | 160 | 71 | 200 | 93 | 210 | 99 |
| Ammonia gas | | | 140 | 60 | 140 | 60 | 140 | 60 | x | x | 210 | 99 | x | x | 140 | 60 | 190 | 88 |
| Ammonium bifluoride | x | x | | | 300 | 148 | 140 | 60 | 140 | 60 | 210 | 99 | x | x | x | x | 180 | 82 |
| Ammonium carbonate | 190 | 88 | 140 | 60 | 300 | 148 | 180 | 82 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Ammonium chloride 10% | 190 | 88 | 200 | 93 | 210 | 99 | 180 | 82 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Ammonium chloride 50% | 190 | 88 | 200 | 93 | 210 | 99 | 180 | 82 | 190 | 88 | 210 | 99 | 150 | 66 | 190 | 88 | 200 | 93 |
| Ammonium chloride, sat. | 190 | 88 | 200 | 93 | 300 | 148 | 180 | 82 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Ammonium fluoride 10% | 150 | 66 | 200 | 93 | 210 | 99 | 210 | 99 | 140 | 60 | 210 | 99 | 160 | 71 | 100 | 38 | 200 | 93 |
| Ammonium fluoride 25% | 150 | 66 | | | 300 | 148 | 140 | 60 | 140 | 60 | 210 | 99 | 80 | 27 | 200 | 93 | 120 | 49 |
| Ammonium hydroxide 25% | 190 | 88 | 250 | 121 | 100 | 38 | 140 | 60 | 190 | 88 | 210 | 99 | x | x | 200 | 93 | 200 | 93 |



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| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ammonium hydroxide, sat, | 190 | 88 | 250 | 121 | 100 | 38 | 140 | 60 | 190 | 88 | 210 | 99 | 90 | 32 | 210 | 99 | 200 | 93 |
| Ammonium nitrate | 180 | 82 | 200 | 93 | 250 | 121 | 180 | 82 | x | x | 300 | 148 | 170 | 77 | 200 | 93 | 180 | 82 |
| Ammonium persulfate | 190 | 88 | 80 | 27 | 300 | 148 | 210 | 99 | 140 | 60 | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Ammonium phosphate | 180 | 82 | 140 | 60 | 300 | 148 | 180 | 82 | 180 | 82 | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Ammonium sulfate 10–40% | 190 | 88 | 200 | 93 | 300 | 148 | 180 | 82 | 180 | 82 | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Ammonium sulfide | | | 200 | 93 | 300 | 148 | 210 | 99 | x | x | 210 | 99 | | | 160 | 71 | 180 | 82 |
| Ammonium sulfite | | | | | | | | | | | 210 | 99 | | | | | 160 | 71 |
| Amyl acetate | x | x | 60 | 16 | 210 | 99 | x | x | x | x | 210 | 99 | x | x | x | x | x | x |
| Amyl alcohol | 180 | 82 | 200 | 93 | 210 | 99 | 180 | 82 | 200 | 93 | 210 | 99 | 150 | 66 | 200 | 93 | 180 | 82 |
| Amyl chloride | | | x | x | x | x | x | x | 190 | 88 | 210 | 99 | x | x | x | x | x | x |
| Aniline | 150 | 66 | 140 | 60 | 140 | 60 | x | x | 230 | 110 | 250 | 121 | x | x | x | x | x | x |
| Antimony trichloride | 150 | 66 | 140 | 60 | 300 | 148 | x | x | 190 | 88 | 210 | 99 | | | 140 | 60 | | |
| Aqua regina 3:1 | | | | | x | x | x | x | 190 | 88 | 210 | 99 | x | x | x | x | x | x |
| Barium carbonate | | | 200 | 93 | 300 | 148 | 180 | 82 | 250 | 121 | 210 | 99 | 180 | 82 | 160 | 71 | 180 | 82 |
| Barium chloride | 190 | 88 | 250 | 121 | 250 | 121 | 180 | 82 | 190 | 88 | | | 150 | 66 | 200 | 93 | 200 | 93 |
| Barium hydroxide | 190 | 88 | 250 | 121 | 250 | 121 | 180 | 82 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Barium sulfate | | | 200 | 93 | 300 | 148 | 180 | 82 | 190 | 88 | 210 | 99 | 180 | 82 | 160 | 71 | 180 | 82 |
| Barium sulfide | 190 | 88 | 200 | 93 | 140 | 60 | 140 | 60 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Benzaldehyde | 90 | 32 | x | x | 150 | 66 | x | x | x | x | 210 | 99 | x | x | x | x | x | x |
| Benzene | x | x | x | x | x | x | x | x | 190 | 88 | 210 | 99 | x | x | x | x | x | x |
| Benzene sulfonic acid 10% | 90 | 32 | x | x | x | x | x | x | 170 | 77 | 210 | 99 | x | x | 100 | 38 | x | x |
| Benzoic acid | 150 | 66 | 200 | 93 | x | x | 140 | 60 | 190 | 88 | 310 | 154 | 150 | 66 | 200 | 93 | x | x |
| Benzyl alcohol | 190 | 88 | 140 | 60 | x | x | x | x | 350 | 177 | 210 | 99 | x | x | x | x | 140 | 60 |
| Benzyl chloride | x | x | x | x | x | x | x | x | 110 | 43 | 210 | 99 | x | x | x | x | x | x |
| Borax | 190 | 88 | 200 | 93 | 300 | 148 | 210 | 99 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 180 | 82 |
| Boric acid | 190 | 88 | 290 | 143 | 190 | 88 | 140 | 60 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 180 | 82 |
| Bromine gas, dry | | | 60 | 16 | x | x | x | x | | | 210 | 99 | | | x | x | x | x |
| Bromine gas, moist | | | 60 | 16 | x | x | | | | | | | | | x | x | x | x |
| Bromine liquid | | | 60 | 16 | x | x | x | x | 350 | 177 | 140 | 60 | | | x | x | x | x |
| Butadiene | | | x | x | x | x | x | x | 190 | 88 | 210 | 99 | | | 140 | 60 | 200 | 93 |
| Butyl acetate | x | x | 60 | 16 | 140 | 60 | x | x | x | x | 210 | 99 | x | x | 60 | 16 | x | x |
| Butyl alcohol | 140 | 60 | 250 | 121 | 200 | 93 | 180 | 82 | 250 | 121 | 240 | 116 | 150 | 66 | 200 | 93 | x | x |
| *n*-Butylamine | | | | | | | x | x | x | x | 210 | 99 | | | | | 80 | 27 |
| Butyl phthalate | | | | | | | x | x | 80 | 27 | 210 | 99 | x | x | | | x | x |
| Butyric acid | x | x | x | x | 140 | 60 | x | x | 120 | 49 | x | x | x | x | x | x | x | x |
| Calcium bisulfide | | | | | | | x | x | 190 | 88 | 210 | 99 | | | | | 180 | 82 |



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**Table E.3** (Continued)

| Chemical | Butyl | | Hypalon | | EPDM | | EPT | | Viton A | | Kalrez | | Natural rubber | | Neoprene | | Buna N | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | °F | °C | °F | °C | °F | °C | °F | °C | °F | °C | °F | °C | °F | °C | °F | °C | °F | °C |
| Calcium bisulfite | 120 | 49 | 250 | 121 | x | x | x | x | 190 | 88 | 210 | 99 | 120 | 49 | 180 | 82 | 200 | 93 |
| Calcium carbonate | 150 | 66 | 90 | 32 | 210 | 99 | 140 | 60 | 190 | 88 | 200 | 93 | 180 | 82 | 60 | 16 | 180 | 82 |
| Calcium chlorate | 190 | 88 | 90 | 32 | 140 | 60 | 140 | 60 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Calcium chloride | 190 | 88 | 200 | 93 | 210 | 99 | 180 | 82 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 180 | 82 |
| Calcium hydroxide 10% | 190 | 88 | 200 | 93 | 210 | 99 | 180 | 82 | 190 | 88 | 210 | 99 | 200 | 93 | 220 | 104 | 180 | 82 |
| Calcium hydroxide, sat. | 190 | 88 | 250 | 121 | 220 | 104 | 180 | 82 | 190 | 88 | 210 | 99 | 200 | 93 | 220 | 104 | 180 | 82 |
| Calcium hypochlorite | 190 | 88 | 250 | 121 | 210 | 99 | 180 | 82 | 190 | 88 | 210 | 99 | 200 | 93 | 220 | 104 | 80 | 27 |
| Calcium nitrate | 190 | 88 | 100 | 38 | 300 | 148 | 180 | 82 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Calcium oxide | | | 200 | 93 | 210 | 99 | | | | | | | | | 160 | 71 | 180 | 82 |
| Calcium sulfate | 100 | 38 | 250 | 121 | 300 | 148 | 180 | 82 | 200 | 93 | 210 | 99 | 180 | 82 | 160 | 71 | 180 | 82 |
| Caprylic acid | | | | | | | | | | | 210 | 99 | | | | | | |
| Carbon bisulfide | | | x | x | x | x | x | x | 190 | 88 | 210 | 99 | x | x | x | x | x | x |
| Carbon dioxide, dry | 190 | 88 | 200 | 93 | 250 | 121 | 180 | 82 | x | x | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Carbon dioxide. wet | 190 | 88 | 200 | 93 | 250 | 121 | 180 | 82 | x | x | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Carbon disulfide | 190 | 88 | 230 | 110 | 250 | 121 | 180 | 82 | x | x | 210 | 99 | 150 | 66 | x | x | 200 | 93 |
| Carbon monoxide | x | x | x | x | x | x | x | x | 190 | 88 | 210 | 99 | x | x | x | x | x | x |
| Carbon tetrachloride | 90 | 32 | 200 | 93 | 250 | 121 | 180 | 82 | 190 | 88 | 210 | 99 | x | x | 200 | 93 | 180 | 82 |
| Carhonic acid | x | x | x | x | x | x | x | x | 350 | 177 | 210 | 99 | x | x | x | x | x | x |
| Cellosolve | 150 | 66 | | | 300 | 148 | x | x | x | x | 210 | 99 | x | x | x | x | x | x |
| Chloroacetic acid, 50% water | 150 | 66 | | | | | x | x | x | x | 210 | 99 | x | x | x | x | x | x |
| Chloroacetic acid | 160 | 71 | x | x | 160 | 71 | x | x | x | x | 210 | 99 | x | x | x | x | x | x |
| Chlorine gas, dry | x | x | x | x | x | x | x | x | 190 | 88 | 210 | 99 | x | x | x | x | x | x |
| Chlorine gas, wet | | | 90 | 32 | x | x | x | x | 190 | 88 | | | | | x | x | x | x |
| Chlorine liquid | x | x | | | x | x | x | x | 190 | 88 | 210 | 99 | x | x | x | x | x | x |
| Chlorobenzene | x | x | x | x | x | x | x | x | 190 | 88 | 210 | 99 | x | x | x | x | x | x |
| Chloroform | x | x | x | x | x | x | x | x | 190 | 88 | 210 | 99 | x | x | x | x | x | x |
| Chlorosulfonic acid | x | x | x | x | x | x | x | x | x | x | 210 | 99 | x | x | x | x | x | x |
| Chromic acid 10% | 100 | 38 | 150 | 66 | | | x | x | 350 | 177 | 210 | 99 | x | x | 140 | 60 | 190 | 88 |
| Chromic acid 50% | x | x | 160 | 71 | x | x | x | x | 350 | 177 | 210 | 99 | x | x | 100 | 38 | 190 | 88 |
| Chromyl chloride | | | | | | | | | | | 210 | 99 | | | | | | |
| Citric acid 15% | 190 | 88 | 250 | 121 | 210 | 99 | 180 | 82 | | | 210 | 99 | 110 | 43 | 200 | 93 | 180 | 82 |



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| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Citric acid, conc. | 190 | 88 | 250 | 121 | 210 | 99 | 180 | 82 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 180 | 82 |
| Copper acetate | | | x | x | 100 | 38 | 100 | 38 | x | x | 210 | 99 | | | 160 | 71 | 180 | 82 |
| Copper carbonate | | | | | 210 | 99 | 210 | 99 | 190 | 88 | 210 | 99 | | | | | x | x |
| Copper chloride | 190 | 88 | 200 | 93 | 210 | 99 | 180 | 82 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Copper cyanide | | | 250 | 121 | 210 | 99 | 210 | 99 | 190 | 88 | 210 | 99 | 160 | 71 | 160 | 71 | 180 | 82 |
| Copper sulfate | 190 | 88 | 250 | 121 | 210 | 99 | 180 | 82 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Cresol | x | x | x | x | x | x | 100 | 38 | x | x | 210 | 99 | x | x | x | x | x | x |
| Cupric chloride 5% | | | 200 | 93 | 210 | 99 | 210 | 99 | 180 | 82 | | | | | 210 | 99 | 210 | 99 |
| Cupric chloride 50% | | | 200 | 93 | 210 | 99 | 210 | 99 | 180 | 82 | | | | | 160 | 71 | 180 | 82 |
| Cyclohexane | x | x | x | x | x | x | x | x | 190 | 88 | 210 | 99 | x | x | x | x | 180 | 82 |
| Cyclohexanol | | | x | x | x | x | x | x | 190 | 88 | 210 | 99 | | | x | x | x | x |
| Dichloroacetic acid | | | | | | | | | | | 210 | 99 | | | x | x | | |
| Dichloroethane | x | x | x | x | x | x | x | x | 190 | 88 | 210 | 99 | x | x | x | x | x | x |
| Ethylene glycol | 190 | 88 | 200 | 93 | 210 | 99 | 180 | 82 | 350 | 177 | 210 | 99 | 150 | 66 | 160 | 71 | 200 | 93 |
| Ferric chloride | 190 | 88 | 250 | 121 | 220 | 104 | 180 | 82 | 190 | 88 | 210 | 99 | 150 | 66 | 160 | 71 | 200 | 93 |
| Ferric chloride, 50% water | 160 | 71 | 250 | 121 | 210 | 99 | 180 | 82 | 180 | 82 | 210 | 99 | 150 | 66 | 160 | 71 | 180 | 82 |
| Ferric nitrate 10–50% | 190 | 88 | 250 | 121 | 210 | 99 | 180 | 82 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 200 | 93 |
| Ferrous chloride | 190 | 88 | 250 | 121 | 200 | 93 | 180 | 82 | 180 | 82 | 210 | 99 | 150 | 66 | 90 | 32 | 200 | 93 |
| Ferrous nitrate | 190 | 88 | | | 210 | 99 | 180 | 82 | 210 | 99 | | | 150 | 66 | 200 | 93 | 200 | 93 |
| Fluorine gas, dry | x | x | 140 | 60 | | | x | x | x | x | x | x | x | x | x | x | x | x |
| Fluorine gas, moist | | | | | 60 | 16 | 100 | 38 | x | x | x | x | x | x | x | x | x | x |
| Hydrobromic acid, dil. | 150 | 66 | 90 | 32 | 90 | 32 | 140 | 60 | 190 | 88 | 210 | 99 | 100 | 38 | x | x | x | x |
| Hydrobromic acid 20% | 160 | 71 | 100 | 38 | 140 | 60 | 140 | 60 | 190 | 88 | 210 | 99 | 110 | 43 | x | x | x | x |
| Hydrobromic acid 50% | 110 | 43 | 100 | 38 | 140 | 60 | 140 | 60 | 190 | 88 | 210 | 99 | 150 | 66 | x | x | x | x |
| Hydrochloric acid 20% | x | x | 160 | 71 | 100 | 38 | x | x | 350 | 177 | 210 | 99 | 150 | 66 | 90 | 32 | 130 | 54 |
| Hydrochloric acid 38% | x | x | 140 | 60 | 90 | 32 | x | x | 350 | 177 | 210 | 99 | 160 | 71 | 90 | 32 | x | x |
| Hydrocyanic acid 10% | 140 | 60 | 90 | 32 | 200 | 93 | x | x | 190 | 88 | 210 | 99 | 90 | 32 | x | x | 200 | 93 |
| Hydrofluoric acid 30% | 350 | 177 | 90 | 32 | 60 | 16 | 140 | 60 | 210 | 99 | 210 | 99 | 100 | 38 | 200 | 93 | x | x |
| Hydrofluoric acid 70% | 150 | 66 | 90 | 32 | x | x | x | x | 350 | 177 | 210 | 99 | x | x | 200 | 93 | x | x |
| Hydrofluoric acid 100% | x | x | 90 | 32 | x | x | x | x | 60 | 16 | 210 | 99 | x | x | x | x | x | x |
| Hypochlorous acid | x | x | x | x | 300 | 148 | 140 | 60 | 190 | 88 | 190 | 88 | 150 | 66 | x | x | x | x |
| Iodine solution 10% | | | | | 140 | 60 | 140 | 60 | 190 | 88 | | | | | 80 | 27 | 80 | 27 |
| Ketones, general | | | x | x | x | x | | | x | x | 210 | 99 | x | x | x | x | x | x |
| Lactic acid 25% | 120 | 49 | 140 | 60 | 140 | 60 | 210 | 99 | 190 | 88 | 210 | 99 | x | x | 140 | 60 | x | x |
| Lactic acid, concentrated | 120 | 49 | 80 | 27 | | | 210 | 99 | 150 | 66 | 210 | 99 | 80 | 27 | 90 | 32 | x | x |
| Magnesium chloride | 200 | 93 | 250 | 121 | 250 | 121 | 180 | 82 | 180 | 82 | 150 | 66 | 150 | 66 | 210 | 99 | 180 | 82 |



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**Table E.3** (Continued)

| Chemical | Butyl | | Hypalon | | EPDM | | EPT | | Viton A | | Kalrez | | Natural rubber | | Neoprene | | Buna N | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | °F | °C | °F | °C | °F | °C | °F | °C | °F | °C | °F | °C | °F | °C | °F | °C | °F | °C |
| Malic acid | x | x | | | x | x | 80 | 26 | 190 | 88 | 210 | 99 | 80 | 27 | | | 180 | 82 |
| Manganese chloride | | | 180 | 82 | | | 210 | 99 | 180 | 82 | 210 | 99 | | | 200 | 93 | 100 | 38 |
| Methyl chloride | 90 | 32 | x | x | x | x | x | x | 190 | 88 | | | x | x | x | x | x | x |
| Methyl ethyl ketone | 100 | 38 | x | x | 80 | 27 | x | x | x | x | 210 | 99 | x | x | x | x | x | x |
| Methyl isobutyl ketone | 80 | 27 | x | x | 60 | 16 | x | x | x | x | 210 | 99 | x | x | x | x | x | x |
| Muriatic acid | x | x | 140 | 60 | | | x | x | 350 | 177 | 210 | 99 | | | x | x | x | x |
| Nitric acid 5% | 160 | 71 | 100 | 38 | 60 | 16 | x | x | 190 | 88 | 210 | 99 | x | x | x | x | x | x |
| Nitric acid 20% | 160 | 71 | 100 | 38 | 60 | 16 | x | x | 190 | 88 | 210 | 99 | x | x | x | x | x | x |
| Nitric acid 70% | 90 | 32 | x | x | x | x | x | x | 190 | 88 | 160 | 71 | x | x | x | x | x | x |
| Nitric acid, anhydrous | x | x | x | x | x | x | x | x | 190 | 88 | x | x | x | x | x | x | x | x |
| Nitrous acid, concentrated | 120 | 49 | | | | | | | 100 | 38 | 210 | 99 | x | x | x | x | x | x |
| Oleum | x | x | x | x | x | x | x | x | 190 | 88 | 210 | 99 | x | x | x | x | x | x |
| Perchloric acid 10% | 150 | 66 | 100 | 38 | 140 | 60 | 190 | 88 | 190 | 88 | 210 | 99 | 150 | 66 | | | x | x |
| Perchloric acid 70% | | | 90 | 32 | | | 140 | 60 | 190 | 88 | | | | | x | x | x | x |
| Phenol | 150 | 66 | x | x | | | 80 | 27 | 210 | 99 | 210 | 99 | x | x | x | x | x | x |
| Phosphoric acid 50–80% | 150 | 66 | 200 | 93 | 140 | 60 | 180 | 82 | 190 | 88 | 210 | 99 | 110 | 43 | | | x | x |
| Picric acid | | | 80 | 27 | 300 | 148 | 140 | 60 | 190 | 88 | 210 | 99 | x | x | 200 | 93 | 130 | 54 |
| Potassium bromide 30% | | | 250 | 121 | 210 | 99 | 180 | 82 | 190 | 88 | 210 | 99 | 160 | 71 | 160 | 71 | 180 | 82 |
| Salicylic acid | 80 | 27 | | | 210 | 99 | 180 | 82 | 190 | 88 | 210 | 99 | | | | | | |
| Silver bromide 10% | | | | | | | | | | | 210 | 99 | | | | | | |



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| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sodium carbonate | 180 | 82 | 250 | 121 | 300 | 148 | 180 | 82 | 190 | 88 | 210 | 99 | 180 | 82 | 200 | 93 | 200 | 93 |
| Sodium chloride | 180 | 82 | 240 | 116 | 140 | 60 | 180 | 82 | 190 | 88 | 210 | 99 | 130 | 54 | 200 | 93 | 180 | 82 |
| Sodium hydroxide 10% | 180 | 82 | 250 | 121 | 210 | 99 | 210 | 99 | x | x | 210 | 99 | 150 | 66 | 200 | 93 | 160 | 71 |
| Sodium hydroxide 50% | 190 | 88 | 250 | 121 | 180 | 82 | 200 | 93 | x | x | 210 | 99 | 150 | 66 | 200 | 93 | 150 | 66 |
| Sodium hydroxide conc. | 180 | 82 | 250 | 121 | 180 | 82 | 80 | 27 | x | x | 210 | 99 | 150 | 66 | 200 | 93 | 150 | 66 |
| Sodium hypochlorite 20% | 130 | 54 | 250 | 121 | 300 | 148 | x | x | 190 | 88 | | | 90 | 32 | x | x | x | x |
| Sodium hypochlorite | 90 | 32 | | | 300 | 148 | x | x | 190 | 88 | | | 90 | 32 | x | x | x | x |
| Sodium sulfide to 50% | 150 | 66 | 250 | 121 | 300 | 148 | 210 | 99 | 190 | 88 | 210 | 99 | 150 | 66 | 200 | 93 | 180 | 82 |
| Stannic chloride | 150 | 66 | 90 | 32 | 300 | 148 | 210 | 99 | 180 | 82 | 210 | 99 | 150 | 66 | 210 | 99 | 180 | 82 |
| Stannous chloride | 150 | 66 | 200 | 93 | 280 | 138 | 210 | 99 | 190 | 88 | 210 | 99 | 150 | 66 | 160 | 71 | 180 | 82 |
| Sulfuric acid 10% | 150 | 66 | 250 | 121 | 150 | 66 | 210 | 99 | 350 | 177 | 240 | 116 | 150 | 66 | 200 | 93 | 150 | 66 |
| Sulfuric acid 50% | 150 | 66 | 250 | 121 | 150 | 66 | 210 | 99 | 350 | 177 | 210 | 99 | 100 | 38 | 200 | 93 | 200 | 93 |
| Sulfuric acid 70% | 100 | 38 | 160 | 71 | 140 | 60 | 210 | 99 | 350 | 177 | 150 | 66 | x | x | 200 | 93 | x | x |
| Sulfuric acid 90% | x | x | x | x | x | x | 80 | 27 | 350 | 177 | 150 | 66 | x | x | x | x | x | x |
| Sulfuric acid 98% | x | x | 110 | 43 | x | x | x | x | 350 | 177 | | | x | x | x | x | x | x |
| Sulfuric acid 100% | x | x | x | x | x | x | x | x | 190 | 88 | | | x | x | x | x | x | x |
| Sulfuric acid, fuming | | | x | x | x | x | x | x | | | 210 | 99 | | | x | x | x | x |
| Sulfurous acid | 150 | 66 | 160 | 71 | x | x | 180 | 82 | 190 | 88 | 210 | 99 | x | x | x | x | x | x |
| Thionyl chloride | x | x | | | | | | | x | x | 210 | 99 | x | x | x | x | x | x |
| Toluene | x | x | x | x | x | x | x | x | 190 | 88 | 80 | 27 | x | x | x | x | 150 | 66 |
| Trichloroacetic acid | x | x | | | 80 | 27 | x | x | 190 | 88 | 210 | 99 | x | x | x | x | x | x |
| While liquor | | | | | 300 | 148 | 180 | 82 | 190 | 88 | 210 | 99 | x | x | 140 | 60 | 140 | 60 |
| Zinc chloride | 190 | 88 | 250 | 121 | 300 | 148 | 180 | 82 | 210 | 99 | 210 | 99 | 150 | 66 | 160 | 71 | 190 | 88 |

The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available Incompatibility is indicated by an x. A blank space indicates that data are unavailable.

*Source:* Schweitzer, Philip A. *Corrosion Resistance Tables*. 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.



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Large quantities of elastomeric materials arc used to produce a myriad of products such as hoses, cable insulation, O-rings, seals and gaskets, belting, vibration mounts, flexible couplings, expansion joints, automotive and airplane parts, electrical parts and accessories, and many other items. With such a wide variety of applications requiring very diverse properties, it is essential that an understanding of the properties of each elastomer be acquired so that proper choices can be made.

See Refs. 1–3.

## ELECTROCHEMICAL CORROSION

Corrosion of metals is caused by the flow of energy (electricity). This flow may be from one metal to another metal, or from one part of the surface of a metal to another part of the same metal, or from a metal to a recipient of some kind. This flow of electricity can take place in the atmosphere, underwater, or underground as long as a moist conductor or electrolyte such as water or especially salt water is present.

The difference in potential that causes the electric currents is mainly due to contact between dissimilar metallic conductors, or differences in concentration of the solution, generally related to dissolved oxygen in natural waters. Any lack of homogeneity on the metal surface may initiate attack by causing a difference in potentials that results in localized corrosion.

The flow of electricity (energy) may also be from a metal to a metal recipient of some kind, such as soil. Soils frequently contain dispersed metallic particles or bacterial pockets that provide a natural pathway with buried metal. The electrical path will be from metal to soil, with corrosion resulting.

The presence of water is the key factor for corrosion to take place. For example, in dry air such as a desert location, the corrosion of steel does not take place, and when the relative humidity of air is below 30% at normal or lower temperatures, corrosion is negligible.

Since aqueous corrosion is electrochemical in nature, it is possible to measure the corrosion rate by employing electrochemical techniques. Two methods based on electrochemical polarization are available: Tafel extrapolation and linear polarization. These methods permit rapid and precise corrosion rate measurement and may be used to measure corrosion rate in systems that cannot be visually inspected or subjected to weight loss tests.

### Tafel Extrapolation Method

The Tafel extrapolation method is based on the mixed-potential theory, which is illustrated in Fig. E.1. The dashed lines represent the anodic and cathodic components of the mixed electrodes involved in the corrosion process, the intersecting point of which corresponds to $i_{corr}$ and $E_{corr}$. When a corroding specimen is polarized by the applied current, usually cathodic, the experimental polarization curve originates at $E_{corr}$ and at high current densities becomes linear on a semilogarithmic plot. This linear portion coincides with the extended reduction curve as shown by the bold line in the figure. It is evident that an extrapolation of the linear portion of the experimental curve will intersect the $E_{corr}$ horizontal at the point that corresponds to $i_{corr}$.

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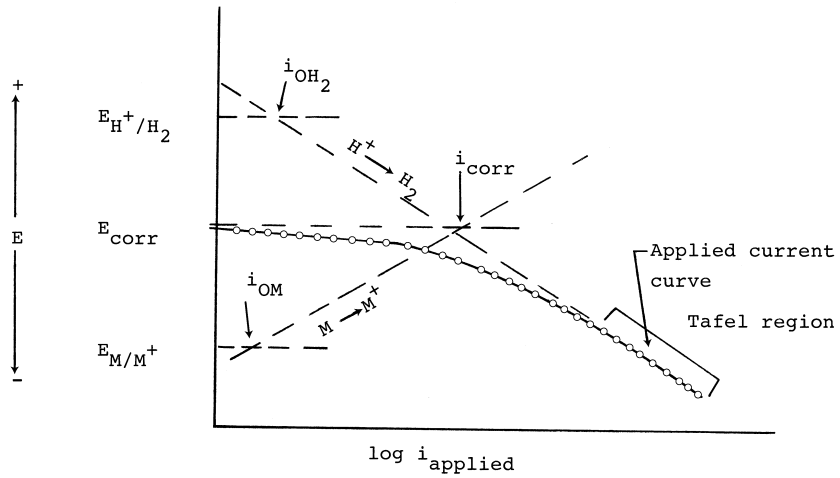



**Figure E.1** Tafel extrapolation method of corrosion rate measurement through cathodic polarization.

This method is rapid. However, the linear portion should extend over a considerable length, not less than one order of magnitude, to ensure accuracy in extrapolation. Where more than one reduction process is prevailing, the linearity is also affected. These disadvantages are largely overcome in the linear polarization method.

## Linear Polarization Method

Within 10 mV more noble or more active than the corrosion potential, the applied current density is a linear function of the electrode potential. This is shown in Fig. E.2. The slope of the linear polarization curve is given by

$$\frac{\Delta E}{\Delta i_{\text{app}}} = \frac{\beta_a \beta_c}{2.3(i_{\text{corr}})(\beta_a + \beta_c)}$$

where $\beta_a$ and $\beta_c$ are the Tafel slopes for anodic and cathodic reactors, respectively. The slope is in the unit of ohms and is referred to as the polarization resistance $R_p$. This method is also known as the polarization resistance method. Although the linearity of the curve deviates at higher overvoltages, the slope of the curve at the origin is independent of the degree of linearity. The slope of the linear curve is inversely proportional to the corrosion current $i_{\text{corr}}$.

Assuming $\beta_a = \beta_c = 0.12$ V,

$$\frac{\Delta E}{\Delta i_{\text{app}}} = \frac{0.026}{i_{\text{corr}}}$$

From this equation the corrosion rate can be calculated without knowledge of the kinetic parameters. This principle is utilized in commercial instruments designed for corrosion rate measurement. These instruments are based on galvanic circuitry and have two-electrode or three-electrode configurations.

See Refs. 4, 6.

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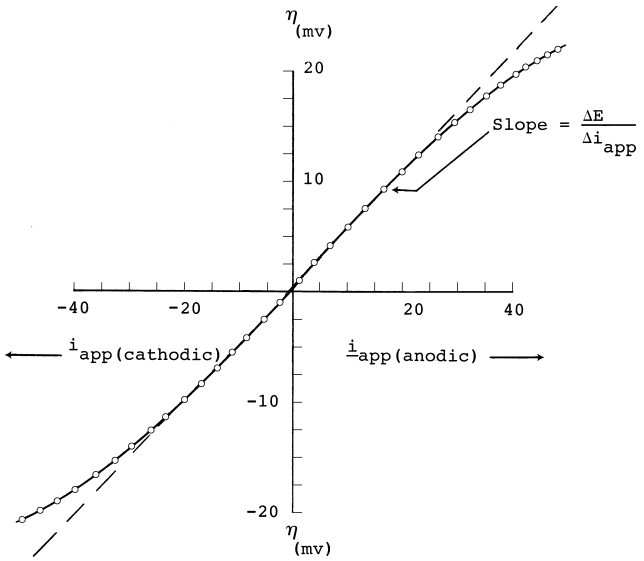



**Figure E.2** Applied-current linear polarization curve for corrosion rate measurement.

## ELECTROLYSIS

Electrolysis is the process of the passage of an electric current through a solution with simultaneous chemical changes either in the electrodes or in the solutions in contact with the electrodes, or both. Corrosion of a buried or immersed structure due to stray DC from an external source, such as an electric motor or welding machine, is known as electrolysis. The first observance of this phenonemon was around electric railways which were designed to furnish DC on an overhead wire and to have the current return to its source via the track or third rail. If the current found it easier to return to its source via an underground sewer system or water line, it would protect the pipe at the point of entry but cause severe corrosion damage at the point of discharge via the soil to the power source.

Similar problems have been experienced in the form of localized pitting when underground austenitic stainless steel pipe is welded in place.

## ELECTROLYTE

An electrolyte is any substance that, when in solution or fused, forms a liquid that will conduct an electric current. Acids, bases, and salts are common electrolytes.

## EMBEDDED IRON CORROSION

Embedded iron corrosion occurs when, during fabrication of stainless steel equipment, iron is embedded in the stainless steel surface. When exposed to moist air, or wetted, the iron corrodes, leaving rust streaks and possibly initiating crevice corrosion attack in the stainless steel.

## EMBRITTLEMENT

This is the severe loss of ductility or toughness in a material, which may result in cracking. Some metals, when stressed, crack on exposure to corrosive environments, but corrosion is not necessarily a part of crack initiation or crack growth. This type of failure is not properly called stress corrosion cracking.

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The most frequent occurrence of this form of attack is in steel equipment handling solutions containing hydrogen sulfide. Under these conditions corrosion of the steel generates atomic hydrogen, which penetrates the steel and at submicroscopic discontinuity of pressures high enough to cause cracking or blistering Failures of this kind are called hydrogen cracking or hydrogen stress cracking.

See "Hydrogen Damage."

See Refs. 7–10.

## ENAMELING

See "Glass Linings."

## ENGINEERING PLASTIC

This term is used interchangeably with the terms engineering polymers and high-performance polymers. The *ASM Handbook* defines engineering plastics as synthetic polymers of a resin-based material that have load-bearing characteristics and high-performance properties that permit them to be used in the same manner as metals and ceramics. In other words, these materials are plastics and polymeric compositions having well-defined mechanical properties such that engineering rather than empirical methods can be used for the design and manufacture of products that require definite and predictable performance in structural applications over a substantial temperature range. Many engineering polymers are reinforced and/or alloy polymers, blends of different polymers.

Among the engineering plastics are poly (*p*-phenyleneterephthalamide) (aromatic polyamide or aramid), polyaromatic ester, polyetherketone, polyphenylene sulfide, polyamide-imidepolyether sulfone, polyether-imide, polysulfone, and polyimide (thermoplastic).

Elastomers are cross-linked linear thermoplastic polymers and many fall into the engineering category. However, the major products of the polymer industry, such as polyethylene, polyvinyl chloride, polypropylene, and polystyrene, are not considered engineering products because of their low strength.

## EPOXY RESINS

See also "Polymers" and "Thermoset Polymers." The epoxy resins are a family of resins as are the vinyl ester resins. They exhibit good resistance to alkalies, nonoxidizing acids, and many solvents. Specifically, they are compatible with acids such as 10% acetic, benzoic, butyric, 10% hydrochloric. 20% sulfuric, oxalic, and fatty acids. On the alkaline side they are compatible with 50% sodium hydroxide, 10% sodium sulfite, calcium hydroxide, trisodium phosphate, magnesium hydroxide, aluminum, barium, calcium, iron, magnesium, potassium, and sodium. Solvents such as methanol, ethanol, isopropanol, benzene, ethyl acetate, naphtha, toluene, and xylene can also be handled safely.

Bromine water, chromic acid, bleaches, fluorine, methylene chloride, hydrogen peroxide, sulfuric acid above 80%, wet chlorine gas, and wet sulfur dioxide will attack the epoxies. Refer to Table E.4 for the compatibility of epoxies with selected corrodents.

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**Table E.4** Compatibility of Epoxy with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | 150 | 66 | Barium sulfide | 300 | 149 |
| Acetamide | 90 | 32 | Benzaldehyde | x | x |
| Acetic acid 10% | 190 | 88 | Benzene | 160 | 71 |
| Acetic acid 50% | 110 | 43 | Benzene sulfonic acid 10% | 160 | 71 |
| Acetic acid 80% | 110 | 43 | Benzoic acid | 200 | 93 |
| Acetic anhydride | x | x | Benzyl alcohol | x | x |
| Acetone | 110 | 43 | Benzyl chloride | 60 | 16 |
| Acetyl chloride | x | x | Borax | 250 | 121 |
| Acrylic acid | x | x | Boric acid 4% | 200 | 93 |
| Acrylonitrile | 90 | 32 | Bromine gas, dry | x | x |
| Adipic acid | 250 | 121 | Bromine gas, moist | x | x |
| Allyl alcohol | x | x | Bromine liquid | x | x |
| Allyl chloride | 140 | 60 | Butadiene | 100 | 38 |
| Alum | 300 | 149 | Butyl acetate | 170 | 77 |
| Aluminum chloride, | | | Butyl alcohol | 140 | 60 |
| aqueous 1% | 300 | 149 | *n*-Butylamine | x | x |
| Aluminum chloride, dry | 90 | 32 | Butyric acid | 210 | 99 |
| Aluminum fluoride | I80 | 82 | Calcium bisulfide | | |
| Aluminum hydroxide | 180 | 82 | Calcium bisulfite | 200 | 93 |
| Aluminum nitrate | 250 | 121 | Calcium carbonate | 300 | 149 |
| Aluminum sulfate | 300 | 149 | Calcium chlorate | 200 | 93 |
| Ammonia gas, dry | 210 | 99 | Calcium chloride 37.5% | 190 | 88 |
| Ammonium bifluoride | 90 | 32 | Calcium hydroxide, sat. | 180 | 82 |
| Ammonium carbonate | 140 | 60 | Calcium hypochlorite 70% | 150 | 66 |
| Ammonium chloride, sat. | 180 | 82 | Calcium nitrate | 250 | 121 |
| Ammonium fluoride 25% | 150 | 66 | Calcium sulfate | 250 | 121 |
| Ammonium hydroxide 25% | 140 | 60 | Caprylic acid | x | x |
| Ammonium hydroxide, sat. | 150 | 66 | Carbon bisulfide | 100 | 38 |
| Ammonium nitrate 25% | 250 | 121 | Carbon dioxide, dry | 200 | 93 |
| Ammonium persulfate | 250 | 121 | Carbon disulfide | 100 | 38 |
| Ammonium phosphate | 140 | 60 | Carbon monoxide | 80 | 27 |
| Ammonium sulfate 10–40% | 300 | 149 | Carbon tetrachloride | 170 | 77 |
| Ammonium sulfite | 100 | 38 | Carbonic acid | 200 | 93 |
| Amyl acetate | 80 | 27 | Cellosolve | 140 | 60 |
| Amyl alcohol | 140 | 60 | Chloracetic acid, 92% water | 150 | 66 |
| Amyl chloride | 80 | 27 | Chloracetic acid | x | x |
| Aniline | 150 | 66 | Chlorine gas, dry | 150 | 66 |
| Antimony trichloride | 180 | 82 | Chlorine gas, wet | x | x |
| Aqua regia 3:1 | x | x | Chlorobenzene | 150 | 66 |
| Barium carbonate | 240 | 116 | Chloroform | 110 | 43 |
| Barium chloride | 250 | 121 | Chlorosulfonic acid | x | x |
| Barium hydroxide 10% | 200 | 93 | Chromic acid 10% | 110 | 43 |
| Barium sulfate | 250 | 121 | Chromic acid 50% | x | x |

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**Table E.4** Compatibility of Epoxy with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Citric acid 15% | 190 | 88 | Methyl isobutyl ketone | 140 | 60 |
| Citric acid, 32% | 190 | 88 | Muriatic acid | 140 | 60 |
| Copper acetate | 200 | 93 | Nitric acid 5% | 160 | 71 |
| Copper carbonate | 150 | 66 | Nitric acid 20% | 100 | 38 |
| Copper chloride | 250 | 121 | Nitric acid 70% | x | x |
| Copper cyanide | 150 | 66 | Nitric acid, anhydrous | x | x |
| Copper sulfate 17% | 210 | 99 | Nitric acid, concentrated | x | x |
| Cresol | 100 | 38 | Oleum | x | x |
| Cupric chloride 5% | 80 | 27 | Perchloric acid 10% | 90 | 32 |
| Cupric chloride 50% | 80 | 27 | Perchloric acid 70% | 80 | 27 |
| Cyclohexane | 90 | 32 | Phenol | x | x |
| Cyclohexanol | 80 | 27 | Phosphoric acid 50–80% | 110 | 43 |
| Dichloroacetic acid | x | x | Picric acid | 80 | 27 |
| Dichloroethane | | | Potassium bromide 30% | 200 | 93 |
| (ethylene dichloride) | x | x | Salicylic acid | 140 | 60 |
| Ethylene glycol | 300 | 149 | Sodium carbonate | 300 | 149 |
| Ferric chloride | 300 | 149 | Sodium chloride | 210 | 99 |
| Ferric chloride 50% in water | 250 | 121 | Sodium hydroxide 10% | 190 | 88 |
| Ferric nitrate 10–50% | 250 | 121 | Sodium hydroxide 50% | 200 | 93 |
| Ferrous chloride | 250 | 121 | Sodium hypochlorite 20% | x | x |
| Ferrous nitrate | | | Sodium hypochlorite | | |
| Fluorine gas, dry | 90 | 32 | concentrated | x | x |
| Hydrobromic acid, dilute | 180 | 82 | Sodium sulfide to 10% | 250 | 121 |
| Hydrobromic acid 20% | 180 | 82 | Stannic chloride | 200 | 93 |
| Hydrobromic acid 50% | 110 | 43 | Stannous chloride | 160 | 71 |
| Hydrochloric acid 20% | 200 | 93 | Sulfuric acid 10% | 140 | 60 |
| Hydrochloric acid 38% | 140 | 60 | Sulfuric acid 50% | 110 | 43 |
| Hydrocyanic acid 10% | 160 | 71 | Sulfuric acid 70% | 110 | 43 |
| Hydrofluoric acid 30% | x | x | Sulfuric acid 90% | x | x |
| Hydrofluoric acid 70% | x | x | Sulfuric acid 98% | x | x |
| Hydrofluoric acid 100% | x | x | Sulfuric acid 100% | x | x |
| Hypochlorous acid | 200 | 93 | Sulfuric acid, fuming | x | x |
| Ketones, general | x | x | Sulfurous acid 20% | 240 | 116 |
| Lactic acid 25% | 220 | 104 | Thionyl chloride | x | x |
| Lactic acid, concentrated | 200 | 93 | Toluene | 150 | 66 |
| Magnesium chloride | 190 | 88 | Trichloroacetic acid | x | x |
| Methyl chloride | x | x | White liquor | 90 | 32 |
| Methyl ethyl ketone | 90 | 32 | Zinc chloride | 250 | 121 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that the data are unavailable.

*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

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Refer to Ref. 4 for the compatibility of the epoxies over a wider range of selected corrodents.

See Refs. 2, 3, 11, and 12.

## EROSION CORROSION

The term erosion applies to deterioration due to mechanical forces. When the factors contributing to erosion accelerate the rate of corrosion of a metal, the attack is called erosion corrosion. Erosion corrosion is usually caused by a corrodent, aqueous or gaseous, flowing over the metal surface or impinging on it. The mechanical deterioration may be aggravated by the presence of a corrodent, as in the case of fretting corrosion or corrosive wear.

The attack takes the form of grooves, i.e., scooped-out rounded areas, horseshoe-shaped depressions, gullies, or waves, all of which often show directionality. At times the attack may be an assembly of pits. Ultimate perforation due to thinning or progression of pits, and rupture due to failure of the thinned wall to resist the internal fluid pressure are also common. All equipment exposed to flowing fluid are subject to erosion corrosion, but piping systems and heat exchangers are the most commonly affected.

Erosion corrosion is affected by velocity, turbulence, impingement, presence of suspended solids, temperature, and prevailing cavitation conditions. The acceleration of attack is due to the distribution or removal of the protective surface film by mechanical forces exposing fresh metal surfaces that are anodic to the uneroded neighboring film. A hard, dense, adherent and continuous film such as on stainless steel is more resistant than a soft, brittle film as on lead. The nature of the protective film depends largely on the corrosive itself.

In most metals and alloys corrosion rates increase with increased velocity, but a marked increase is experienced only when a critical velocity is reached.

Turbulence is caused when the liquid flows from a larger area to a small-diameter pipe, as in the inlet ends of tubing in heat exchangers. Internal deposits in the pipes or any obstruction to the flow inside a pipe by a foreign body, such as a carried-in pebble, can also cause turbulence.

Impingement, direct impact of the corrodent on the metal surface, occurs at bends, elbows, and tees in a piping system and causes intense attack. Impingement is also encountered on the surfaces of impellers and turbines in areas in front of inlet pipes in tanks and in many other situations. The attack appears as horseshoe-shaped pits with deep undercut and the end pointing in the direction of flow.

Attack is further aggravated at higher temperatures and when the solution contains solids in suspension. Steam carrying water condensate droplets provides an aggressive medium for erosion corrosion of steel and cast iron piping. The impingement of water droplets at the return bends destroys the protective oxide film and accelerates the attack on the substrate.

Soft and low-strength metals such as copper, aluminum, and lead are especially susceptible to erosion corrosion. So are the metals and alloys that are inherently less corrosion resistant, such as carbon steels.

Stainless steels of all grades, in general, are resistant to erosion corrosion. The addition of nickel, chromium, and molybdenum further improves their performance. Stainless steels and chromium steels are resistant as a result of their tenacious protective surface films.

As a rule, solid solution alloys provide better resistance than alloys hardened by heat treatment because the latter are heterogeneous in structure.

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Cast irons usually perform better than steel. Alloy cast irons containing nickel and chromium show better performance. Duriron containing 14.5% silicon gives excellent performance under severe erosion corrosion conditions.

Impingement attack can be avoided by smoothing the bends in a piping system. Increasing the pipe diameter will ensure a laminar flow and less turbulence.

## ESTERS

Esters are organic compounds formed by reaction between alcohols and acids. When the organic radical is not specified in the name, ethyl is often understood; e.g., acetic ester is ethylacetate.

## ETHYLENE-ACRYLIC (EA) RUBBER

Ethylene-acrylic rubber is produced from ethylene and acrylic acid. As with other synthetic elastomers, the properties of the EA rubbers can be altered by compounding. Basically, EA is a cost-effective hot-oil–resistant rubber with good low-temperature properties.

### Physical and Mechanical Properties

Ethylene-acrylic elastomers have good tear strength and tensile strength and high elongation at break. Exceptionally low compression set values are an added advantage, making the product suitable for many hose, sealing, and cut gasket applications. A unique feature is its practically constant damping characteristics over broad ranges of temperature, frequency, and amplitude. Very little change in damping value takes place between –4 and 320°F (–20 and 160°C). This property, which shows up as a poor rebound in resiliency tests, is actually a design advantage. Combined with EA's heat and chemical resistance, it allows the use of EA in vibration-damping applications. This elastomer provides heat resistance surpassed by only the more expensive polymers such as the fluorocarbon or fluorosilicone elastomers. In measurements of dry heat resistance, EA outlasts other moderately priced oil-resistant rubbers. Parts retain elasticity and remain functional after continuous air-oven exposures from 18 months at 250°F (121°C) to 7 days at 400°F (204°C). Parts fabricated of EA will perform at least as long as parts made of Hypalon or general-purpose nitrile rubber, but at exposure temperatures 50–100°F (27°C) higher.

The low-temperature performance of EA is inherently superior to that of most other heat- and oil-resistant rubbers, including standard fluoroelastomers, chlorosulfonated polyethylene, polyacrylates, and polyepichlorhydrin. Typical unplasticized compounds are flexible to –20°F (–29°C) and have brittle points as low as –75°F (–60°C).

Compounding EA with ester plasticizers will extend its low-temperature flexibility limits to –50°F (–46°C). When exposed to flame, EA has poor flame resistance but does have low smoke emission.

The physical and mechanical properties of ethylene-acrylic rubber are given in Table E.5.

### Resistance to Sun, Weather, and Ozone

The EA elastomers have extremely good resistance to sun, weather, and ozone. Long-term exposures have no effect on these rubbers.

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**Table E.5** Physical and Mechanical Properties of Ethylene-Acrylic (EA) Rubber[a]

| | |
|---|---|
| Specific gravity | 1.08–1.12 |
| Hardness, Shore A | 40–95 |
| Tensile strength, psi | 2500 |
| Elongation, % at break | 650 |
| Compression set, % | Good |
| Tear resistance | Good |
| Maximum temperature, continuous use | 340°F (170°C) |
| Brittle point | –75°F (–60°C) |
| Water absorption, %/24 hr | Very low |
| Abrasion resistance | Excellent |
| Resistance to sunlight | Excellent |
| Effect of aging | Nil |
| Resistance to heat | Excellent |
| Dielectric strength | Good |
| Electrical insulation | Fair to good |
| Permeability to gases | Very low |

[a]These are representative values since they may be altered by compounding.

### Chemical Resistance

The ethylene-acrylic elastomers exhibit very good resistance to hot oils, to hydrocarbon- or glycol-based proprietary lubricants, and to transmission and power steering fluids. The swelling characteristics of EA will be retained better than those of the silicone rubbers after oil immersion.

Ethylene-acrylic rubber also has outstanding resistance to hot water. Its resistance to water absorption is very good. Good resistance is also displayed to dilute acids, aliphatic hydrocarbons, gasoline, and animal and vegetable oils. Ethylene-acrylic rubber is not recommended for immersion in esters, ketones, highly aromatic hydrocarbons, or concentrated acids. Neither should it be used in applications calling for long-term exposure to high-pressure steam.

### Applications

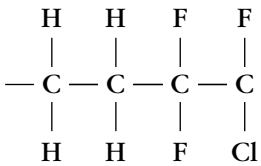
Ethylene-acrylic rubber is used in such products as gaskets, hoses, seals, boots, damping components, low-smoke floor tiling, and cable jackets for offshore oil platforms, ships, and building plenum installations. Ethylene-acrylic rubber in engine parts provides good resistance to heat, fluids, and wear as well as good low-temperature sealing ability.

See Refs. 1 and 3.

## ETHYLENE-CHLOROTRIFLUOROETHYLENE (ECTFE)

ECTFE is a 1:1 alternating copolymer of ethylene and chlorotrifluorethylene The chemical structure of this thermoplast is

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This chemical structure provides the polymer with a unique combination of properties. It possesses excellent chemical resistance, a broad use temperature range from cryogenic to 340°F (171°C) with continuous service to 300°F (149°C), and excellent abrasion resistance.

ECTFE exhibits excellent impact strength over its entire operating range, even in the cryogenic range. It also possesses good tensile, flexural, and wear-related properties. ECTFE is also one of the most corrosion-resistant polymers. Other important properties include a low coefficient of friction and the ability to be pigmented. Table E.6 lists the physical and mechanical properties of ECTFE.

ECTFE is resistant to strong mineral and oxidizing acids, alkalies, metal etchants, liquid oxygen, and practically all organic solvents except hot amines (aniline, dimethylamine, etc.). ECTFE is not subject to chemically induced stress cracking from strong acids, bases, or solvents. Some halogenated solvents can cause ECTFE to become slightly plasticized when it comes into contact with them. Under normal circumstances this does not affect the usefulness of the polymer since upon removal of the solvent from contact and upon drying, its mechanical properties return to their original values, indicating that no chemical attack has taken place. Like other fluoropolymers, ECTFE will be attacked by metallic sodium and potassium. Table E.7 lists the compatibility of ECTFE with selected corrodents. Reference 3 provides a wide range of compatibility of ECTFE with selected corrodents.

See Refs. 2 and 3.

**Table E.6** Physical and Mechanical Properties of ECTFE

| | |
|---|---|
| Specific gravity | 1.68 |
| Water absorption, 24 h at 73°F/23°C, % | $< 0.01$ |
| Tensile strength at 73°F/23°C, psi | 4500 |
| Modulus of elasticity in tension at 73°F/23°C $\times 10^5$ psi | 2.4 |
| Flexural strength, psi | 7000 |
| Izod impact strength, notched at 73°F/23°C, ft-lb/in | No break |
| Linear coefficient of thermal expansion, in./in. °F at | |
| –22 to 122°F/–30 to 50°C | $4.4 \times 10^{-5}$ |
| 122 to I 85°F/50 to 80°C | $5.6 \times 10^{-5}$ |
| 185 to 257°F/85 to 125°C | $7.5 \times 10^{-5}$ |
| 257 to 365°F/125 to 180°C | $9.2 \times 10^{-5}$ |
| Thermal conductivity Btu/h/ft$^2$/°F/in | 1.07 |
| Heat distortion temperature, °F/°C | |
| at 66 psi | 195/91 |
| at 264 psi | 151/66 |
| Limiting oxygen index | 60 |
| Underwriters lab rating, Sub 94 | V-0 |

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**Table E.7** Compatibility of ECTFE with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetic acid 10% | 250 | 121 | Barium sulfide | 300 | 149 |
| Acetic acid 50% | 250 | 121 | Benzaldehyde | 150 | 66 |
| Acetic acid 80% | 150 | 66 | Benzene | 150 | 66 |
| Acetic acid, glacial | 200 | 93 | Benzene sulfonic acid 10% | 150 | 66 |
| Acetic anhydride | 100 | 38 | Benzoic acid | 250 | 121 |
| Acetone | 150 | 66 | Benzyl alcohol | 300 | 149 |
| Acetyl chloride | 150 | 66 | Benzyl chloride | 300 | 149 |
| Acrylonitrile | 150 | 66 | Borax | 300 | 149 |
| Adipic acid | 150 | 66 | Boric acid | 300 | 149 |
| Allyl chloride | 300 | 149 | Bromine gas, dry | x | x |
| Alum | 300 | 149 | Bromine liquid | 150 | 66 |
| Aluminum chloride, aqueous | 300 | 149 | Butadiene | 250 | 121 |
| Aluminum chloride, dry | | | Butyl acetate | 150 | 66 |
| Aluminum fluoride | 300 | 149 | Butyl alcohol | 300 | 149 |
| Aluminum hydroxide | 300 | 149 | Butyric acid | 250 | 121 |
| Aluminum nitrate | 300 | 149 | Calcium bisulfide | 300 | 149 |
| Aluminum oxychloride | 150 | 66 | Calcium bisulfite | 300 | 149 |
| Aluminum sulfate | 300 | 149 | Calcium carbonate | 300 | 149 |
| Ammonia gas | 300 | 149 | Calcium chlorate | 300 | 149 |
| Ammonium bifluoride | 300 | 149 | Calcium chloride | 300 | 149 |
| Ammonium carbonate | 300 | 149 | Calcium hydroxide 10% | 300 | 149 |
| Ammonium chloride 10% | 290 | 143 | Calcium hydroxide, sat. | 300 | 149 |
| Ammonium chloride 50% | 300 | 149 | Calcium hypochlorite | 300 | 149 |
| Ammonium chloride, sat. | 300 | 149 | Calcium nitrate | 300 | 149 |
| Ammonium fluoride 10% | 300 | 149 | Calcium oxide | 300 | 149 |
| Ammonium fluoride 25% | 300 | 149 | Calcium sulfate | 300 | 149 |
| Ammonium hydroxide 25% | 300 | 149 | Caprylic acid | 220 | 104 |
| Ammonium hydroxide, sat. | 300 | 149 | Carbon bisulfide | 80 | 27 |
| Ammonium nitrate | 300 | 149 | Carbon dioxide, dry | 300 | 149 |
| Ammonium persulfate | 150 | 66 | Carbon dioxide, wet | 300 | 149 |
| Ammonium phosphate | 300 | 149 | Carbon disulfide | 80 | 27 |
| Ammonium sulfate 10–40% | 300 | 149 | Carbon monoxide | 150 | 66 |
| Ammonium sulfide | 300 | 149 | Carbon tetrachloride | 300 | 149 |
| Amyl acetate | 160 | 71 | Carbonic acid | 300 | 149 |
| Amyl alcohol | 300 | 149 | Cellosolve | 300 | 149 |
| Amyl chloride | 300 | 149 | Chloracetic acid, 50% water | 250 | 121 |
| Aniline | 90 | 32 | Chloracetic acid | 250 | 121 |
| Antimony trichloride | 100 | 38 | Chlorine gas, dry | 150 | 66 |
| Aqua regia 3:1 | 250 | 121 | Chlorine gas, wet | 250 | 121 |
| Barium carbonate | 300 | 149 | Chlorine, liquid | 250 | 121 |
| Barium chloride | 300 | 149 | Chlorobenzene | 150 | 66 |
| Barium hydroxide | 300 | 149 | Chloroform | 250 | 121 |
| Barium sulfate | 300 | 149 | Chlorosulfonic acid | 80 | 27 |

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**Table E.7** Compatibility of ECTFE with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Chromic acid 10% | 250 | 121 | Muriatic acid | 300 | 149 |
| Chromic acid 50% | 250 | 121 | Nitric acid 5% | 300 | 149 |
| Citric acid 15% | 300 | 149 | Nitric acid 20% | 250 | 121 |
| Citric acid, conc. | 300 | 149 | Nitric acid 70% | 150 | 66 |
| Copper carbonate | 150 | 66 | Nitric acid, anhydrous | 150 | 66 |
| Copper chloride | 300 | 149 | Nitrous acid, concentrated | 250 | 121 |
| Copper cyanide | 300 | 149 | Oleum | x | x |
| Copper sulfate | 300 | 149 | Perchloric acid 10% | 150 | 66 |
| Cresol | 300 | 149 | Perchloric acid 70% | 150 | 66 |
| Cupric chloride 5% | 300 | 149 | Phenol | 150 | 66 |
| Cupric chloride 50% | 300 | 149 | Phosphoric acid 50–80% | 250 | 12I |
| Cyclohexane | 300 | 149 | Picric acid | 80 | 27 |
| Cyclohexanol | 300 | 149 | Potassium bromide 30% | 300 | 149 |
| Ethylene glycol | 300 | 149 | Salicylic acid | 250 | 121 |
| Ferric chloride | 300 | 149 | Sodium carbonate | 300 | 149 |
| Ferric chloride 50% in water | 300 | 149 | Sodium chloride | 300 | 149 |
| Ferric nitrate 1 0-50% | 300 | 149 | Sodium hydroxide 10% | 300 | 149 |
| Ferrous chloride | 300 | 149 | Sodium hydroxide 50% | 250 | 121 |
| Ferrous nitrate | 300 | 149 | Sodium hydroxide, | | |
| Fluorine gas, dry | x | x | concentrated | 150 | 66 |
| Fluorine gas, moist | 80 | 27 | Sodium hypochlorite 20% | 300 | 149 |
| Hydrobromic acid, dilute | 300 | 149 | Sodium hypochlorite, | | |
| Hydrobromic acid 20% | 300 | 149 | concentrated | 300 | 149 |
| Hydrobromic acid 50% | 300 | 149 | Sodium sulfide to 50% | 300 | 149 |
| Hydrochloric acid 20% | 300 | 149 | Stannic chloride | 300 | 149 |
| Hydrochloric acid 38% | 300 | 149 | Stannous chloride | 300 | 149 |
| Hydrocyanic acid 10% | 300 | 149 | Sulfuric acid 10% | 250 | 121 |
| Hydrofluoric acid 30% | 250 | 121 | Sulfuric acid 50% | 250 | 121 |
| Hydrofluoric acid 70% | 240 | 116 | Sulfuric acid 70% | 250 | 121 |
| Hydrofluoric acid 100% | 240 | 116 | Sulfuric acid 90% | 150 | 66 |
| Hypochlorous acid | 300 | 149 | Sulfuric acid 98% | 150 | 66 |
| Iodine solution 10% | 250 | 121 | Sulfuric acid 100% | 80 | 27 |
| Lactic acid 25% | 150 | 66 | Sulfuric acid, fuming | 300 | 149 |
| Lactic acid, concentrated | 150 | 66 | Sulfurous acid | 250 | 121 |
| Magnesium chloride | 300 | 149 | Thionyl chloride | 150 | 66 |
| Malic acid | 250 | 121 | Toluene | 150 | 66 |
| Methyl chloride | 300 | 149 | Trichloroacetic acid | 150 | 66 |
| Methyl ethyl ketone | 150 | 66 | White liquor | 250 | 121 |
| Methyl isobutyl ketone | 150 | 66 | Zinc chloride | 300 | 149 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable.

*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols 1–3. New York: Marcel Dekker, 1995.

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## ETHYLENE-CHLOROTRIFLUOROETHYLENE (ECTFE) ELASTOMER

Ethylene-chlorotrifluoroethylene (ECTFE) elastomer is a 1:1 alternating copolymer of ethylene and chlorotrifluoroethylene. This chemical structure gives the polymer a unique combination of properties. It possesses excellent chemical resistance, good electrical properties, and a broad use temperature range (from cryogenic to 340°F [171°C]) and meets the requirements of the UL-94V-0 vertical flame test in thicknesses as low as 7 mils. ECTFE is a tough material with excellent impact strength over its entire operating range. Of all the fluoropolymers, ECTFE ranks among the best for abrasion resistance.

Most techniques used for processing polyethylene can be used to process ECTFE. It can be extruded, injection molded, rotomolded, and applied by ordinary fluidized bed or electrostatic coating techniques.

### Physical and Mechanical Properties

ECTFE possesses advantageous electrical properties. It has high resistivity and low loss. The dissipation factor varies somewhat with frequency, particularly above 1 kHz. The AC loss properties of ECTFE are superior to those of vinilydene fluoride and come close to those of PTFE. The dielectric constant is stable across a broad temperature and frequency range. Refer to Table E.8.

According to ASTM D-149, the dielectric strength of ECTFE has a value of 2000 V/mil in 1 mil thickness and 500 V/mil in $\frac{1}{8}$ in. thickness, which arc similar to those obtained for PTFE or polyethylene.

The resistance to permeation by oxygen, carbon dioxide, chlorine gas, or hydrochloric acid is superior to that of PTFE and FEP, being 10–100 times better. Water absorption is less than 0.1%.

Other important physical properties include low coefficient of friction, excellent machinability, and the ability to be pigmented. In thicknesses as low as 7 mils, ECTFE has a UL-94-V-0 rating. The oxygen index (ASFM D2863) is 60 on a $\frac{1}{16}$ in. thick sample and 48 on a 0.0005 in. filament yarn. ECTFE is a strong, highly impact-resistant material that retains useful properties over a wide range of temperatures. Outstanding in this respect are properties related to impact at low temperatures. ECTFE can be applied at elevated temperatures in the range of 300–340°F (149–171°C). (Refer to Table E.8.)

In addition to its excellent impact properties, ECTFE also possesses good tensile, flexural, and wear-related properties.

The resistance of ECIFE to degradation by heat is excellent. It can resist temperatures of 300–340°F (149–171°C) for extended periods of time without degradation. It is one of the most radiation-resistant polymers. Laboratory testing has determined that the following useful life can be expected at the temperatures indicated:

| Temperature | | |
|---|---|---|
| °F | °C | Useful-life years |
| 329 | 165 | 10 |
| 338 | 170 | 4.5 |
| 347 | 175 | 2 |
| 356 | 180 | 1.25 |

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**Table E.8** Physical and Mechanical Properties of ECTFE[a] Elastomer

| | |
|---|---|
| Specific gravity | 1.68 |
| Refractive index, nD | 1.44 |
| Specific heat, Btu/lb-°F | 0.28 |
| Brittle point | –105°F (–76°C) |
| Insulation resistance, ohms | $>10^{15}$ |
| Thermal conductivity at 203°F (93°C) | |
| Btu-in./h-ft$^2$-°F | 1.09 |
| Coefficient of linear expansion, °F$^{-1}$ or °C$^{-1}$ | |
| –22 to 122°F | $4.4 \times 10^{-5}$ |
| 122 to 185°F | $5.6 \times 10^{-5}$ |
| 185 to 257°F | $7.5 \times 10^{-5}$ |
| 257 to 356°F | $9.2 \times 10^{-5}$ |
| –30 to 50°C | $8 \times 10^{-5}$ |
| 50 to 85°C | $10 \times 10^{-5}$ |
| 85 to 125°C | $13.3 \times 10^{-5}$ |
| 125 to 180°C | $16.5 \times 10^{-5}$ |
| Dielectric strength, V/mil | |
| 0.0001 in. thick | 2000 |
| 1/8 in. thick | 490 |
| Dielectric constant | |
| at 60 Hz | 2.6 |
| at $10^3$ Hz (1 kHz) | 2.5 |
| at $10^6$ Hz (1 MHz) | 2.5 |
| Dissipation factor at 60 Hz | <0.0009 |
| at $10^3$ Hz (1 kHz) | 0.005 |
| at $10^6$ Hz (1 MHz) | 0.003 |
| Arc resistance, s | 135 |
| Moisture absorption, % | <0.1 |
| Tensile strength, psi | 6000–7000 |
| Elongation at break, % at room temperature | 200–300 |
| Hardness, Shore D | 75 |
| impact resistance, ft-lb/in. notch | |
| at 73°F (23°C) | No break |
| at –40°F (–40°C) | 2–3 |
| Abrasion resistance. Armstrong (ASTM D1242) | |
| 30 lb load, volume loss, cm$^3$ | 0.3 |
| Coefficient of friction | |
| static | 0.15 |
| dynamic, 50 cm/s | 0.65 |
| Maximum temperature, continuous use | 340°F (171°C) |
| Machining qualities | Excellent |
| Resistance to sunlight | Excellent |
| Effect of aging | Good |
| Resistance to heat | Good |

[a]These are representative values since they may be altered by compounding.

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### Resistance to Sun, Weather, and Ozone

ECTFE is extremely resistant to sun, weather, and ozone attack. Its physical properties undergo very little change after long exposures.

### Chemical Resistance

The chemical resistance of ECTFE is outstanding It is resistant to most of the common corrosive chemicals encountered in industry. Included in this list of chemicals are strong mineral and oxidizing acids, alkalies, metal etchants, liquid oxygen, and practically all organic solvents except hot amines (aniline, dimethylamine, etc.). No known solvent dissolves or stress cracks ECTFE at temperatures up to 250°F (120°C).

Some halogenated solvents can cause ECTFE to become slightly plasticized when it comes into contact with them. Under normal circumstances this does not impair the usefulness of the polymer. When the part is removed from contact with the solvent and allowed to dry, its mechanical properties return to their original values, indicating that no chemical attack has taken place.

As with other fluoropolymers, ECTFE will he attacked by metallic sodium and potassium.

The useful properties of ECTFE are maintained on exposure to cobalt-60 radiation of 200 Mrad. Refer to Table E.7 for the compatibility of ECTFE with selected corrodents.

### Applications

This elastomer finds many applications in the electrical industry such as wire and cable insulation; jacketing plenum cable insulation; oil well wire and cable insulation; logging wire jacketing; jacketing for cathodic protection; aircraft, mass transit, and automotive wire; connectors; coil forms; resistor sleeves; wire tie wraps; tapes; tubing; flexible printed circuitry; and flat cable.

Applications are also found in other industries as diaphragms, flexible tubing, closures, seals, gaskets, and convoluted tubing and hose, particularly in the chemical, cryogenic, and aerospace industries.

Materials of ECTFE are also used for lining vessels, pumps, and other equipment.

See Refs. 1 and 3.

## ETHYLENE-PROPYLENE RUBBERS (EPDM AND EPT)

Ethylene-propylene rubber is a synthetic hydrocarbon-based rubber made either from ethylene-propylene diene monomer or from ethylene-propylene terpolymer. These monomers are combined so as to produce an elastomer with a completely saturated backbone and pendant unsaturation for sulfur vulcanization. As a result of this configuration, vulcanates of EPDM elastomers are extremely resistant to attack by ozone, oxygen, and weather.

Ethylene-propylene rubber possesses many properties superior to those of natural rubber and conventional general-purpose elastomers. In some applications it will perform better than other materials, while in other applications it will last longer or require less maintenance and may even cost less.

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EPDM has exceptional heat resistance, being able to operate at temperatures of 300–350°F (148–176°C), while also finding application at temperatures as low as –70°F (–56°C). Experience has shown that EPDM has exceptional resistance to steam. Hoses manufactured from EPDM have had lives several times longer than those of hoses manufactured from other elastomers.

Dynamic properties of EPDM remain constant over a wide temperature range, making this elastomer suitable for a variety of applications. It also has a very high resistance to sunlight, aging, and weather, excellent electrical properties, and good chemical resistance. However, being hydrocarbon based, it is not resistant to petroleum-based oils or flame.

This material may be processed and vulcanized by the same techniques and with the same equipment as those used for processing other general-purpose elastomers. As with other elastomers, compounding plays an important part in tailoring the properties of EPDM to meet the needs of a specific application. Each of the properties of the elastomer can be enhanced or reduced by the addition or deletion of chemicals and fillers. Because of this, the properties discussed must be considered in general terms.

Ethylene-propylene terpolymer is a synthetic hydrocarbon-based rubber produced from an ethylene-propylene terpolymer. It is very similar in physical and mechanical properties to EPDM.

## Physical and Mechanical Properties

It is possible to compound EPDM to provide either higher resilience or higher damping. When compounded to provide high resilience, the products are similar to natural rubber in liveliness and minimum hysteresis values. The energy-absorbing compounds have low resilience values approaching those of specialty elastomers used for shock and vibration damping. Whether the compound has been compounded for resilience or high damping, its properties remain relatively constant over a wide temperature range. As can be seen from Table E.9, a temperature variation of 200°F (110°C) has little effect on the resilience of the compound. The isolation efficiency (based on the percentage of disturbing force transmitted) over a temperature range of 0–180°F (–18–82°C) varies by only 10%. This property is particularly important in vibration isolation applications such as in automotive body mounts.

EPDM exhibits little sensitivity to changes in load. When properly compounded, it has excellent resistance to creep under both static and dynamic conditions.

Flexibility at low temperature is another advantage of this elastomer. Standard compounds have brittle points of –90°F (–68°C) or below. Special compounding can supply material with stiffness values of –90°F (–68°C) and brittle points below –100°F (–73°C).

The electrical properties of EPDM are excellent, particularly for high-voltage insulation. The properties are also stable after long periods of immersion in water. Excellent resistance is also provided against cutting caused by high-voltage corona discharge.

Ethylene-propylene rubber can be produced in any color, including white and pastel shades. The color stability is excellent, with aging characteristics that are available in other elastomers only in black. Since techniques have been developed whereby the material can be painted with permanent waterproof colors, the elastomer can be produced in a black stock providing the maximum physical properties.

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**Table E.9** Physical and Mechanical Properties of Ethylene-Propylene Rubber (EPDM)[a]

| | |
|---|---|
| Specific gravity | 0.85 |
| Specific heat, cal/g | 0.56 |
| Brittle point | –90°F (–68°C) |
| Resilience, % | |
| at 212°F (100°C) | 78 |
| at 75°F (24°C) | 77 |
| at 14°F (–10°C) | 63 |
| Dielectric strength, V/mil | 800 |
| Insulation resistance, megohms/1000 ft | 25,500 |
| Insulation resistance, constant *K*, megohms/1000 ft | 76,400 |
| Permeability to air at 86°F (30°C), $cm^3/cm^2$-cm-s-atm | $8.5 \times 10^{-8}$ |
| Tensile strength, psi | To 3500 |
| Elongation, % at break | 560 |
| Hardness, Shore A | 30–90 |
| Abrasion resistance | Good |
| Maximum temperature, continuous use | 300°F (148°C) |
| Impact resistance | Good |
| Compression set, % | |
| at 158°F (70°C) | 8–10 |
| at 212°F (100°C) | 12–26 |
| Resistance to sunlight | Excellent |
| Effect of aging | Nil |
| Resistance to heat | Excellent |
| Tear resistance | Good |

[a]These are representative values since they may be altered by compounding.

Ethylene-propylene rubber has a relatively high resistance to heat. Standard formulations can be used continuously at temperatures of 250–300°F (121–148°C) in air. In the absence of air, such as in a steam hose lining or cable insulation covered with an outer jacket, higher temperatures can be tolerated. It is also possible by special compounding to produce material that can be used in services up to 350°F (176°C). Standard compounds can be used in intermittent service at 350°F (176°C).

Other advantageous properties of EPDM include good resistance to impact, tearing, abrasion, and cut growth over a wide temperature range. These properties make the elastomer suitable for applications that involve continuous flexing or twisting during operation.

Ethylene-propylene rubber exhibits a low degree of permanent deformation. Table E.9 gives examples of these values. The ranges shown are for both standard and special compounds. In addition, compounds can he supplied that will have a permanent deformation of only 26% after compression at 350°F (176°C).

## Resistance to Sun, Weather, and Ozone

Ethylene-propylene rubber is particularly resistant to sun, weather, and ozone attack. Excellent weather resistance is obtained whether the material is formulated in color,

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white, or black. The elastomer remains free of surface crazing and retains a high percentage of its properties after years of exposure. Ozone resistance is inherent in the polymer, and for all practical purposes it can be considered immune to ozone attack. It is not necessary to add any special compounding ingredients to produce this resistance.

## Chemical Resistance

Ethylene-propylene rubber resists attack from oxygenated solvents such as acetone, methyl ethyl ketone, ethyl acetate, weak acids and alkalies, detergents, phosphate esters, alcohols, and glycols. It exhibits exceptional resistance to hot water and high-pressure steam. The elastomer, being hydrocarbon based, is not resistant to hydrocarbon solvents or oils, chlorinated hydrocarbons, or turpentine. However, by proper compounding, its resistance to oil can be improved to provide adequate service life in many applications where such resistance is required. Ethylene-propylene terpolymer rubbers are in general resistant to most of the same corrodents as EPDM but do not have as broad a resistance to mineral acids and some organics. Table E.10 lists the compatibility of EPDM rubber with selected corrodents.

## Applications

Extensive use is made of ethylene-propylene rubber in the automotive industry. Because of its paintability, this elastomer is used as the gap-filling panel between the grills and the bumper, which provides a durable and elastic element. Under-hood components such as radiator hose, ignition wire insulation, overflow tubing, window washing tubing, exhaust emission control tubing, and various other items make use of EPDM because of its resistance to heat, chemicals, and ozone. Other automotive applications include body mounts, spring mounting pads, miscellaneous body seals, floor mats, and pedal pads. Each application takes advantage of one or more specific properties of the elastomer.

Appliance manufacturers, especially washer manufacturers, have also found wide use for EPDM. Its heat and chemical resistance combined with its physical properties make it ideal for such applications as door seals and cushions, drain and water circulating hoses, bleach tubing, inlet nozzles, boots, seals, gaskets, diaphragms, vibration isolators, and a variety of grommets. The elastomer is also used in dishwashers, refrigerators, ovens, and a variety of small appliances.

Ethylene-propylene rubber finds application in the electrical industry and in the manufacture of electrical equipment. One of the primary applications is as an insulating material. It is used for medium voltage (up to 35 kV) and secondary network power cable, coverings for line and multiplex distribution wire, jacketing and insulation for types S and SJ flexible cords, and insulation for automotive ignition cable.

Accessory items such as molded terminal covers, plugs, transformer connectors, line tap and switching devices, splices, and insulating and semiconductor tape are also produced from EPDM.

Medium- and high-voltage underground power distribution cable insulated with EPDM offers many advantages. It provides excellent resistance to tearing and failure caused by high-voltage contaminants and stress. Its excellent electrical properties make it suitable for high-voltage cable insulation. It withstands heavy corona discharge without sustaining damage.

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**Table E.10** Compatibility of EPDM Rubber with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | 200 | 93 | Barium sulfide | 140 | 60 |
| Acetamide | 200 | 93 | Benzaldehyde | l50 | 66 |
| Acetic acid 10% | 140 | 60 | Benzene | x | x |
| Acetic acid 50% | 140 | 60 | Benzene sulfonic acid 10% | x | x |
| Acetic acid 80% | 140 | 60 | Benzoic acid | x | x |
| Acetic acid, glacial | 140 | 60 | Benzyl alcohol | x | x |
| Acetic anhydride | x | x | Benzyl chloride | x | x |
| Acetone | 200 | 93 | Borax | 200 | 93 |
| Acetyl chloride | x | x | Boric acid | 190 | 88 |
| Acrylonitrile | 140 | 60 | Bromine gas, dry | x | x |
| Adipic acid | 200 | 93 | Bromine gas, moist | x | x |
| Allyl alcohol | 200 | 93 | Bromine liquid | x | x |
| Allyl chloride | x | x | Butadiene | x | x |
| Alum | 200 | 93 | Butyl acetate | 140 | 60 |
| Aluminum fluoride | 190 | 88 | Butyl alcohol | 200 | 93 |
| Aluminum hydroxide | 200 | 93 | Butyric acid | 140 | 60 |
| Aluminum nitrate | 200 | 93 | Calcium bisulfite | x | x |
| Aluminum sulfate | 190 | 88 | Calcium carbonate | 200 | 93 |
| Ammonia gas | 200 | 93 | Calcium chlorate | 140 | 60 |
| Ammonium bifluoride | 200 | 93 | Calcium chloride | 200 | 93 |
| Ammonium carbonate | 200 | 93 | Calcium hydroxide 10% | 200 | 93 |
| Ammonium chloride 10% | 200 | 93 | Calcium hydroxide, sat. | 200 | 93 |
| Ammonium chloride 50% | 200 | 93 | Calcium hypochlorite | 200 | 93 |
| Ammonium chloride, sat. | 200 | 93 | Calcium nitrate | 200 | 93 |
| Ammonium fluoride 10% | 200 | 93 | Calcium oxide | 200 | 93 |
| Ammonium fluoride 25% | 200 | 93 | Calcium sulfate | 200 | 93 |
| Ammonium hydroxide 25% | 100 | 38 | Carbon bisulfide | x | x |
| Ammonium hydroxide, sat. | 100 | 38 | Carbon dioxide, dry | 200 | 93 |
| Ammonium nitrate | 200 | 93 | Carbon dioxide, wet | 200 | 93 |
| Ammonium persulfate | 200 | 93 | Carbon disulfide | 200 | 93 |
| Ammonium phosphate | 200 | 93 | Carbon monoxide | x | x |
| Ammonium sulfate 10–40% | 200 | 93 | Carbon tetrachloride | 200 | 93 |
| Ammonium sulfide | 200 | 93 | Carbonic acid | x | x |
| Amyl acetate | 200 | 93 | Cellosolve | 200 | 93 |
| Amyl alcohol | 200 | 93 | Chloracetic acid | 160 | 71 |
| Amyl chloride | x | x | Chlorine gas, dry | x | x |
| Aniline | 140 | 60 | Chlorine gas, wet | x | x |
| Antimony trichloride | 200 | 93 | Chlorine, liquid | x | x |
| Aqua regia 3:1 | x | x | Chlorobenzene | x | x |
| Barium carbonate | 200 | 93 | Chloroform | x | x |
| Barium chloride | 200 | 93 | Chlorosulfonic acid | x | x |
| Barium hydroxide | 200 | 93 | Chromic acid 50% | x | x |
| Barium sulfate | 200 | 93 | Citric acid 15% | 200 | 93 |

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**Table E.10** Compatibility of EPDM Rubber with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Citric acid, concentrated | 200 | 93 | Methyl chloride | x | x |
| Copper acetate | 100 | 38 | Methyl ethyl ketone | 80 | 27 |
| Copper carbonate | 200 | 93 | Methyl isobutyl ketone | 60 | 16 |
| Copper chloride | 200 | 93 | Nitric acid 5% | 60 | 16 |
| Copper cyanide | 200 | 93 | Nitric acid 20% | 60 | 16 |
| Copper sulfate | 200 | 93 | Nitric acid 70% | x | x |
| Cresol | x | x | Nitric acid, anhydrous | x | x |
| Cupric chloride 5% | 200 | 93 | Oleum | x | x |
| Cupric chloride 50% | 200 | 93 | Perchloric acid 10% | 140 | 60 |
| Cyclohexane | x | x | Phosphoric acid 50–80% | 140 | 60 |
| Cyclohexanol | x | x | Picric acid | 200 | 93 |
| Dichloroethane | | | Potassium bromide 30% | 200 | 93 |
| (ethylene dichloride) | x | x | Salicylic acid | 200 | 93 |
| Ethylene glycol | 200 | 93 | Sodium carbonate | 200 | 93 |
| Ferric chloride | 200 | 93 | Sodium chloride | 140 | 60 |
| Ferric chloride 50% in water | 200 | 93 | Sodium hydroxide 10% | 200 | 93 |
| Ferric nitrate 10–50% | 200 | 93 | Sodium hydroxide 50% | 180 | 82 |
| Ferrous chloride | 200 | 93 | Sodium hydroxide, | | |
| Ferrous nitrate | 200 | 93 | concentrated | 180 | 82 |
| Fluorine gas, moist | 60 | 16 | Sodium hypochlorite 20% | 200 | 93 |
| Hydrobromic acid, dilute | 90 | 32 | Sodium hypochlorite, | | |
| Hydrobromic acid 20% | 140 | 60 | concentrated | 200 | 93 |
| Hydrobromic acid 50% | 140 | 60 | Sodium sulfide to 30% | 200 | 93 |
| Hydrochloric acid 20% | 100 | 38 | Stannic chloride | 200 | 93 |
| Hydrochloric acid 38% | 90 | 32 | Stannous chloride | 200 | 93 |
| Hydrocyanic acid 10% | 200 | 93 | Sulfuric acid 10% | 150 | 66 |
| Hydrofluoric acid 30% | 60 | 16 | Sulfuric acid 50% | 150 | 66 |
| Hydrofluoric acid 70% | x | x | Sulfuric acid 70% | 140 | 60 |
| Hydrofluoric acid 100% | x | x | Sulfuric acid 90% | x | x |
| Hypochlorous acid | 200 | 93 | Sulfuric acid 98% | x | x |
| Iodine solution 10% | 140 | 60 | Sulfuric acid 100% | x | x |
| Ketones. general | x | x | Sulfuric acid, fuming | x | x |
| Lactic acid 25% | 140 | 60 | Toluene | x | x |
| Lactic acid, concentrated | | | Trichloroacetic acid | 80 | 27 |
| Magnesium chloride | 200 | 93 | White liquor | 200 | 93 |
| Malic acid | x | x | Zinc chloride | 200 | 93 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that the data are unavailable.

*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols 1–3. New York: Marcel Dekker, 1995.

Manufacturers of other industrial products take advantage of the heat and chemical resistance, physical durability, ozone resistance, and dynamic properties of EPDM.

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Typical applications include high-pressure steam hose, high-temperature conveyor belting, water and chemical hose, hydraulic hose for phosphate-type liquids, vibration mounts, industrial tires, tugboat and dock bumpers, tank and pump linings, O-rings, gaskets, and a variety of molded products. Standard formulations of EPDM are also used for such consumer items as garden hose, bicycle tires, sporting goods, and tires for garden equipment.

See Refs. 1 and 3.

## ETHYLENE-TETRAFLUOROETHYLENE (ETFE)

This thermoplast is sold under the trade name of Tefzel by DuPont. ETFE is a partially fluorinated copolymer of ethylene and tetrafluoroethylene. It has a maximum service temperature of 300°F (149°C). The physical and mechanical properties are given in Table E.11.

ETFE is inert to strong mineral acids, halogens, inorganic bases, and metal salt solutions. Carboxylic acids, aldehydes, aromatic and aliphatic hydrocarbons, alcohols, aldehydes, ketones, ethers, esters, chlorocarbons, and classic polymer solvents have little effect on Tefzel.

Very strong oxidizing acids such as nitric, and organic bases such as amines and sulfonic acids at high concentrations and near their boiling points will affect ETFE to various degrees. Refer to Table E.12 for the compatibility of ETFE with selected corrodents.

**Table E.11** Physical and Mechanical Properties of ETFE

| | |
|---|---|
| Specific gravity | 1.70 |
| Tensile strength, psi | 6500 |
| Modulus of elasticity, psi $\times 10^5$ | 2.17 |
| Elongation, % | 300 |
| Flexural modulus, psi $\times 10^5$ | 1.7 |
| Impact strength, ft-lb/in. | No break |
| Hardness, Shore D | 67 |
| Water absorption, 24 h at 73°F/2°C, % | $<0.03$ |
| Thermal conductivity, Btu/h/ft$^2$/°F/in. | 1.6 |
| Heat distortion temperature °F/°C | |
| at 66 psi | 220/104 |
| at 264 psi | 160/71 |
| Limiting oxygen index, % | 30 |
| Underwriters lab rating, Sub 94 | V-0 |

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**Table E.12** Compatibility of ETFE with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | 200 | 93 | Barium hydroxide | 300 | 149 |
| Acetamide | 250 | 121 | Barium sulfate | 300 | 149 |
| Acetic acid 10% | 250 | 121 | Barium sulfide | 300 | 149 |
| Acetic acid 50% | 250 | 121 | Benzaldehyde | 210 | 99 |
| Acetic acid 80% | 230 | 110 | Benzene | 210 | 99 |
| Acetic acid, glacial | 230 | 110 | Benzene sulfonic acid 10% | 210 | 99 |
| Acetic anhydride | 300 | 149 | Benzoic acid | 270 | 132 |
| Acetone | 150 | 66 | Benzyl alcohol | 300 | 149 |
| Acetyl chloride | 150 | 66 | Benzyl chloride | 300 | 149 |
| Acrylonitrile | 150 | 66 | Borax | 300 | 149 |
| Adipic acid | 280 | 138 | Boric acid | 300 | 49 |
| Allyl alcohol | 210 | 99 | Bromine gas, dry | 150 | 66 |
| Allyl chloride | 190 | 88 | Bromine water 10% | 230 | 110 |
| Alum | 300 | 149 | Butadiene | 250 | 121 |
| Aluminum chloride, aqueous | 300 | 149 | Butyl acetate | 230 | 110 |
| Aluminum chloride, dry | 300 | 149 | Butyl alcohol | 300 | 149 |
| Aluminum fluoride | 300 | 149 | *n*-Butylamine | 120 | 49 |
| Aluminum hydroxide | 300 | 149 | Butyl phthalate | 150 | 66 |
| Aluminum nitrate | 300 | 149 | Butyric acid | 250 | 121 |
| Aluminum oxychloride | 300 | 149 | Calcium bisulfide | 300 | 149 |
| Aluminum sulfate | 300 | 149 | Calcium carbonate | 300 | 149 |
| Ammonium bifluoride | 300 | 149 | Calcium chlorate | 300 | 149 |
| Ammonium carbonate | 300 | 149 | Calcium chloride | 300 | 149 |
| Ammonium chloride 10% | 300 | 149 | Calcium hydroxide 10% | 300 | 149 |
| Ammonium chloride 50% | 290 | 143 | Calcium hydroxide, sat. | 300 | 149 |
| Ammonium chloride, sat. | 300 | 149 | Calcium hypochlorite | 300 | 149 |
| Ammonium fluoride 10% | 300 | 149 | Calcium nitrate | 300 | 149 |
| Ammonium fluoride 25% | 300 | 149 | Calcium oxide | 260 | 127 |
| Ammonium hydroxide 25% | 300 | 149 | Calcium sulfate | 300 | 149 |
| Ammonium hydroxide, sat. | 300 | 149 | Caprylic acid | 210 | 99 |
| Ammonium nitrate | 230 | 110 | Carbon bisulfide | 150 | 66 |
| Ammonium persulfate | 300 | 149 | Carbon dioxide, dry | 300 | 149 |
| Ammonium phosphate | 300 | 149 | Carbon dioxide, wet | 300 | 149 |
| Ammonium sulfate 10–40% | 300 | 149 | Carbon disulfide | 150 | 66 |
| Ammonium sulfide | 300 | 149 | Carbon monoxide | 300 | 149 |
| Amyl acetate | 250 | 121 | Carbon tetrachloride | 270 | 132 |
| Amyl alcohol | 300 | 149 | Carbonic acid | 300 | 149 |
| Amyl chloride | 300 | 149 | Cellosolve | 300 | 149 |
| Aniline | 230 | 110 | Chloracetic acid, 50% water | 230 | 110 |
| Antimony trichloride | 210 | 99 | Chloracetic acid 50% | 230 | 110 |
| Aqua regia 3:1 | 210 | 99 | Chlorine gas. dry | 210 | 99 |
| Barium carbonate | 300 | 149 | Chlorine gas, wet | 250 | 121 |
| Barium chloride | 300 | 149 | Chlorine, water | 100 | 38 |

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**Table E.12** Compatibility of ETFE with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Chlorobenzene | 210 | 99 | Methyl ethyl ketone | 230 | 110 |
| Chloroform | 230 | 110 | Methyl isobutyl ketone | 300 | 149 |
| Chlorosulfonic acid | 80 | 27 | Muriatic acid | 300 | 149 |
| Chromic acid 10% | 150 | 66 | Nitric acid 5% | 150 | 66 |
| Chromic acid 50% | 150 | 66 | Nitric acid 20% | 150 | 66 |
| Chromyl chloride | 210 | 99 | Nitric acid 70% | 80 | 27 |
| Citric acid 15% | 120 | 49 | Nitric acid, anhydrous | x | x |
| Copper chloride | 300 | 149 | Nitrous acid, concentrated | 210 | 99 |
| Copper cyanide | 300 | 149 | Oleum | 150 | 66 |
| Copper sulfate | 300 | 149 | Perchloric acid 10% | 230 | 110 |
| Cresol | 270 | 132 | Perchloric acid 70% | 150 | 66 |
| Cupric chloride 5% | 300 | 149 | Phenol | 210 | 99 |
| Cyclohexane | 300 | 149 | Phosphoric acid 50–80% | 270 | 132 |
| Cyclohexanol | 250 | 121 | Picric acid | 130 | 54 |
| Dichloroacetic acid | 150 | 66 | Potassium bromide 30% | 300 | 149 |
| Ethylene glycol | 300 | 149 | Salicylic acid | 250 | 121 |
| Ferric chloride 50% in water | 300 | 149 | Sodium carbonate | 300 | 149 |
| Ferric nitrate 10–50% | 300 | 149 | Sodium chloride | 300 | 149 |
| Ferrous chloride | 300 | 149 | Sodium hydroxide 10% | 230 | 110 |
| Ferrous nitrate | 300 | 149 | Sodium hydroxide 50% | 230 | 110 |
| Fluorine gas, dry | 100 | 38 | Sodium hypochlorite 20% | 300 | 149 |
| Fluorine gas. moist | 100 | 38 | Sodium hypochlorite. | | |
| Hydrobromic acid, dilute | 300 | 149 | concentrated | 300 | 149 |
| Hydrobromic acid 20% | 300 | 149 | Sodium sulfide to 50% | 300 | 149 |
| Hydrobromic acid 50% | 300 | 149 | Stannic chloride | 300 | 149 |
| Hydrochloric acid 20% | 300 | 149 | Stannous chloride | 300 | 149 |
| Hydrochloric acid 38% | 300 | 149 | Sulfuric acid 10% | 300 | 149 |
| Hydrocyanic acid 10% | 300 | 149 | Sulfuric acid 50% | 300 | 149 |
| Hydrofluoric acid 30% | 270 | 132 | Sulfuric acid 70% | 300 | 149 |
| Hydrofluoric acid 70% | 250 | 121 | Sulfuric acid 90% | 300 | 149 |
| Hydrofluoric acid 100% | 230 | 110 | Sulfuric acid 98% | 300 | 149 |
| Hypochlorous acid | 300 | 149 | Sulfuric acid 100% | 300 | 149 |
| Lactic acid 25% | 250 | 121 | Sulfuric acid, fuming | 120 | 49 |
| Lactic acid, concentrated | 250 | 121 | Sulfurous acid | 210 | 99 |
| Magnesium chloride | 300 | 149 | Thionyl chloride | 210 | 99 |
| Malic acid | 270 | 132 | Toluene | 250 | 121 |
| Manganese chloride | 120 | 49 | Trichloroacetic acid | 210 | 99 |
| Methyl chloride | 300 | 149 | Zinc chloride | 300 | 149 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols 1–3. New York: Marcel Dekker, 1995.

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## ETHYLENE-TETRAFLUOROETHYLENE (ETFE) ELASTOMER

Ethylene-tetrafluoroethylene (ETFE) is a modified partially fluorinated copolymer of ethylene and polytetrafluoroethylene (PTFE). Since it contains more than 75% TFE by weight, it has better resistance to abrasion and cut-through than TFE while retaining most of the corrosion resistance properties.

### Physical and Mechanical Properties

Ethylene-tetrafluoroethylene has excellent mechanical strength, stiffness, and abrasion resistance, with a service temperature range of –370 to 300°F (–223 to 149°C). It also exhibits good tear resistance and good electrical properties. However, its outstanding property is its resistance to a wide range of corrodents.

The physical and mechanical properties of ETFE are given in Table E.13.

### Resistance to Sun, Weather, and Ozone

Ethylene-tetrafluoroethylene has outstanding resistance to sunlight, ozone, and weather. This feature, coupled with its wide range of corrosion resistance, makes the material particularly suitable for outdoor applications subject to atmospheric corrosion.

### Chemical Resistance

Ethylene tetrafluoroethylene is inert to strong mineral acids, inorganic bases, halogens, and metal salt solutions. Even carboxylic acids, anhydrides, aromatic and aliphatic hydrocarbons, alcohols, aldehydes, ketones, ethers, esters, chlorocarbons, and classic polymer solvents have little effect on ETFE.

**Table E.13** Physical and Mechanical Properties of ETFE Elastomer[a]

| | |
|---|---|
| Specific gravity | 1.7 |
| Hardness range, Rockwell | R-50 to D-75 |
| Tensile strength, psi | 6500 |
| Elongation, % at break | 100–400 |
| Tear resistance | Good |
| Maximum temperature, continuous use | 300°F (149°C) |
| Brittle point | –150°F (–101°C) |
| Water absorption, %/24 h | 0.029 |
| Abrasion resistance | Good |
| Volume resistivity, ohm-cm | $>10^{16}$ |
| Dielectric strength, kV/mm | 16 (3 mm) |
| Dielectric constant ($10^{-3}$ to $10^{6}$ Hz range) | 2.6 |
| Dissipation (power) factor | $8 \times 10^{-4}$ |
| Resistance to sunlight | Excellent |
| Resistance to heat | Good |
| Machining qualities | Good |

[a]These are representative values since they may be altered by compounding.

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Very strong oxidizing acids near their boiling points, such as nitric acid at high concentration, will affect ETFF in varying degrees, as will organic bases such as amines and sulfonic acids. Refer to Table E.12 for the compatibility of ETFE with selected corrodents.

### Applications

The principal applications for ETFE are found in such products as gaskets, packings, and seals O-rings, lip, and X-rings) in areas where corrosion is a problem. The material is also used for sleeve, split curled, and thrust bearings, and for bearing pads for pipe and equipment support where expansion and contraction or movement may occur.

## EXFOLIATION CORROSION

When intergranular corrosion takes place in a metal with a highly directional grain structure, it propagates internally, parallel to the surface of the metal. The corrosion product formed is about five times as voluminous as the metal consumed, and it is trapped beneath the surface. As a result, an internal stress is produced that splits off the overlying layers of metal—hence the name exfoliation.

This is a dangerous form of corrosion, since the splitting off of uncorroded metal rapidly reduces load-carrying ability. The splitting action continually exposes film-free metal, so the rate of corrosion is not self-limiting.

Exfoliation corrosion is mostly found in certain alloys and tempers of aluminum, particularly in areas of high chloride content such as de-icing salts and seacoast atmospheres. In these applications an aluminum with a resistant temper should be used.

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# F

## FERRITE

Pure iron when heated to 1670°F (910°C) changes its internal crystalline structure from a body-centered cubic arrangement of atoms, alpha iron, to a face-centered cubic structure, gamma iron. At 2535°F (1393°C) it changes back to the body-centered cubic structure, delta iron, and at 2802°F (1538°C) the iron melts. When carbon is added to iron, it is found that it has only slight solid solubility in alpha iron (less than 0.001 percent at room temperature). On the other hand, gamma iron will hold up to 2.0% carbon in solution at 2066°F (1129°C). The alpha iron containing carbon or any other element in solid solution is called ferrite. Usually when not in solution in the iron the carbon forms a compound $Fe_3C$ (iron carbide), which is extremely hard and brittle and is known as cementite. The physical properties of the ferrite are approximately that of pure iron and are characteristic of the metal. The presence of cementite does not in itself cause steel to be hard, but rather it is the shape and distribution of the carbides in the iron that determine the hardness of the steel.

Since ferrite does not contain enough carbon to permit the formation of martensite, it cannot be hardened by heat treatment. Therefore, steels composed of only ferrite are not hardenable by heat treatment.

The generic term ferritic steel is used to refer to carbon or low-alloy steels that contain other phases in addition to ferrite. These steels are usually hardenable by heat treatment.

## FERRITIC STAINLESS STEELS

The ferritic stainless steels are the simplest of the stainless steel family of alloys since they are principally iron–chromium alloys. They are magnetic, have body-centered cubic structures, and possess mechanical properties similar to those of carbon steel, though less ductile. Refer to Table F.1 for the physical and mechanical properties of ferritic stainless steels.

This class of alloys usually contains 15–18% chromium, although they can go as low as 11% in special cases, under the influence of other alloying elements, or as high as 30%. Continued additions of chromium will improve corrosion resistance in severe environments. Chromium additions are particularly beneficial in terms of resistance in oxidizing environments, at both moderate and elevated temperatures. Addition of chromium is the most cost-effective means of increasing corrosion resistance of steel.

These materials are historically known as 400 series stainless as they were identified with numbers beginning with 400 when the American Institute for Iron and Steel (AISI) had the authority to designate alloy compositions. Under the new UNS system, the old three-digit numbers were retained, such as the old 405, a basic 12% chromium, balance iron material, which is now S40500.



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**Table F.1** Physical and Mechanical Properties of Ferritic Stainless Steels

| Property | Type of alloy | | |
|---|---|---|---|
| | 430 | 444 | XM-27 |
| Modulus of elasticity $\times 10^6$ | 29 | 29 | |
| Tensile strength $\times 10^3$, psi | 60 | 60 | 70 |
| Yield strength 0.2% offset $\times 10^3$, psi | 35 | 40 | 56 |
| Elongation in 2 in., % | 20 | 20 | 30 |
| Hardness, Brinell | B-165 | 217 | Rock. B-83 |
| Density, lb/in.$^3$ | 0.278 | 0.28 | 0.28 |
| Specific gravity | 7.75 | 7.75 | 7.66 |
| Specific heat (32–212°F), Btu/lb°F | 0.11 | 0.102 | 0.102 |
| Thermal conductivity, Btu/lb°F | | | |
| at 70°F (20°C) | 15.1 | 17.5 | |
| at 1500°F (815°C) | 15.2 | | |
| Thermal expansion coefficient (32–212°F) $10^{-6}$ in./in.°F | 6.0 | 6.1 | 5.9 |

Corrosion resistance is rated good, although ferritic alloys do not resist reducing acids, such as hydrochloric. Mildly corrosive conditions and oxidizing media are handled satisfactorily. Type 403 finds wide application in nitric acid plants. Increasing the chromium content to 24% and 30% improves the resistance to oxidizing conditions at elevated temperatures. These alloys are useful for all types of furnace parts not subject to high stress.

Ferritic stainless steels offer useful resistance to mild atmospheric corrosion and most fresh waters. They will corrode with exposure to seawater atmospheres.

## Type 405 (S40500)

Type 405 stainless is designed for use in the as-welded condition; however, heat treatment improves corrosion resistance. The chemical composition is given in Table F.2.

This alloy is resistant to nitric acid, organic acids, and alkalies. It will be attacked by sulfuric, hydrochloric, hydrofluoric, and phosphoric acids as well as seawater. It is resistant to chloride stress corrosion cracking.

**Table F.2** Chemical Composition of Ferritic Stainless Steels

| AISI type | Nominal composition (%) | | | | |
|---|---|---|---|---|---|
| | C max. | Mn max. | Si max. | Cr | Other[a] |
| 405 | 0.08 | 1.00 | 1.00 | 11.50–14.50 | 0.10–0.30 Al |
| 430 | 0.12 | 1.00 | 1.00 | 14.00–18.00 | |
| 430F | 0.12 | 1.25 | 1.00 | 14.00–18.00 | 0.15 S min. |
| 430(Se) | 0.12 | 1.25 | 1.00 | 14.00–18.00 | 0.15 Se min. |
| 444 | 0.025 | 1.00 | 1.00 max. | 17.5–19.5 | 1.75–2.50 Mo |
| 446 | 0.20 | 1.50 | 1.00 | 23.00–17.00 | 0.25 max. N |
| XM–27[b] | 0.002 | 0.10 | 0.20 | 26.00 | |

[a]Elements in addition to those shown are as follows: phosphorus–0.06% max. in types 430F and 430(Se), 0.0 15% in XM-27; sulfur–0.03% max. in types 405, 430, 444, and 446, 0.15% min. type 430F, 0.01% in XM-27; nickel–1.00% max. in type 444, 0.15% in XM-27; titanium + niobium–0.80% max. in type 444; copper–0.02% in XM-27; nitrogen–0.010% in XM-27.
[b]E-Brite 26-1 Trademark of Allegheny Ludlum Industries Inc.

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Applications include heat exchanger tubes in the refining industry and other areas where exposure may result in the 885°F (475°C) or sigma temperature range. It has an allowable maximum continuous operating temperature of 1300°F (705°C) with an intermittent allowable temperature of 1500°F (815°C).

### Type 409 (S40900)

This is an 11% chromium alloy stabilized with titanium. It has the following composition:

| Chemical | Weight Percent |
|---|---|
| Carbon | 0.08 |
| Manganese | 1 |
| Silicon | 1 |
| Chromium | 10.5–11.75 |
| Nickel | 0.5 |
| Phosphorus | 0.045 |
| Sulfur | 0.045 |
| Titanium | 0.6 × % Cr min. to 0.75% max |
| Iron | Balance |

The primary application for alloy 409 is in the automotive industry as mufflers, catalytic converters, and tailpipes. It has proven an attractive replacement for carbon steel because it combines economy and good resistance to oxidation and corrosion.

### Type 430 (S43000)

This is the most widely used of the ferritic stainless steels. The chemical composition will be found in Table F.2. In continuous service, type 430 may be operated to a maximum temperature of 1500°F (815°C) and 1600°F (870°C) in intermittent service. However, it is subject to 885°F (475°C) embrittlement and loss of ductility at subzero temperatures.

Type 430 stainless is resistant to chloride stress corrosion cracking and elevated sulfide attack. Applications are found in nitric acid services, water and food processing, automobile trim, heat exchangers in petroleum and chemical processing industries, reboilers for desulfurized naphtha, heat exchangers in sour water strippers, and hydrogen plant effluent coolers. The compatibility of type 430 stainless steel with selected corrodents is provided in Table F.3.

Stainless steel type 430F is a modification of type 430. The carbon content is reduced to 0.065%, manganese to 0.80%, and silicon to 0.3–0.7% while 0.5% molybdenum and 0.60% nickel have been added. This is an alloy used extensively in solenoid armatures and top plugs. It has also been used in solenoid cores and housings operating in corrosive atmospheres.

Type 430F stainless should be considered when making machined articles from a 17% chromium steel. The composition has been altered by increasing the manganese content to 1.25% and the phosphorus content to 0.06%, with the sulfur content at 0.15% minimum and the addition of 0.60% molybdenum. This material will not harden by heat treatment. It has been used in automatic screw machines for parts requiring good corrosion resistance such as aircraft parts and gears.

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**Table F.3** Compatibility of Ferritic Stainless Steels with Selected Corrodents[a]

| Chemical | 430 (°F/°C) | 444 (°F/°C) | XM-27 (°F/°C) |
|---|---|---|---|
| Acetaldehyde | | | |
| Acetamide | | | |
| Acetic acid 10% | 70/21 | 200/93 | 200/93 |
| Acetic acid 50% | x | 200/93 | 200/93 |
| Acetic acid 80% | 70/21 | 200/93 | 130/54 |
| Acetic acid, glacial | 70/21 | | 140/60 |
| Acetic anhydride 90% | 150/66 | | 300/149 |
| Aluminum chloride, aqueous | x | | 110/43 |
| Aluminum hydroxide | 70/21 | | |
| Aluminum sulfate | x | | |
| Ammonia gas | 212/100 | | |
| Ammonium carbonate | 70/21 | | |
| Ammonium chloride 10% | | | 200/93 |
| Ammonium hydroxide 25% | 70/21 | | |
| Ammonium hydroxide, sat. | 70/21 | | |
| Ammonium nitrate | 212/100 | | |
| Ammonium persulfate | 70/21 | | |
| Ammonium phosphate | 70/21 | | |
| Ammonium sulfate 10–40% | x | | |
| Amyl acetate | 70/21 | | |
| Amyl chloride | x | | |
| Aniline | 70/21 | | |
| Antimony trichloride | x | | |
| Aqua regia 3:1 | | | x |
| Barium carbonate | 70/21 | | |
| Barium chloride | 70/21[b] | | |
| Barium sulfate | 70/21 | | |
| Barium sulfide | 70/21 | | |
| Benzaldehyde | | | 210/99 |
| Benzene | 70/21 | | |
| Benzoic acid | 70/21 | | |
| Borax 5% | 200/93 | | |
| Boric acid | 200/93[a] | | |
| Bromine gas, dry | x | | |
| Bromine gas, moist | x | | |
| Bromine liquid | x | | |
| Butyric acid | 200/93 | | |
| Calcium carbonate | 200/93 | | |
| Calcium chloride | x | | |
| Calcium hypochlorite | x | | |
| Calcium sulfate | 70/21 | | |
| Carbon bisulfide | 70/21 | | |
| Carbon dioxide, dry | 70/21 | | |
| Carbon monoxide | 1600/871 | | |
| Carbon tetrachloride, dry | 212/100 | | |

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**Table F.3** Compatibility of Ferritic Stainless Steels with Selected Corrodents[a] (Continued)

| Chemical | 430 (°F/°C) | 444 (°F/°C) | XM-27 (°F/°C) |
|---|---|---|---|
| Carbonic acid | x | | |
| Chloracetic acid, 50% water | x | | |
| Chloracetic acid | x | | |
| Chlorine gas, dry | x | | |
| Chlorine gas, wet | x | | |
| Chloroform, dry | 70/21 | | |
| Chromic acid 10% | 70/21 | | 120/49 |
| Chromic acid 50% | x | | x |
| Chromyl chloride | | | |
| Citric acid 15% | 70/21 | 200/93 | 200/93 |
| Citric acid, concentrated | x | | |
| Copper acetate | 70/21 | | |
| Copper carbonate | 70/21 | | |
| Copper chloride | x | | x |
| Copper cyanide | 212/100 | | |
| Copper sulfate | 212/100 | | |
| Cupric chloride 5% | x | | |
| Cupric chloride 50% | x | | |
| Ethylene glycol | 70 /21 | | |
| Ferric chloride | x | | 80/27 |
| Ferric chloride 10% in water | | | 75/25 |
| Ferric nitrate 10–50% | 70/21 | | |
| Ferrous chloride | x | | |
| Ferrous nitrate | | | |
| Fluorine gas. dry | x | | |
| Fluorine gas, moist | x | | |
| Hydrobromic acid, dilute | x | | |
| Hydrobromic acid 20% | x | | |
| Hydrobromic acid 50% | x | | |
| Hydrochloric acid 20% | x | | |
| Hydrochloric acid 38% | x | | |
| Hydrocyanic acid 10% | x | | |
| Hydrofluoric acid 30% | x | | x |
| Hydrofluoric acid 70% | x | | x |
| Hydrofluoric acid 100% | x | | x |
| Iodine solution 10% | x | | |
| Lactic acid 20% | x | 200/93 | 200/93 |
| Lactic acid, concentrated | x | | |
| Magnesium chloride | | | 200/93 |
| Malic acid | 200/93 | | |
| Muriatic acid | x | | |
| Nitric acid 5% | 70/21 | 200/93 | 320/160 |
| Nitric acid 20% | 200/93 | 200/93 | 320/160 |
| Nitric acid 70% | 70/21 | x | 210/99 |
| Nitric acid, anhydrous | x | x | |
| Nitrous acid 5% | 70/21 | | |

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**Table F.3** Compatibility of Ferritic Stainless Steels with Selected Corrodents[a] (Continued)

| Chemical | 430 (°F/°C) | 444 (°F/°C) | XM-27 (°F/°C) |
|---|---|---|---|
| Phenol | 200/93 | | |
| Phosphoric acid 50–80% | x | 200/93 | 200/93 |
| Picric acid | x | | |
| Silver bromide 10% | x | | |
| Sodium chloride | 70/21[b] | | |
| Sodium hydroxide 10% | 70/21 | 212/100 | 200/93 |
| Sodium hydroxide 50% | | x | 180/82 |
| Sodium hydroxide, concentrated | | x | |
| Sodium hypochlorite 30% | | | 90/32 |
| Sodium sulfide to 50% | x | | |
| Stannic chloride | x | | |
| Stannous chloride 10% | | | 90/32 |
| Sulfuric acid 10% | x | x | x |
| Sulfuric acid 50% | x | x | x |
| Sulfuric acid 70% | | x | x |
| Sulfuric acid 90% | | x | x |
| Sulfuric acid 98% | | x | 280/138 |
| Sulfuric acid 100% | 70/21 | x | |
| Sulfuric acid, fuming | | x | |
| Sulfurous acid 5% | x | | 360/182 |
| Thionyl chloride | | | |
| Toluene | | | 210/99 |
| Trichloroacetic acid | x | | |
| White liquor | | | |
| Zinc chloride 20% | 70/21[b] | | 200/93 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable. When compatible, the corrosion rate is < 20 mpy.
[b]Pitting may occur.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3 New York: Marcel Dekker, 1995.

Type 430FR alloy has the same chemical composition as type 430F except for increasing the silicon content to 1.00–1.50%. This alloy is used for solenoid valve magnetic core components, which must combat corrosion from atmospheric fresh water and corrosive environments.

## Type 439L (S43035)

The composition of this alloy is as follows:

| Chemical | Weight Percent |
|---|---|
| Carbon | 0.07 max. |
| Manganese | 1.00 max. |
| Silicon | 1.00 max. |
| Chromium | 17.0–19.0 |
| Nitrogen | 0.50 |
| Titanium | 12 × % C min. |
| Aluminum | 0.15 max. |

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This alloy resists intergranular attack and formation of martensite in the as-welded heat-affected zone but is subject to 885°F (475°C) embrittlement.

Alloy 439L is resistant to chloride stress corrosion, organic acids, alkalies, and nitric acid. It will be attacked by sulfuric hydrochloric, hydrofluoric, and phosphoric acids, as well as seawater.

Applications include heat exchangers, condensers, feedwater heaters, tube oil coolers, and moisture separator reheaters.

### Type 444 (S44400)

The chemical composition of this alloy will be found in Table F.2. This is a low-carbon alloy with molybdenum added to improve chloride pitting resistance. It is virtually immune to chloride stress corrosion cracking. The alloy is subject to 885°F (475°C) embrittlement and loss of ductility at subzero temperatures.

The chloride pitting resistance of this alloy is similar to that of types 430 and 439L. Like all ferritic stainless steels, type 444 series relies on a passive film to resist corrosion but exhibits rather high corrosion rates when activated. This characteristic explains the abrupt transition in corrosion rates that occur at particular acid concentrations. For example, it is resistant to very dilute solutions of sulfuric acid at boiling temperature but corrodes rapidly at higher concentrations. The corrosion rates of type 444 in strongly concentrated sodium hydroxide solutions are also higher than those for austenitic stainless steels. The compatibility of type 444 alloy with selected corrodents will be found in Table F.3. In general, the corrosion rate of type 444 is considered equal to that of type 304 stainless steel.

This alloy is used for heat exchangers in chemical, petroleum, and food processing industries as well as piping.

### Type 446 (S44600)

Type 446 is a heat-resisting grade of ferritic stainless steel. It has a maximum temperature rating of 2000°F (1095°C) for continuous service and a maximum temperature rating of 2150°F (1175°C) for intermittent service. The chemical composition will be found in Table F.2.

This nonhardenable chromium steel exhibits good resistance to reducing sulfurous gases and fuel-ash corrosion. It also has good general corrosion in mild atmospheric environments, fresh water, mild chemicals, and mild oxidizing conditions.

Applications include furnace parts, kiln linings, and annealing boxes.

See Refs. 2 and 3.

## FIBERGLASS

Fiberglass was developed during and immediately after World War II. Fiberglass is made by a number of different processes, such as melt spinning or by drawing from a marble. At the present time E and C glass predominate, which are boroaluminosilicate and aluminosilicate glass, respectively. The major use is as a reinforcing material for various plastic resins. To improve adhesion of these glasses to resins, various so-called binders have been developed, the most common of which are the silanes.

Also refer to "Thermoset Reinforcing Materials."

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## FIBER-REINFORCED PLASTICS (COMPOSITES)

Plastic resins, particularly the thermosets, require some type of reinforcing material to provide strength and stability. Reinforcement is also used with thermoplasts on occasion to provide additional strength.

Many types of fibers are used as reinforcing materials, with glass being the predominant material used. Other materials used include carbon, boron, silicon carbide, polyester fibers, and aramid fibers. It is essential that the polymer and reinforcing fiber both be resistant to the chemical being handled and that they both be suitable for use at the maximum temperature desired.

Additional information can be found by referring to the specific fiber and resin.

## FILIFORM CORROSION

Metals with semipermeable coatings or films may undergo a type of corrosion resulting in numerous meandering threadlike filaments of corrosion beneath the coatings or films. The essential conditions for this form of corrosion to develop are generally high humidity (65% to 95% relative humidity at room temperature), sufficient water permeability of the film, stimulation by impurities, and the presence of film defects (mechanical damage, pores, insufficient coverage of localized areas, air bubbles, salt crystals, or dust particles).

The threadlike filaments of corrosion spread in a zigzag manner. The filaments are 0.1 to 0.5 mm wide and grow steadily but do not cross each other. Each filament has an active head and inactive tail. If an advancing head meets another filament, it gets diverted and starts growing in another direction.

Filiform corrosion has been observed on aluminum, steel, zinc, and magnesium, usually under organic coatings such as paints and lacquers. It has also been found under tin, enamel, and phosphate coatings. The attack does not damage the metal to any great extent, but the coated surface loses its appearance.

On steel the tail is usually red-brown and the head blue, indicating the presence of $Fe_2O_3$ or $Fe_2O_3\,nH_2O$ at the tail and $Fe^{2+}$ ions in the head as corrosion product. The growth mechanism is explained by the formation of a differential aeration cell. The head absorbs water from the atmosphere because of the presence of a relatively concentrated solution of ferrous salts, and hydrolysis creates an acidic environment (pH 1–4). Oxygen that diffuses through the film tends to accumulate more at the interface between the head and tail. Lateral diffusion of oxygen serves to keep the main portion of the filament cathodic to the head.

Filiform corrosion can be prevented by reducing the relative humidity of the environment to below 65%. Films having a very low water permeability will also provide protection.

See Refs. 1 and 4.

## FLUOREL

See “Fluoroelastomers.”

## FLUOROELASTOMERS (FKM)

Fluoroelastomers are fluorine-containing hydrocarbon polymers with a saturated structure obtained by polymerizing fluorinated monomers such as vinylidene fluoride, hexafluoroprene,

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and tetrafluoroethylene. The result is a high-performance synthetic rubber with exceptional resistance to oils and chemicals at elevated temperatures. Initially this material was used to produce O-rings for use in severe conditions. Although this remains a major area of application, these compounds have found wide use in other applications because of their chemical resistance at high temperatures and other desirable properties.

As with other rubbers, fluoroelastomers are capable of being compounded with various additives to enhance specific properties for particular applications. Fluoroelastomers are suitable for all rubber processing applications, including compression molding, injection molding, injection/compression molding, transfer molding, extrusion, calendering, spreading, and dipping.

These compounds possess the rapid recovery from deformation, or resilience, of a true elastomer and exhibit mechanical properties of the same order of magnitude as those of conventional synthetic rubbers.

Fluoroelastomers are manufactured under various trade names by different manufacturers. Three typical materials are listed below.

| Trade name | Manufacturer |
|---|---|
| Viton | DuPont |
| Technoflon | Ausimont |
| Fluorel | 3M |

These elastomers have the ASTM designation of FKM.

## Physical and Mechanical Properties

The general physical and mechanical properties of fluoroelastomers are similar to those of other synthetic rubbers. General-purpose compounds have a hardness of 70–75 Shore A. Formulations are produced that have hardnesses ranging from 45 to 95 Shore A. At elevated temperatures, 250–500°F(121–260°C), hardness may decrease by 5–15 points depending upon the polymer and the formulation. These variations must he taken into account when specifying hardness of products to be used at elevated temperatures.

Fluoroelastomer compounds have good tensile strengths, ranging from 188 to 2900 psi. In general, the tensile strength of any elastomer tends to decrease at elevated temperatures; however, this loss in tensile strength is much less with the fluoroelastomers. Percent elongation at break is an indication of operating life. A high percentage is essential when high resistance to bending stress is required for the application. These elastomers have a range of 100–400%. The ability of fluoroelastomers to recover their original dimension after compression and their exceptional thermal resistance make it possible to fabricate cured items with very low set compression values even under the most severe operating conditions. These values become even more meaningful at elevated temperatures when it is realized that most rubbers have a maximum service temperature of less than 250°F (121°C). Table F.4 lists the physical and mechanical properties of the fluoroelastomers.

The resilience of the fluoroelastomers makes them suitable for application as vibration isolators at elevated temperatures and as vibration dampers (energy absorbers) at room temperature. In the latter case, because of cost, they would normally be used only

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**Table F.4** Physical and Mechanical Properties of Fluoroelastomers[a]

| | |
|---|---|
| Specific gravity | 1.8 |
| Specific heat | 0.395 |
| Brittle point | –25 to –75°F (–32 to –59°C) |
| Coefficient of linear expansion | $88 \times 10^{-6}$/°F, $16 \times 10^{-5}$/°C |
| Thermal conductivity | |
| Btu-in./h-ft$^2$ °F at 100°F | 1.58 |
| kg-cal/cm-cm$^2$-°C-h at 38°C | 1.96 |
| Electrical properties | |
| Dielectric constant at 1000 Hz | |
| at 75°F (24°C) | 10.5 |
| at 300°F (149°C) | 7.1 |
| at 390°F (199°C) | 9.1 |
| Dissipation factor at 1000 Hz | |
| at 75°F (24°C) | 0.034 |
| at 300°F (149°C) | 0.273 |
| at 390°F (199°C) | 0.39–1.19 |
| Permeability, cm$^3$ /cm$^2$-cm-sec-atm | |
| at 75°F (24°C) | |
| to air | $0.0099 \times 10^{-7}$ |
| to helium | $0.892 \times 10^{-7}$ |
| to nitrogen | $0.0054 \times 10^{-7}$ |
| at 86°F (30°C) | |
| to carbon dioxide | $0.59 \times 10^{-7}$ |
| to oxygen | $0.11 \times 10^{-7}$ |
| Tensile strength, psi | 1800–2900 |
| Elongation, % at break | 400 |
| Hardness, Shore A | 45–95 |
| Abrasion resistance | Good |
| Maximum temperature, continuous use | 400°F (205°C) |
| Compression set, % | |
| at 70°F (21°C) | 21 |
| at 300°F (149°C) | 32 |
| at 392°F (200°C) | 98 |
| Tear resistance | Good |
| Resistance to sunlight | Excellent |
| Effect of aging | Nil |
| Resistance to heat | Excellent |

[a]These are representative values since they may be altered by compounding.

in extremely corrosive atmospheres. These rubbers can be applied as coatings to fabrics or adhered to a variety of metals to provide fluid resistance to the substrate.

The temperature resistance of the fluoroelastomers is exceptionally good over a wide temperature range. At high temperatures their mechanical properties are retained better than those of any other elastomer. Compounds remain usefully elastic indefinitely when exposed to aging up to 400°F (204°C). Continuous service limits are generally considered to be as in the table.

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| |
|---|
| 3000 h at 450°F (232°C) |
| 1000 h at 500°F (260°C) |
| 240 h at 550°F (288°C) |
| 48 h at 600°F (313°C) |

On the low-temperature side, these rubbers are generally serviceable in dynamic applications down to –10°F (–23°C). Flexibility at low temperature is a function of the material thickness The thinner the cross-section, the less stiff the material is at every temperature. The brittle point at a thickness of 0.075 in. (1.9 mm) is in the neighborhood of –50°F (–45°C). This temperature can have a range of –25° to –75°F (–32 to –59°C) depending upon the thickness and hardness of the material. Fluoroelastomers are relatively impermeable to air and gases, ranking about midway between the best and the poorest elastomers in this respect. This permeability can he modified considerably by the way they are compounded. In all cases permeability increases rapidly with increasing temperature. Table F.4 provides some data on the permeability of the fluoroelastomers.

Being halogen-containing polymers, these elastomers are more resistant to burning than are exclusively hydrocarbon rubbers. Normally compounded material will burn when directly exposed to flame but will stop burning when the flame is removed. Natural rubber and synthetic hydrocarbon rubbers under the same conditions will continue to burn when the flame is removed. However, it must be remembered that under an actual fire condition fluoroelastomers will burn. During combustion, fluorinated products such as hydrofluoric acid can be given off. Special compounding can improve the flame resistance. One such formulation has been developed for the space program that will not ignite under conditions of the NASA test, which specifies 100% oxygen at 6.2 psi absolute.

The fluoroelastomers will increase in stiffness and hardness when exposed to gamma radiation from a cobalt-60 source. For dynamic applications, radiation exposure should not exceed $1 \times 10^7$ roentgens. Higher dosages are permissible for static applications. There is no evidence of radiation-induced stress cracking. There are other elastomers that exhibit superior radiation resistance. However, high temperatures are frequently encountered along with exposure to radiation, and in many cases these elevated temperatures will rule out the more radiation-resistant elastomers.

Fluoroelastomers are particularly recommended when resistance to ozone, high temperatures, or highly corrosive fluids is required in addition to radiation resistance.

The dielectric properties of the fluoroelastomers permit them to be used as insulating materials at low tension and frequency in high-temperature applications and in the presence of higher concentrations of ozone and highly aggressive chemicals. The values of the individual properties can be greatly influenced by formulation but are generally in the following ranges:

| | |
|---|---|
| Direct current resistivity | $2 \times 10^{13}$ ohm-cm |
| Dielectric constant | 10–15 |
| Dissipation factor | 0.01–0.05 |
| Dielectric strength | 500 V/mil (2000 V/mm) |

Fluoroelastomers have been approved by the U.S. Food and Drug Administration for use in repeated contact with food products. More details are available in the Federal Register Vol. 33, No. 5, Tuesday, January 9, 1968, Part 121—Food Additives, Subpart

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F—Food Additives Resulting from Contact with Containers or Equipment and Food Additives Otherwise Affecting Food—Rubber Articles Intended for Repeated Use.

The biological resistance of fluoroelastomers is excellent. A typical compound tested against specification MIL E-5272C showed no fungus growth for 30 days. This specification covers four common fungus groups.

## Resistance to Sun, Weather, and Ozone

Because of their chemically saturated structure, the fluoroelastomers exhibit excellent weathering resistance to sunlight and especially to ozone. After 13 years of exposure in Florida in direct sunlight, samples showed little or no change in properties or appearance. Similar results were experienced with samples exposed to various tropical conditions in Panama for a period of 10 years. Products made of this elastomer are unaffected by ozone concentrations as high as 100 ppm. No cracking occurred in a bent loop test after one year exposure to 100 ppm of ozone in air at 100°F (38°C) or in a sample held at 356°F (180°C) for several hundred hours. This property is particularly important considering that standard tests, such as in the automotive industry, require resistance to only 0.5 ppm ozone.

## Chemical Resistance

The fluoroelastomers provide excellent resistance to oils, fuels, lubricants, most mineral acids, many aliphatic and aromatic hydrocarbons (carbon tetrachloride, benzene, toluene, xylene) that act as solvents for other rubbers, gasoline, naphtha, chlorinated solvents, and pesticides. Special formulations can be produced to obtain resistance to hot mineral acids, steam, and hot water.

These elastomers are not suitable for use with low-molecular-weight esters and ethers, ketones, certain amines, or hot anhydrous hydrofluoric or chlorosulfonic acids. Their solubility in low-molecular-weight ketones is an advantage in producing solution coatings of fluoroelastomers. Table F.5 provides the compatibility of fluoroelastomers with selected corrodents.

## Applications

The main applications for the fluoroelastomers are in those products requiring resistance to high operating temperatures together with high chemical resistance to aggressive fluids and to those characterized by severe operating conditions that no other elastomer can withstand. By proper formulation, cured items can he produced that will meet the rigid specifications of the industrial, aerospace, and military communities.

Recent changes in the automotive industry that have required reduction in environmental pollution, reduced costs, energy saving, and improved reliability have resulted in higher operating temperatures, which in turn require a higher-performance elastomer. The main innovations resulting from these requirements are

Turbocharging
More compact, more efficient, and faster engines
Catalytic exhausts
Cx reduction
Soundproofing

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**Table F.5** Compatibility of Fluoroelastomers with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | x | x | Barium hydroxide | 400 | 204 |
| Acetamide | 210 | 199 | Barium sulfate | 400 | 204 |
| Acetic acid 10% | 190 | 88 | Barium sulfide | 400 | 204 |
| Acetic acid 50% | 180 | 82 | Benzaldehyde | x | x |
| Acetic acid 80% | 180 | 82 | Benzene | 400 | 204 |
| Acetic acid, glacial | x | x | Benzene sulfonic acid 10% | 190 | 88 |
| Acetic anhydride | x | x | Benzoic acid | 400 | 204 |
| Acetone | x | x | Benzyl alcohol | 400 | 204 |
| Acetyl chloride | 400 | 204 | Benzyl chloride | 400 | 204 |
| Acrylic acid | x | x | Borax | 190 | 88 |
| Acrylonitrile | x | x | Boric acid | 400 | 204 |
| Adipic acid | 190 | 88 | Bromine gas, dry, 25% | 180 | 82 |
| Allyl alcohol | 190 | 88 | Bromine gas, moist, 25% | 180 | 82 |
| Allyl chloride | 100 | 38 | Bromine liquid | 350 | 177 |
| Alum | 190 | 88 | Butadiene | 400 | 204 |
| Aluminum acetate | 180 | 82 | Butyl acetate | x | x |
| Aluminum chloride, aqueous | 400 | 204 | Butyl alcohol | 400 | 204 |
| Aluminum fluoride | 400 | 204 | *n*-Butylamine | x | x |
| Aluminum hydroxide | 190 | 88 | Butyl phthalate | 80 | 27 |
| Aluminum nitrate | 400 | 204 | Butyric acid | 120 | 49 |
| Aluminum oxychloride | x | x | Calcium bisulfide | 400 | 204 |
| Aluminum sulfate | 390 | 199 | Calcium bisulfite | 400 | 204 |
| Ammonia gas | x | x | Calcium carbonate | I90 | 88 |
| Ammonium bifluoride | 140 | 60 | Calcium chlorate | 190 | 88 |
| Ammonium carbonate | 190 | 88 | Calcium chloride | 300 | 149 |
| Ammonium chloride 10% | 400 | 204 | Calcium hydroxide 10% | 300 | 149 |
| Ammonium chloride 50% | 300 | 149 | Calcium hydroxide, sat. | 400 | 204 |
| Ammonium chloride, sat. | 300 | 149 | Calcium hypochlorite | 400 | 204 |
| Ammonium fluoride 10% | 140 | 60 | Calcium nitrate | 400 | 204 |
| Ammonium fluoride 25% | 140 | 60 | Calcium sulfate | 200 | 93 |
| Ammonium hydroxide 25% | 190 | 88 | Carbon bisulfide | 400 | 204 |
| Ammonium hydroxide, sat. | 190 | 88 | Carbon dioxide, dry | 80 | 27 |
| Ammonium nitrate | x | x | Carbon dioxide, wet | x | x |
| Ammonium persulfate | 140 | 60 | Carbon disulfide | 400 | 204 |
| Ammonium phosphate | 180 | 82 | Carbon monoxide | 400 | 204 |
| Ammonium sulfate 10–40% | 180 | 82 | Carbon tetrachloride | 350 | 177 |
| Ammonium sulfide | x | x | Carbonic acid | 400 | 204 |
| Amyl acetate | x | x | Cellosolve | x | x |
| Amyl alcohol | 200 | 93 | Chloracetic acid, 50% water | x | x |
| Amyl chloride | 190 | 88 | Chloracetic acid | x | x |
| Aniline | 230 | 110 | Chlorine gas, dry | 190 | 88 |
| Antimony trichloride | 190 | 88 | Chlorine wet | 190 | 88 |
| Aqua regia 3:1 | 190 | 88 | Chlorine, liquid | 190 | 88 |
| Barium carbonate | 250 | 121 | Chlorobenzene | 400 | 204 |
| Barium chloride | 400 | 204 | Chloroform | 400 | 204 |

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**Table F.5** Compatibility of Fluoroelastomers with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Chlorosulfonic acid | x | x | Methyl chloride | 190 | 88 |
| Chromic acid 10% | 350 | 177 | Methyl ethyl ketone | x | x |
| Chromic acid 50% | 350 | 177 | Methyl isobutyl ketone | x | x |
| Citric acid 15% | 300 | 149 | Muriatic acid | 350 | 177 |
| Citric acid, concentrated | 400 | 204 | Nitric acid 5% | 400 | 204 |
| Copper acetate | x | x | Nitric acid 20% | 400 | 204 |
| Copper carbonate | 190 | 88 | Nitric acid 70% | 190 | 88 |
| Copper chloride | 400 | 204 | Nitric acid, anhydrous | 190 | 88 |
| Copper cyanide | 400 | 204 | Nitrous acid, concentrated | 90 | 32 |
| Copper sulfate | 400 | 204 | Oleum | 190 | 88 |
| Cresol | x | x | Perchloric acid 10% | 400 | 204 |
| Cupric chloride 5% | 180 | 82 | Perchloric acid 70% | 400 | 204 |
| Cupric chloride 50% | I80 | 82 | Phenol | 210 | 99 |
| Cyclohexane | 400 | 204 | Phosphoric acid 50–80% | 300 | 149 |
| Cyclohexanol | 400 | 204 | Picric acid | 400 | 204 |
| Dichloroethane (ethylene dichloride) | 190 | 88 | Potassium bromide 30% | 190 | 88 |
| Ethylene glycol | 400 | 204 | Salicylic acid | 300 | 149 |
| Ferric chloride | 400 | 204 | Sodium carbonate | 190 | 88 |
| Ferric chloride 50% in water | 400 | 204 | Sodium chloride | 400 | 204 |
| Ferric nitrate 10–50% | 400 | 204 | Sodium hydroxide 10% | x | x |
| Ferrous chloride | 180 | 82 | Sodium hydroxide 50% | x | x |
| Ferrous nitrate | 210 | 99 | Sodium hydroxide, concentrated | x | x |
| Fluorine gas, dry | x | x | Sodium hypochlorite 20% | 400 | 204 |
| Fluorine gas, moist | x | x | Sodium hypochlorite, concentrated | 400 | 204 |
| Hydrobromic acid, dilute | 400 | 204 | Sodium sulfide to 50% | 190 | 88 |
| Hydrobromic acid 20% | 400 | 204 | Stannic chloride | 400 | 204 |
| Hydrobromic acid 50% | 400 | 204 | Stannous chloride | 400 | 204 |
| Hydrochloric acid 20% | 350 | 177 | Sulfuric acid 10% | 350 | 149 |
| Hydrochloric acid 38% | 350 | 177 | Sulfuric acid 50% | 350 | 149 |
| Hydrocyanic acid 10% | 400 | 204 | Sulfuric acid 70% | 350 | 149 |
| Hydrofluoric acid 30% | 210 | 99 | Sulfuric acid 90% | 350 | 149 |
| Hydrofluoric acid 70% | 350 | 177 | Sulfuric acid 98% | 350 | 149 |
| Hydrofluoric acid 100% | x | x | Sulfuric acid 100% | 180 | 88 |
| Hypochlorous acid | 400 | 204 | Sulfuric acid, fuming | 200 | 93 |
| Iodine solution 10% | 190 | 88 | Sulfurous acid | 400 | 204 |
| Ketones, general | x | x | Thionyl chloride | x | x |
| Lactic acid 25% | 300 | 149 | Toluene | 400 | 204 |
| Lactic acid, concentrated | 400 | 201 | Trichloroacetic acid | 190 | 88 |
| Magnesium chloride | 390 | 199 | White liquor | 190 | 88 |
| Malic acid | 390 | 199 | Zinc chloride | 400 | 204 |
| Manganese chloride | 180 | 82 | | | |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

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In addition, the use of lead-free fuels, alternative fuels, sour gasoline lubricants, and antifreeze fluids have caused automotive fluids to be more corrosive to elastomers. At the present time, fluoroelastomers are being applied as shaft seals, valve stem seals, O-rings (water-cooled cylinders and injection pumps), engine head gaskets, filter casing gaskets, diaphragms for fuel pumps, water pump gaskets, turbocharge lubricating circuit bellows, carburetor accelerating pump diaphragms, carburetor needle-valve tips, fuel hoses, and seals for exhaust gas pollution-control equipment.

In the field of aerospace applications, the reliability of materials under extreme exposure conditions is of prime importance. The high- and low-temperature properties of the fluoroelastomers have permitted them to give reliable performance in a number of aircraft and missile components, specifically manifold gaskets, coated manifold gaskets, coated fabrics, firewall seals, heat-shrinkable tubing and fittings for wire and cable, mastic adhesive sealants, protective coatings, and numerous types of O-ring seals.

The ability of the fluoroelastomers to seal under extreme vacuum conditions in the range of $10^{-9}$ mm Hg is an additional feature that makes these materials useful for components used in space.

The exploitation of oil fields in difficult areas such as desert or offshore sites has increased the problems of high temperatures and pressures, high viscosities, and high alkalinity. These extreme operating conditions require elastomers that have a high chemical resistance, thermal stability, and overall reliability to reduce maintenance. The same problems exist in the chemical industry. The fluoroplastics provide a solution to these problems and are used for O-rings, V-rings, U-rings, gaskets, valve seats, diaphragms for metering pumps, hoses, expansion joints, safety clothing and gloves, linings for valves, and maintenance coatings.

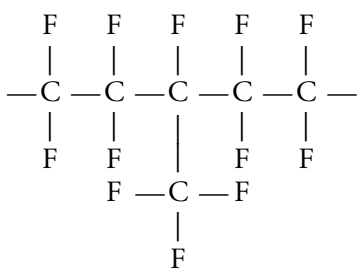
An important application for these elastomers is in the production of coatings and linings. Their chemical stability solves the problem of chemical corrosion by making it possible to use them for such purposes as

A protective lining for power station stacks operated with high-sulfur fuels
A coating on rolls for the textile industry to permit scouring of fabrics
Tank linings for the chemical industry

See Refs. 5 and 6.

## FLUORINATED ETHYLENE PROPYLENE (FEP)

FEP is a fully fluorinated thermoplast with some branching but consists mainly of linear chains having the following formula:



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**Table F.6** Physical and Mechanical Properties of FEP

| | |
|---|---|
| Specific gravity | 2.15 |
| Water absorption 24 h at 73°F (23°C), % | <0.01 |
| Tensile strength at 73°F (23°C) psi | 2700–3100 |
| Modulus of elasticity in tension at 73°F (23°C) $\times 10^5$ psi | 0.9 |
| Compressive strength, psi | 16,000 |
| Flexural strength, psi | 3000 |
| Izod impact strength, notched at 73°F (23°C) | no break |
| Coefficient of thermal expansion, in./in. °F $\times 10^{-5}$ | 8.3–10.5 |
| Thermal conductivity Btu/h/ft$^2$/°F/in. | 0.11 |
| Heat distortion temperature, at 66 psi °F/°C | 158/70 |
| Resistance to heat at continuous drainage, °F/°C | 400/204 |
| Limiting oxygen index, % | 95 |
| Flame spread | Nonflammable |

FEP has a maximum operating temperature of 375°F (190°C). After prolonged exposure at 400°F (204°C) it exhibits changes in physical strength. It is a relatively soft plastic with lower tensile strength, wear resistance, and creep resistance than other plastics. It is insensitive to notched impact forces and has excellent permeation resistance except to some chlorinated hydrocarbons. Table F.6 lists the physical and mechanical properties. FEP may he subject to permeation by specific materials. Refer to "Permeation" for details.

FEP basically exhibits the same corrosion resistance as PTFE, with a few exceptions, but at lower operating temperatures. It is resistant to practically all chemicals, the exceptions being extremely potent oxidizers, such as chlorine trifluoride and related compounds. Some chemicals will attack FEP when present in high concentrations at or near the service temperature limit. Refer to Table F.7 for the compatibility of FEP with selected corrodents. Reference 6 lists the compatibility of FEP with a wide range of selected corrodents.

## FLUOROCARBON RESINS

Fluorocarbon resins are organic compounds in which the hydrogen atoms have been replaced by fluorine. They are fully fluorinated, while fluoropolymer resins are only partially fluorinated. Included in this group of resins are polytetrafluoroethylene (PTFE), fluorinated ethylene propylene (FEP), and perfluoralkoxy (PFA). They are characterized by the following properties:

1. Nonpolarity: The carbon backbone of the linear polymer is completely sheathed by the tightly held electron cloud of fluorine atoms, with electronegatives balanced.
2. High C–F and C–C bond strengths.
3. Low interchain forces: Interactive forces between the two adjacent polymer chains are significantly lower than the bond forces within one chain.
4. Crystallinity.
5. High degree of polymerization.

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**Table F.7** Compatibility of FEP with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | 200 | 93 | Barium hydroxide | 400 | 204 |
| Acetamide | 400 | 204 | Barium sulfate | 400 | 204 |
| Acetic acid 10% | 400 | 204 | Barium sulfide | 400 | 204 |
| Acetic acid 50% | 400 | 204 | Benzaldehyde[b] | 400 | 204 |
| Acetic acid 80% | 400 | 204 | Benzene[b,c] | 400 | 204 |
| Acetic acid, glacial | 400 | 204 | Benzene sulfonic acid 10% | 400 | 204 |
| Acetic anhydride | 400 | 204 | Benzoic acid | 400 | 204 |
| Acetone[b] | 400 | 204 | Benzyl alcohol | 400 | 204 |
| Acetyl chloride | 400 | 204 | Benzyl chloride | 400 | 204 |
| Acrylic acid | 200 | 93 | Borax | 400 | 204 |
| Acrylontrile | 400 | 204 | Boric acid | 400 | 204 |
| Adipic acid | 400 | 204 | Bromine gas, dry[c] | 200 | 93 |
| Allyl alcohol | 400 | 204 | Bromine gas, moist[c] | 200 | 93 |
| Allyl chloride | 400 | 204 | Bromine liquid[b,c] | 400 | 204 |
| Alum | 400 | 204 | Butadiene[c] | 400 | 204 |
| Aluminum acetate | 400 | 204 | Butyl acetate | 400 | 204 |
| Aluminum chloride, aqueous | 400 | 204 | Butyl alcohol | 400 | 204 |
| Aluminum chloride, dry | 300 | 149 | *n*-Butylamine[b] | 400 | 204 |
| Aluminum fluoride[c] | 400 | 204 | Butyl phthalate | 400 | 204 |
| Aluminum hydroxide | 400 | 204 | Butyric acid | 400 | 204 |
| Aluminum nitrate | 400 | 204 | Calcium bisulfide | 400 | 204 |
| Aluminum oxychloride | 400 | 204 | Calcium bisulfite | 400 | 204 |
| Aluminum sulfate | 400 | 204 | Calcium carbonate | 400 | 204 |
| Ammonia gas[c] | 400 | 204 | Calcium chlorate | 400 | 204 |
| Ammonium bifluoride[c] | 400 | 204 | Calcium chloride | 400 | 204 |
| Ammonium carbonate | 400 | 204 | Calcium hydroxide 10% | 400 | 204 |
| Ammonium chloride 10% | 400 | 204 | Calcium hydroxide, sat. | 400 | 204 |
| Ammonium chloride 50% | 400 | 204 | Calcium hypochlorite | 400 | 204 |
| Ammonium chloride, sat. | 400 | 204 | Calcium nitrate | 400 | 204 |
| Ammonium fluoride 10%[c] | 400 | 204 | Calcium oxide | 400 | 204 |
| Ammonium fluoride 25%[c] | 400 | 204 | Calcium sulfate | 400 | 204 |
| Ammonium hydroxide 25% | 400 | 204 | Caprylic acid | 400 | 204 |
| Ammonium hydroxide, sat. | 400 | 204 | Carbon bisulfide[c] | 400 | 204 |
| Ammonium nitrate | 400 | 204 | Carbon dioxide, dry | 400 | 204 |
| Ammonium persulfate | 400 | 204 | Carbon dioxide, wet | 400 | 204 |
| Ammonium phosphate | 400 | 204 | Carbon disulfide | 400 | 204 |
| Ammonium sulfate 10–40% | 400 | 204 | Carbon monoxide | 400 | 204 |
| Ammonium sulfide | 400 | 204 | Carbon tetrachloride[b,c,d] | 400 | 204 |
| Ammonium sulfite | 400 | 204 | Carbonic acid | 400 | 204 |
| Amyl acetate | 400 | 204 | Cellosolve | 400 | 204 |
| Amyl alcohol | 400 | 204 | Chloracetic acid, 50% water | 400 | 204 |
| Amyl chloride | 400 | 204 | Chloracetic acid | 400 | 204 |
| Aniline[b] | 400 | 204 | Chlorine gas, dry | x | x |
| Antimony trichloride | 250 | 121 | Chlorine gas, wet[c] | 400 | 204 |
| Aqua regia 3:1 | 400 | 204 | Chlorine liquid[b] | 400 | 204 |
| Barium carbonate[c] | 400 | 204 | Chlorobenzene[c] | 400 | 204 |
| Barium chloride | 400 | 204 | Chloroform[c] | 400 | 204 |

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**Table F.7** Compatibility of FEP with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Chlorosulfonic acid[b] | 400 | 204 | Manganese chloride | 300 | 149 |
| Chromic acid 10% | 400 | 204 | Methyl chloride[c] | 400 | 204 |
| Chromic acid 50% | 400 | 204 | Methyl ethyl ketone[c] | 400 | 204 |
| Chromyl chloride | 400 | 204 | Methyl isobutyl ketone[c] | 400 | 204 |
| Citric acid 15% | 400 | 204 | Muriatic acid[c] | 400 | 204 |
| Citric acid, concentrated | 400 | 204 | Nitric acid 5%[c] | 400 | 204 |
| Copper acetate | 400 | 204 | Nitric acid 20% | 400 | 204 |
| Copper carbonate | 400 | 204 | Nitric acid 70%[c] | 400 | 204 |
| Copper chloride | 400 | 204 | Nitric acid, | 400 | 204 |
| Copper cyanide | 400 | 204 | Nitrous acid, concentrated | 400 | 204 |
| Copper sulfate | 400 | 204 | Oleum | 400 | 204 |
| Cresol | 400 | 204 | Perchloric acid 10% | 400 | 204 |
| Cupric chloride 5% | 400 | 204 | Perchloric acid 70% | 400 | 204 |
| Cupric chloride 50% | 400 | 204 | Phenol[c] | 400 | 204 |
| Cyclohexane | 400 | 204 | Phosphoric acid 50–80% | 400 | 204 |
| Cyclohexanol | 400 | 204 | Picric acid | 400 | 204 |
| Dichloroacetic acid | 400 | 204 | Potassium bromide 30% | 400 | 204 |
| Dichloroethane (ethylene dichloride)[c] | 400 | 204 | Salicylic acid | 400 | 204 |
| Ethylene glycol | 400 | 204 | Silver bromide 10% | 400 | 204 |
| Ferric chloride | 400 | 204 | Sodium carbonate | 400 | 204 |
| Ferric chloride 50% in water[b] | 260 | 127 | Sodium chloride | 400 | 204 |
| Ferric nitrate 10–50% | 260 | 127 | Sodium hydroxide 10%[b] | 400 | 204 |
| Ferrous chloride | 400 | 204 | Sodium hydroxide 50% | 400 | 204 |
| Ferrous nitrate | 400 | 204 | Sodium hydroxide, concentrated | 400 | 204 |
| Fluorine gas, dry | 200 | 93 | Sodium hypochlorite 20% | 400 | 204 |
| Fluorine gas, moist | x | x | Sodium hypochlorite concentrated | 400 | 204 |
| Hydrobromic acid, dilute | 400 | 204 | Sodium sulfide to 50% | 400 | 204 |
| Hydrobromic acid 20%[c,d] | 400 | 204 | Stannic chloride | 400 | 204 |
| Hydrobromic acid 50%[c,d] | 400 | 204 | Stannous chloride | 400 | 204 |
| Hydrochloric acid 20%[c,d] | 400 | 204 | Sulfuric acid 10% | 400 | 204 |
| Hydrochloric acid 38% | 400 | 204 | Sulfuric acid 50% | 400 | 204 |
| Hydrocyanic acid 10% | 400 | 204 | Sulfuric acid 70% | 400 | 204 |
| Hydrofluoric acid 30%[c] | 400 | 204 | Sulfuric acid 90% | 400 | 204 |
| Hydrofluoric acid 70%[c] | 400 | 204 | Sulfuric acid 98% | 400 | 204 |
| Hydrofluoric acid 100%[c] | 400 | 204 | Sulfuric acid 100% | 400 | 204 |
| Hypochlorous acid | 400 | 204 | Sulfuric acid, fuming[c] | 400 | 204 |
| Iodine solution 10%[c] | 400 | 204 | Sulfurous acid | 400 | 204 |
| Ketones, general | 400 | 204 | Thionyl chloride[c] | 400 | 204 |
| Lactic acid 25% | 400 | 204 | Toluene[c] | 400 | 204 |
| Lactic acid, concentrated | 400 | 204 | Trichloroacetic acid | 400 | 204 |
| Magnesium chloride | 400 | 204 | White liquor | 400 | 204 |
| Malic acid | 400 | 204 | Zinc chloride[d] | 400 | 204 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x.
[b]Material will be absorbed.
[c]Material will permeate.
[d]Material can cause stress cracking.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

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These properties provide the following advantages to these materials:

1. High melting point
2. High thermal stability
3. High upper service temperatures
4. Inertness to chemical attack by almost all chemicals
5. Low coefficient of friction
6. Low water absorbability
7. Weatherability
8. Flame resistance
9. Toughness

Listed in the table are the properties of the fluorocarbon resins.

| Property | ASTM Standard | PTFE | FEP | PFA |
|---|---|---|---|---|
| Specific gravity | D792 | 2.13–2.22 | 2.15 | 2.15 |
| Tensile strength, psi | D638 | 2500–4000 | 3400 | 3600 |
| Elongation, % | D638 | 200–400 | 325 | 300 |
| Flexural modulus, psi | D790 | 27000 | 90000 | 90000 |
| Impact strength, ft-lb/in. | D256 | 3.5 | no break | no break |
| Hardness. Shore D | D2240 | 50–65 | 56 | 60 |
| Coefficient of friction | D1894 | 0.1 | 0.2 | 0.2 |
| Upper service temp., °F/°C | UL746B | 500/260 | 400/204 | 500/260 |
| Flame rating | UL94 | VO | VO | VO |
| Limiting oxygen index, % | D2863 | 95 | 95 | 95 |
| Chemical/solvent resistance | D543 | | outstanding | |
| Water absorption, 24 h | D570 | 0.01 | 0.01 | 0.03 |

For more information on the fluorocarbon resins, refer to the specific resin and thermoplasts.

## FLUOROPOLYMER RESINS

The fluoropolymers are resistant to a broader range of chemicals at higher temperatures than chlorinated or hydrogenated polymers, polyesters, and polyamides. However, their properties are significantly different from those of fully fluorinated resins (fluorocarbons). Included in this category are ethylene tetrafluoroethylene (ETFE), sold under the trade name of Tefzel by DuPont; polyvinylidene fluoride (PVDF), sold under the trade names of Kynar by Elf Atochem, Solef by Solvay, Hylar by Ausimont USA, and Super Pro and Iso by Asahi/America; and ethylene chlorotrifluoroethylene (ECTFE), sold under the trade name of Halar by Ausimont USA.

The polarity of these resins is increased as the result of substituting hydrogen or chlorine, which have different electronegatives relative to fluorine. The length of their bonds to the carbon backbone also differs from those with fluorine. The centers of electronegativity and electropositivity are not held as tightly as with carbon–fluorine bonds. As a result, differential separation of charge can be induced chemically between atoms in adjacent chains to permit electrostatic interaction between chains. Higher mechanical

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properties are produced because of the increased interpolymer chain attraction along with the interlocking of differently sized atoms. In addition, the increased polarity/interpolymer attraction reduces the permeation of penetrants through the resin. Because of the substitution of hydrogen or of hydrogen and chlorine for fluorine, chemical and thermal stability are sacrificed.

The chemical stability is affected by the arrangement of the substituting elements along the polymer chain. Solubility can be a leading indicator. For example, ETFE has no known solvent under ordinary circumstances, while PVDF is soluble in common industrial ketones (e.g., methyl ethyl ketone) and ECTFE is soluble in some fluorinated solvents. While the fully fluorinated polymers are resistant to strong acids and alkalies, the substituted polymers are adversely affected. However, these resins do possess advantageous properties both mechanical and chemically resistant. Typical properties of the fluoropolymer resins are shown in the table.

| Property | ASTM Std | ETFE | PVDF | ECTFE |
|---|---|---|---|---|
| Specific gravity | D792 | 1.70 | 1.78 | 1.68 |
| Tensile strength, psi | D638 | 6300 | 4500 | 7000 |
| Elongation, % | D638 | 300 | 50 | 210 |
| Flexural modulus, psi $\times 10^5$ | D790 | 1.7 | 2.5 | 2.4 |
| Impact strength ft-lb/in. | D256 | no break | 2 | no break |
| Hardness, Shore D | D2240 | 67 | 78 | 75 |
| Coefficient of friction | D1894 | 0.4 | | |
| Upper service temperature, °F/°C | UL746 | 300/150 | 300/150 | 300/150 |
| Flame rating | UL94 | VO | VO | VO |
| Limiting oxygen index, % | D2863 | 30 | 30 | 30 |
| Chemical/solvent resistance | D543 | excellent | fair | good |
| Water absorption, 24 h | D570 | <0.03 | <0.03 | <0.1 |

For additional information, see the specific fluoropolymer and thermoplast.

## FLUOROSILICONE RUBBER

See "Silicone Rubbers and Fluorosilicone."

## FORMS OF CORROSION

The several forms of corrosion to which a metal may be subjected are

1. Electrochemical corrosion
2. Uniform corrosion
3. Intergranular corrosion
4. Galvanic corrosion
5. Crevice corrosion
6. Pitting
7. Erosion corrosion
8. Stress corrosion cracking (SCC)

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9. Biological corrosion
10. Dezincification (dealloying)
11. Concentration cell
12. Embrittlement
13. Filiform corrosion
14. Corrosion fatigue
15. Fretting corrosion
16. Graphitization

Not all of these forms of corrosion are present in all applications, but it is possible to have more than one form present. In addition, not all metals are subject to all of these forms of corrosion. Understanding when each of these forms of corrosion could be present will permit the designer to take steps to eliminate the condition or to keep the corrosion within acceptable limits. Refer to the specific form of corrosion for details.

## FRETTING CORROSION

Wear is a surface phenomenon that occurs by displacement and detachment of materials. Corrosive wear is the aggravation by corrosion of the wear process. The chemical reaction may take place first, followed by the removal of the corrosion products by mechanical abrasion. Conversely, mechanical action may precede chemical action in which small particles dislodged by abrasion react with the environment. In both cases, the wear rate is increased.

Fretting is also a wear phenomenon occurring between two mating surfaces under loading and having a relative slip of extremely small amplitude, such as would be caused by vibration. Under such conditions, the minute protrusions of one surface, "plough" through the mating surface, dislodging metallic particles or breaking the protective film. Fretting corrosion is the aggravation of this action in the presence of a corrosive liquid.

Fretting corrosion damage is characterized by discoloration of the metal surface and the formation of pits. Fatigue cracks may nucleate at the pits. Fretting corrosion results in the loosening of parts, sometimes seizure of the parts because of the accumulation of corrosion products, loss of dimensional accuracy, and at times fatigue failure. As loads increase, the magnitude of damage also increases, but it will decrease with increasing temperature and increasing moisture. This is an indication that the mechanism is not fully electrochemical.

Fretting and fretting corrosion are encountered in joints, connecting rods, shrink fits, oscillating bearings, splices, and couplings and in many parts of vibrating machinery.

Fretting corrosion can be minimized by reducing wearing action, such as by lubricating the wearing surfaces. This is why increased moisture, through its lubricating effect, reduces fretting corrosion. The use of rubber, Teflon, or any material of high elastic strain limit inserted between the two surfaces will prevent fretting. Induction of residual stresses through shot peening is helpful in preventing fatigue crack propagation initiated by fretting. If practical, the elimination of vibration is ideal.

## FUEL ASH CORROSION

Low-grade fuel oils contain elements, particularly vanadium and sodium, that cause accelerated high-temperature corrosion. At temperatures above 1200°F (650°C), vanadium oxide vapor and sodium sulfate react to form sodium vanadate, which in turn can react with

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metal oxides on the surfaces of heater tubes, tubesheets, etc. The resulting slag can become a low-melting eutectic mixture that is a molten solvent for metal oxides. The slag dissolves protective metal oxides and prevents their reforming. Sulfur in the fuel accelerates the action by means of sulfidation and by additional lowering of the melting point of the vanadium oxide flux. Failures resulting from this mechanism tend to be rapid.

Concentrations of less than 5 ppm vanadium appear to have little effect. Concentrations of up to 20 ppm vanadium are safe as long as the maximum metal temperature is less than 1550°F (845°C). For concentrations of vanadium in excess of 20 ppm, the safe maximum temperature is 1200°F (650°C).

Practically all alloys are susceptible to fuel ash corrosion. However, alloys having a high content of nickel and chromium (50 Cr–50 Ni) offer good protection. The rate of corrosion decreases at very low air concentrations. Reducing the amount of excess air to less than 5% will control fuel ash corrosion.

Also see "High-Temperature Corrosion."

## FURAN RESINS

Also see "Polymers" and "Thermoset Polymers." Since there are different formulations of the furan resins, the supplier should be checked as to the compatibility of a particular resin with the corrodents to be encountered. Corrosion charts will indicate the compatibility of at least one formulation.

The strong point of the furan resins is their excellent resistance to solvents in combination with acids and alkalies. They are compatible with the following corrodents:

| Solvents | |
|---|---|
| Acetone | Methyl ethyl ketone |
| Benzene | Perchlorethylene |
| Carbon disulfide | Styrene |
| Chlorobenzene | Toluene |
| Ethanol | Trichloroethylene |
| Ethyl acetate | Xylene |
| Methanol | |
| **Acids** | |
| Acetic | Phosphoric |
| Hydrochloric | 60% Sulfuric |
| 5% Nitric | |
| **Bases** | |
| Dimethylamine | Sodium sulfide |
| Sodium carbonate | Sodium hydroxide |

The furans are not resistant to bleaches, such as peroxides and hypochlorites, concentrated sulfuric acid, phenol and free chlorine, or higher concentrations of chromic or nitric acids.

Refer to Table F.8 for the compatibility of furan resins with selected corrodents.

See Refs. 6–8, 9.

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F

**Table F.8** Compatibility of Furan Resins with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | x | x | Bromine liquid 3% max. | 300 | 149 |
| Acetic acid 10% | 212 | 100 | Butadiene | | |
| Acetic acid 50% | 160 | 71 | Butyl acetate | 260 | 127 |
| Acetic acid 80% | 80 | 27 | Butyl alcohol | 212 | 100 |
| Acetic acid, glacial | 80 | 27 | *n*-Butylamine | x | x |
| Acetic anhydride | 80 | 27 | Butyric acid | 260 | 127 |
| Acetone | 80 | 27 | Calcium bisulfite | 260 | 127 |
| Acetyl chloride | 200 | 93 | Calcium chloride | 160 | 71 |
| Acrylic acid | 80 | 27 | Calcium hydroxide, sat. | 260 | 127 |
| Acrylonitrile | 80 | 27 | Calcium hypochlorite | x | x |
| Adipic acid 25% | 280 | 138 | Calcium nitrate | 260 | 127 |
| Allyl alcohol | 300 | 149 | Calcium oxide | | |
| Allyl chloride | 300 | 149 | Calcium sulfate | 260 | 127 |
| Alum 5% | 140 | 60 | Caprylic acid | 250 | 121 |
| Aluminum chloride, aqueous | 300 | 149 | Carbon disulfide | 160 | 71 |
| Aluminum chloride, dry | 300 | 149 | Carbon dioxide. dry | 90 | 32 |
| Aluminum fluoride | 280 | 138 | Carbon dioxide, wet | 80 | 27 |
| Aluminum hydroxide | 260 | 127 | Carbon disulfide | 260 | 127 |
| Aluminum sulfate | 160 | 71 | Carbon tetrachloride | 212 | 100 |
| Ammonium carbonate | 240 | 116 | Cellosolve | 240 | 116 |
| Ammonium hydroxide 25% | 250 | 121 | Chloracetic acid, 50%, water | 100 | 38 |
| Ammonium hydroxide, sat. | 200 | 93 | Chloracetic acid | 240 | 116 |
| Ammonium nitrate | 250 | 121 | Chlorine gas, dry | 260 | 127 |
| Ammonium persulfate | 260 | 127 | Chlorine gas, wet | 260 | 127 |
| Ammonium phosphate | 260 | 127 | Chlorine, liquid | x | x |
| Ammonium sulfate 10–40% | 260 | 127 | Chlorobenzene | 260 | 127 |
| Ammonium sulfide | 260 | 127 | Chloroform | x | x |
| Ammonium sulfite | 240 | 116 | Chlorosulfonic acid | 260 | 127 |
| Amyl acetate | 260 | 127 | Chromic acid 10% | x | x |
| Amyl alcohol | 278 | 137 | Chromic acid 50% | x | x |
| Amyl chloride | x | x | Chromyl chloride | 250 | 121 |
| Aniline | 80 | 27 | Citric acid 15% | 250 | 121 |
| Antimony trichloride | 250 | 121 | Citric acid, concentrated | 250 | 121 |
| Aqua regia 3:1 | x | x | Copper acetate | 260 | 127 |
| Barium carbonate | 240 | Il6 | Copper carbonate | | |
| Barium chloride | 260 | 127 | Copper chloride | 260 | 127 |
| Barium hydroxide | 260 | 127 | Copper cyanide | 240 | 116 |
| Barium sulfide | 260 | 127 | Copper sulfate | 300 | 149 |
| Benzaldehyde | 80 | 27 | Cresol | 260 | 127 |
| Benzene | 160 | 71 | Cupric chloride 5% | 300 | 149 |
| Benzene sulfonic acid 10% | 160 | 71 | Cupric chloride 50% | 300 | 149 |
| Benzoic acid | 260 | 127 | Cyclohexane | 141 | 60 |
| Benzyl alcohol | 80 | 27 | Cyclohexanol | | |
| Benzyl chloride | 140 | 60 | Dichloroacetic acid | x | x |
| Borax | 140 | 60 | Dichloroethane (ethylene dichloride) | 250 | 121 |
| Boric acid | 300 | 149 | Ethylene glycol | 160 | 71 |
| Bromine gas, dry | x | x | Ferric chloride | 260 | 127 |
| Bromine gas, moist | x | x | Ferric chloride 50%, water | 160 | 71 |

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**Table F.8** Compatibility of Furan Resins with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Ferric nitrate 10–50% | 160 | 71 | Perchloric acid 10% | x | x |
| Ferrous chloride | 160 | 71 | Perchloric acid 70% | 260 | 127 |
| Ferrous nitrate | | | Phenol | x | x |
| Fluorine gas, dry | x | x | Phosphoric acid 50 | 212 | 100 |
| Fluorine gas, moist | x | x | Picric acid | | |
| Hydrobromic acid, dilute | 212 | 100 | Potassium bromide 30% | 260 | 127 |
| Hydrobromic acid 20% | 212 | 100 | Salicylic acid | 260 | 127 |
| Hydrobromic acid 50% | 212 | 100 | Silver bromide 10% | | |
| Hydrochloric acid 20% | 212 | 100 | Sodium carbonate | 212 | 100 |
| Hydrochloric acid 38% | 80 | 27 | Sodium chloride | 260 | 127 |
| Hydrocyanic acid 10% | 160 | 71 | Sodium hydroxide 10% | x | x |
| Hydrofluoric acid 30% | 230 | 110 | Sodium hydroxide 50% | x | x |
| Hydrofluoric acid 70% | 140 | 60 | Sodium hydroxide, concentrated | x | x |
| Hydrofluoric acid 100% | 140 | 60 | Sodium hypochlorite 15% | x | x |
| Hypochlorous acid | x | x | Sodium hypochlorite, concentrated | x | x |
| Iodine solution 10% | x | x | Sodium sulfide to 10% | 260 | 127 |
| Ketones, general | 100 | 38 | Stannic chloride | 260 | 127 |
| Lactic acid 25% | 212 | 100 | Stannous chloride | 250 | 121 |
| Lactic acid, concentrated | 160 | 71 | Sulfuric acid 10% | 160 | 71 |
| Magnesium chloride | 260 | 127 | Sulfuric acid 50% | 80 | 27 |
| Malic acid 10% | 260 | 127 | Sulfuric acid 70% | 80 | 27 |
| Manganese chloride | 200 | 93 | Sulfuric acid 90% | x | x |
| Methyl chloride | 120 | 49 | Sulfuric acid 98% | x | x |
| Methyl ethyl ketone | 80 | 27 | Sulfuric acid 100% | x | x |
| Methyl isobutyl ketone | 160 | 71 | Sulfuric acid, fuming | x | x |
| Muriatic acid | 80 | 27 | Sulfurous acid | 160 | 71 |
| Nitric acid 5% | x | x | Thionyl chloride | x | x |
| Nitric acid 20% | x | x | Toluene | 212 | 100 |
| Nitric acid 70% | x | x | Trichloroacetic acid 30% | 80 | 27 |
| Nitric acid, anhydrous | x | x | White liquor | 140 | 60 |
| Nitrous acid, concentrated | x | x | Zinc chloride | 160 | 71 |
| Oleum | 190 | 88 | | | |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable.

*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

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# G

## GALVANIC CORROSION

This form of corrosion is sometimes referred to as dissimilar metal corrosion and is found in the most unusual places, often causing professionals the most headaches. Galvanic corrosion is often experienced in older homes where modern copper water tubing is connected to the older existing carbon steel water lines. The coupling of the copper to the carbon steel causes the carbon steel to corrode. The galvanic series of metals provides details of how galvanic current will flow between two metals and which metal will corrode when they are in contact or near each other and an electrolyte is present (e.g., water). Table G.1 lists the galvanic series.

When two different metallic materials are electrically connected and placed in a conductive solution (electrolyte), an electric potential exists. This potential difference will provide a stronger driving force for the dissolution of the less noble (more electrically negative) material. It will also reduce the tendency for the more noble metal to dissolve. Notice in Table G.l that the precious metals of gold and platinum are of the higher potential (more noble, or cathodic) end of the series (protected end), while zinc and magnesium are at the lower potential (less noble, or anodic) end. It is this principle that forms the scientific basis for using such materials as zinc to sacrificially protect a stainless steel drive shaft on a pleasure boat.

You will note that several materials are shown in two phases in the galvanic series, indicated as either active or passive. This is the result of the tendency of some metals and alloys to form surface films, especially in oxidizing environments. These films shift the measured potential in the noble direction. In this state the material is said to be passive.

The particular way in which metals will react can be predicted from the relative positions of the materials in the galvanic series. When it is necessary to use dissimilar metals, two materials should be selected that are relatively close in the galvanic series. The further apart the metals are in the galvanic series, the greater the rate of corrosion.

The rate of corrosion is also affected by the relative areas between the anode and the cathode. Since the flow of current is from the anode to the cathode, the combination of a large cathodic area and a small anodic area is undesirable. Corrosion of the anode can be 100–1000 times greater than if the two areas were equal. Ideally the anode area should be larger than the cathode area.

The passivity of stainless steel is the result of the presence of a corrosion-resistant oxide film on the surface. In most material environments, it will remain in the passive state and tend to be cathodic to ordinary iron or steel. When chloride concentrations are high, such as in seawater or in reducing solutions, a change to the active state will usually



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take place. Oxygen starvation also causes a change to the active state. This occurs when there is no free access to oxygen, such as in crevices and beneath contamination of particularly fouled surfaces.

Differences in soil concentrations such as moisture content and resistivity can be responsible for creating anodic and cathodic areas. Where there is a difference in concentrations of oxygen in the water or in moist soils in contact with metal at different areas, cathodes will develop at relatively high oxygen concentrations, and anodes at points of low concentrations. Strained portions of metals tend to be anodic and unstrained portions cathodic.

When joining two dissimilar metals together, galvanic corrosion can be prevented by insulating the two metals from each other. For example, when bolting flanges of dissimilar metals together, plastic washers can be used to separate the two metals.

See Refs. 1–5.

## GALVANIC PROTECTION

See "Cathodic Protection."

## GALVANIZED IRON

See "Galvanized Steel."

**Table G.1** Galvanic Series of Metals and Alloys

| | |
|---|---|
| *Corroded end (anodic)* | |
| Magnesium | Muntz metal |
| Magnesium alloys | Naval bronze |
| Zinc | Nickel (active) |
| Galvanized steel | Inconel (active) |
| Aluminum 6053 | Hastelloy C (active) |
| Aluminum 3003 | Yellow brass |
| Aluminum 2024 | Admiralty brass |
| Aluminum | Aluminum bronze |
| Alclad | Red brass |
| Cadmium | Copper |
| Mild steel | Silicon bronze |
| Wrought iron | 70–30 Cupro-nickel |
| Cast iron | Nickel (passive) |
| Ni-resist | Inconel (passive) |
| 13% Chromium stainless steel (active) | Monel |
| 50-50 Lead tin solder | Stainless steel type 304 (passive) |
| Ferritic stainless steel 400 series | 18-8-3 Stainless steel type 316 (passive) |
| 18-8 Stainless steel type 304 (active) | Silver |
| 18-8-3 Stainless steel type 316 (active) | Graphite |
| Lead | Gold |
| Tin | Platinum |
| | *Protected end (cathodic)* |

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## GALVANIZED STEEL

See "Zinc and Zinc Alloys" also.

Galvanized steel is steel that has been coated with zinc. The galvanizing process is widely used to protect steel from atmospheric corrosion. Structures, sheet steel, wire, and piping are all forms that are protected by galvanizing. The protection afforded in rural atmospheres is greater than that in urban or industrial atmospheres. In the latter areas, there is a greater concentration of industrial pollutants. The air in these areas is contaminated with various sulfur compounds, which together with the moisture in the air convert the normally impervious corrosion-resistant zinc carbonate and zinc oxide layer into zinc sulfate and zinc sulfite. These water-soluble compounds have poor adhesion to the zinc surface and therefore are washed away relatively easily by rain. This exposes the underlying surface to attack by the oxygen in the air.

Galvanized steel is widely used in contact with many chemical specialty products such as detergents, agricultural chemicals, and similar materials. In most cases, galvanized steel comes into contact with these chemicals during the handling, packaging, and storage of the finished products. Table G.2 shows the compatibility of galvanized steel with selected corrodents.

See Refs. 4 and 5.

**Table G.2** Compatibility of Galvanized Steel with Selected Corrodents

| | | | |
|---|---|---|---|
| Acetic acid | U | Butyl acetate | G |
| Acetone | G | Butyl chloride | G |
| Acetonitrile | G | Butyl ether | G |
| Acrylonitrile | G | Butylphenol | G |
| Acrylic latex | U | Cadmium chloride solution | U |
| Aluminum chloride 26% | U | Cadmium nitrate solution | U |
| Aluminum hydroxide | U | Cadmium sulfate solution | U |
| Aluminum nitrate | U | Calcium hydroxide | |
| Ammonia, dry vapor | U | sat. solution | U |
| Ammonium acetate solution | U | 20% solution | S |
| Ammonium bisulfate | U | Calcium sulfate, sat. solution | U |
| Ammonium bromide | U | Cellosolve acetate | G |
| Ammonium carbonate | U | Chloric acid 20% | U |
| Ammonium chloride 10% | U | Chlorine, dry | G |
| Ammonium dichloride | U | Chlorine water | U |
| Ammonium hydroxide | | Chromium chloride | U |
| Vapor | U | Chromium sulfate solution | U |
| Reagent | U | Copper chloride solution | U |
| Ammonium molybdate | G | Decyl acrylate | G |
| Ammonium nitrate | U | Diamylamine | G |
| Argon | G | Dibutylamine | G |
| Barium hydroxide | | Dibutyl cellosolve | G |
| Barium nitrate solution | S | Dibutyl phthalate | G |
| Barium sulfate solution | S | Dichloroethyl ether | G |
| Beeswax | U | Diethylene glycol | G |
| Borax | S | Dipropylene glycol | G |
| Bromine moist | U | Ethanol | G |
| 2-Butanol | G | Ethyl acetate | G |

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**Table G.2** Compatibility of Galvanized Steel with Selected Corrodents (Continued)

| | | | |
|---|---|---|---|
| Ethyl acrylate | G | Phosphoric acid 0.3-3% | G |
| Ethyl amine 69% | G | Polyvinyl acetate latex | U |
| *N*-Ethyl butylamine | G | Potassium carbonate | |
| 2-Ethyl butyric acid | G | 10% solution | U |
| Ethyl ether | G | 50% solution | U |
| Ethyl hexanol | G | Potassium chloride solution | U |
| Fluorine, dry, pure | G | Potassium bichromate | |
| Formaldehyde | G | 14.7% | G |
| Fruit juices | S | 20% | S |
| Hexanol | G | Potassium disulfate | S |
| Hexylamine | G | Potassium fluoride 5–20% | G |
| Hexylene glycol | G | Potassium hydroxide | U |
| Hydrochloric acid | U | Potassium nitrate | |
| Hydrogen peroxide | S | 5–10% solution | S |
| Iodine, gas | U | Potassium Peroxide | U |
| Isohexanol | G | Potassium persulfate 10% | U |
| Isooctanol | G | Propyl acetate | G |
| Isopropyl ether | G | Propylene glycol | G |
| Lead sulfate | U | Propionaldehyde | G |
| Lead sulfite | S | Propionic acid | U |
| Magnesium carbonate | S | Silver bromide | U |
| Magnesium chloride 42.5% | U | Silver chloride | |
| Magnesium fluoride | G | pure, dry | S |
| Magnesium hydroxide sat. | S | moist, wet | U |
| Magnesium sulfate | | Silver nitrate solution | U |
| 2% solution | S | Sodium acetate | S |
| 10% solution | U | Sodium aluminum sulfate | U |
| Methyl amyl alcohol | G | Sodium bicarbonate solution | U |
| Methyl ethyl ketone | G | Sodium bisulfate | U |
| Methyl propyl ketone | G | Sodium carbonate solution | U |
| Methyl isobutyl ketone | G | Sodium chloride solution | U |
| Nickel ammonium sulfate | U | Sodium hydroxide solution | U |
| Nickel chloride | U | Sodium nitrate solution | U |
| Nickel sulfite | S | Sodium sulfate solution | U |
| Nitric acid | U | Sodium sulfide | U |
| Nitrogen, dry, pure | G | Sodium sulfite | U |
| Nonylphenol | G | Styrene monomeric | G |
| Oxygen | | Styrene oxide | G |
| dry, pure | G | Tetraethylene glycol | G |
| moist | U | 1, 1, 2 Trichloroethane | G |
| Paraldehyde | G | 1, 2, 3 Trichloropropane | G |
| Perchloric acid solution | S | Vinyl acetate | G |
| Permanganate solution | S | Vinyl ethyl ether | G |
| Peroxide | | Vinyl butyl ether | G |
| pure, dry | S | Water | |
| moist | U | potable, hard | G |

G = Suitable application; S = Borderline application; U = Not suitable

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## GASEOUS PHASE CORROSION

See "Reducing Atmosphere Corrosion."

## GENERAL CORROSION

See "Uniform Corrosion."

## GLASS COATINGS

Sec "Glass Linings."

## GLASS FIBER REINFORCEMENT

See "Thermoset Reinforcing Material."

## GLASS LININGS

The bonding of glass to metal is not a recent development. Relics of glass bonded to gold jewelry (enameling) have been found that date back to 400 B.C. Until the early 1800s, enameling continued as an art form. The first application of a glass coating for any purpose other than an art form took place when cast iron sanitary ware was first coated.

The brewing industry was responsible for the development of the first large-scale glassed steel equipment. It was the result of the need to improve the consistency of the quality of the beer. This took place in the early 1880s. Between that time and the start of the Second World War, there were no notable developments in glassed steel composite.

With the advent of war, the need developed for critical chemicals that were often corrosive and sticky. This sparked development programs to find materials to meet these needs. It was during this time that the importance of characteristics other than corrosion resistance of the composite were recognized, specifically thermal loading and mechanical stressing. Since that time, continued research efforts have culminated in a glassed steel product that is one of the major materials of construction used by the chemical processing industry.

There are a variety of glass linings, each of which has been developed for specific needs. The metal substrate provides the required strength and base thermal expansion for the glass lining, while the majority of the end-use requirements must be met by making adjustments to the glass composition. These end-use requirements include resistance to corrosion; adhesion of glass to metal; thermal, mechanical, and electrical type stressing influence; and reduced product adherence.

There are five basic types of glass lining formulations that are available. The most commonly specified is the standard lining, which is widely used by the chemical process industry. This lining represents a balance between chemical and physical property serviceability. The maximum thermal shock (cold-to-hot or hot-to-cold) is in the range of 260°F (127°C). Glass linings are available in blue or white. The white coloration is useful in ensuring the complete clean-out of a dark-colored product.

When low-temperature service is encountered, the substrate is of stainless steel construction, in conjunction with a special glass lining. This combination permits operation down to –200°F (–129°C). In modifying the glass composition to allow the low-temperature operation, some corrosion resistance is lost.

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Glass compositions can also be modified to allow high-temperature operation. These systems extend the operation to 650°F (343°C) with the thermal shock differential increased to 360°F (182°C). There is no reduction in corrosion resistance.

Some applications require low product adherence to the lining. To meet this requirement, a special surface layer free of many microscopic surface imperfections is required. Other properties remain unchanged. If a corrosive etch develops, the surface layer is no longer effective.

Glass is extremely weak in tension but strong in compression. By incorporating crystals in the glass lining, any applied tension-type stresses will be effectively transferred to the stronger crystals. Quartz ($SiO_2$) crystals or other relatively glass-insoluble particles or fibers are used. The addition of these crystals will also improve impact resistance, abrasion resistance, and heat transfer.

In addition to improving the mechanical and physical properties mentioned above, they also have the outstanding ability to inhibit crack propagation. Once a crack has formed in a pure glass system, the crack will continue to propagate, especially under the influence of motion stressing, temperature change, and water. Crystals result in limiting the damage to a relatively small area and permit an economical repair to be made.

## Glass Structure

A glass system used to produce lining can he considered as a three-dimensional network-type structure consisting of one or more oxide groups. The network formers are acidic-type oxides that form the backbone of the glass structure. Silicon dioxide ($SiO_2$) is the primary network former and is obtained from relatively inexpensive beach sand. It is usually present in glasses in amounts exceeding 50 weight percent. The network modifiers are base-type oxides but are not part of the network-forming structure. They cannot form glasses by themselves. As the name implies, these oxides modify the properties of the network formers. The intermediates are amphoteric in nature and can act as either network formers or modifiers, depending upon the concentration, nature, and amounts of the other constituents. Aluminum oxide and titanium dioxide improve general corrosion resistance, while zirconium dioxide improves alkali resistance.

The cover coat systems for glass linings are complex mixtures of up to 15 oxides taken from the above three groups and built around the framework of the silica network.

## Corrosion of Glass

The corrosion of glass linings takes place by means of two basic mechanisms. One relates to the removal of the modifiers and/or the intermediates, while the other is the removal of the network formers.

Acids (fluorine and phosphorus compounds excepted), small ions, and the first stage of water attack invoke removal of the intermediates and modifiers by a diffusion-controlled ion exchange mechanism in which the small ion, e.g., hydrogen from the acid, exchanges for the larger modifier/intermediate ion. This results in stress-relief cracking in the network former that eventually leads to the dulling of the glass.

Corrosive attack by alkalies, fluorine, and phosphorus-containing compounds and the second stage of water attack remove compounds from the network former through a regenerated dissolution-type reaction.

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Dulling of the glass surface is usually the first sign of corrosion. This may be caused by either the ion exchange or the dissolution type of corrosion reaction and is usually uniform in appearance. The corrosive upset of the glass surface leads to localized stress differences, which in turn lead to varying degrees of stress relief and eventually glass chipping.

One of the most serious types of glass corrosion damage is pitting. This type of attack is both corrosive and glass-composition sensitive and can be caused by fluorine-based chemistries and alkalies. Older glass systems and glass/crystal composites are more susceptible to this type of attack.

### Corrosion Resistance of Glass

When considering the application of glassed steel equipment to handle a specific corrosive, thought must also be given to the effects of the corrodent on any tantalum repair plugs that may be present in the vessel. For example, while sulfuric acid can he handled in glassed steel equipment, the presence of small amounts of sulfur trioxide would attack any tantalum present. The same would apply to chlorosulfonic acid and oleum.

In general, the following corrodents may be handled safely in glassed steel equipment:

Hydrochloric acid up to 300°F (149°C)
Chlorides in general
Bromides
Solids
Sulfuric acid up to 450°F (232°C)
Chlorosulfonic acid
Acetic acid
Organic compounds

Corrosives that will attack glassed steel are

Fluorides.
Alkaline compounds.
Salts with small cations, e.g., lithium, magnesium, aluminum, in aqueous media should be used with caution above 150°F (66°C).
Phosphorus compounds frequently contain fluorides, and some phosphorus compounds possess a mutual solubility for glass.

Refer to Table G.3 for the compatibility of glass lining with selected corrodents.

See Refs. 6, 7, and 12.

## GLASSED STEEL

See "Glass Linings."

## GRAPHITE FIBERS

Graphite fibers are used as reinforcing in FRP laminates and to provide conductivity. See "Thermoset Reinforcing Materials."

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**Table G.3** Compatibility of Glass Lining with Selected Corrodents[a]

| Chemical | °F | °C | Chemical | °F | °C |
|---|---|---|---|---|---|
| Acrylic acid | 302 | 150 | Diethylene amine | 212 | 100 |
| Aluminum acetate | 392 | 200 | Diethyl ether | 212 | 100 |
| Aluminum chlorate aq. | 230 | 110 | Dimethyl sulfate | 302 | 150 |
| Aluminum chloride 10% | bp | bp | Ethyl acetate | 392 | 200 |
| Aluminum potassium | | | Ethyl alcohol | 392 | 200 |
| sulfate 50% aq. | 248 | 120 | Ethylenediamine 98% | 176 | 80 |
| Aminoethanol | 338 | 170 | Fatty acids | 302 | 150 |
| Aminophenol sulfuric acid | 266 | 130 | Ferric chloride 10% | bp | bp |
| Ammonium carbonate aq. | bp | bp | Formaldehyde | 302 | 150 |
| Ammonium chloride 10% | 302 | 150 | Formic acid 98% | 356 | 180 |
| Ammonium nitrate aq. | bp | bp | Fumaric acid | 302 | 150 |
| Ammonium phosphate | bp | bp | Gallic acid | 212 | 100 |
| Ammonium sulfate | bp | bp | Glutamic acid | 104 | 40 |
| Ammonium sulfide | 170 | 80 | Glycerine | 212 | 100 |
| Ammonium sulfite | x | x | Glycol | 302 | 150 |
| Aniline | 363 | 184 | Glycolic acid 57% | 302 | 150 |
| Antimony (III) chloride | 428 | 220 | Hydrochloric acid 30% | 266 | 130 |
| Antimony (IV) chloride | 302 | 150 | Hydrogen peroxide 30% | 158 | 70 |
| Aqua regia | 302 | 150 | Hydrogen sulfide aq. | 302 | 150 |
| Barium sulfate | 302 | 150 | Hydroiodic acid 20% | x | x |
| Benzaldehyde | 302 | 150 | Iodine | 392 | 200 |
| Benzene | 482 | 250 | Isopropyl alcohol | 302 | 150 |
| Benzoic acid | 302 | 150 | Lactic acid | bp | bp |
| Benzyl chloride | 266 | 130 | Lead acetate | 572 | 300 |
| Boric acid aq. | 302 | 150 | Lithium chloride | x | x |
| Bromine | 212 | 100 | Lithium hydroxide conc | x | x |
| Butanol | 264 | 140 | Magnesium carbonate aq. | 212 | 100 |
| Carbon dioxide aq. | 302 | 150 | Magnesium chloride 30% | 230 | 110 |
| Carbon dioxide | 482 | 250 | Magnesium sulfate aq | 302 | 150 |
| Carbon disulfide | 392 | 200 | Maleic acid | 356 | 180 |
| Carbon tetrachloride | 392 | 200 | Methanol | 392 | 200 |
| Chloride bleaching agent | 356 | 180 | Monochloroacetic acid | bp | bp |
| Chlorinated parrafin | 356 | 180 | Naphthalene | 419 | 215 |
| Chlorine | 392 | 200 | Nitric acid 50% | 302 | 150 |
| Chlorine water | 356 | 180 | Nitric oxides | 392 | 200 |
| Chlorosulfonic acid | 302 | 150 | Nitrobenzene | 302 | 150 |
| Chloropropionic acid | 347 | 175 | Oleum 10% $SO_3$ | 338 | 170 |
| Chromic acid 30% | 212 | 100 | Oxalic acid 50% | 302 | 150 |
| Chromic acid aq. | 302 | 150 | Palmitic acid | 230 | 110 |
| Citric acid 10% | bp | bp | Perchloric acid 70% | bp | bp |
| Cupric chloride 5% | 302 | 150 | Phenol | 392 | 200 |
| Cupric nitrate 50% | 212 | 100 | Phthalic anhydride | 482 | 260 |
| Cupric sulfate aq | 302 | 150 | Picric acid | 302 | 150 |
| Cyanoacetic acid | 212 | 100 | Potassium bromide aq. | bp | bp |
| Dichloroacetic acid | 302 | 150 | Potassium chloride aq. | bp | bp |
| Dichlorobenzene | 428 | 220 | Pyridine | bp | bp |

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**Table G.3** Compatibility of Glass Lining with Selected Corrodents[a] (Continued)

| Chemical | °F | °C | Chemical | °F | °C |
|---|---|---|---|---|---|
| Sodium bisulfate | 572 | 300 | Sulfuric acid 98% | 428 | 220 |
| Sodium chlorate aq. | 170 | 80 | Tannic acid | 302 | 150 |
| Sodium chloride aq. | bp | bp | Tin chloride | 482 | 250 |
| Sodium nitrate | 606 | 320 | Toluene | 302 | 150 |
| Sodium sulfide 4% | x | x | Trichloroacetic acid | 302 | 150 |
| Stearic acid | 320 | 160 | Trichloroethylene | 302 | 150 |
| Succinic acid 35% | 284 | 140 | Triethanolamine | 482 | 250 |
| Succinic acid sat sol | x | x | Triethylamine 30% | 176 | 80 |
| Sulfur | 302 | 150 | Trisodium phosphate 50% | 176 | 80 |
| Sulfur dioxide | 392 | 200 | Urea | 302 | 150 |
| Sulfuric acid 20% | 284 | 140 | Zinc bromide aq. | bp | bp |
| Sulfuric acid 60% | 320 | 160 | Zinc chloride melt. | 626 | 330 |
| | | | Zinc chloride aq. | 284 | 140 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x.
bp = boiling point
aq. = aqueous

## GRAPHITIZATION (GRAPHITIC CORROSION)

Cast iron is composed of a mixture of ferrite phase (almost pure iron) and graphite flakes. When it corrodes, it forms corrosion products, which in some soils or waters cement together the residual graphite flakes. The resulting structure (e.g., water pipe), although corroded completely, may have sufficient remaining strength, even with low ductility, to continue to operate under the required pressures and stresses.

This form of corrosion occurs only with gray cast iron or ductile cast iron containing spheroidal graphite and not with white iron, which contains cementite and ferrite.

See Refs. 1, 7, 8, and 9.

## GREEN PLAGUE

Green corrosion deposits formed in copper hot water piping and on water faucets are known as green plague. It is thought to be caused by electrical grounding on copper dissolution.

## GREEN ROT

Green rot is the formation of green chromium oxide on chromium-bearing alloys resulting from high-temperature corrosion. The other alloy constituents remain unaffected.

## GREEN RUST

Green rust is a greenish corrosion product formed on ferrous metals. It contains iron in two oxidation states and has a variable anion content and is related structurally to the pyroaurite group of naturally occurring minerals.

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## GROOVING CORROSION

Grooving corrosion is a form of localized corrosion appearing as grooves. When electric-resistance-welded carbon steel pipe is exposed to aggressive waters, grooves caused by the redistribution of sulfide inclusions along the weld line during the welding process are formed in the weld.

## GROUT

There are two types of grout, each of which is used for a specific purpose. The first is a thin, soupy mortar used for filling joints between previously laid tile or brick. These joints are usually approximately $\frac{1}{4}$ in. (6 mm) wide. The grout is applied by squeegeeing it into the open joints using a flat rectangular rubber-faced trowel. This is usually associated with tile-setting.

The second form of grout is used for setting machinery. These grouts are similar to the tilesetting grouts but utilize larger aggregate than the tile grouts. Resin viscosities can also vary from those of the tile grouts.

Both forms of grout are available in the same corrosion-resistant formulations. For additional information regarding the various formulations and their corrosion-resistant properties, see "Mortars," since grouts and mortars are of the same chemical formulations.

See Refs. 10 and 11.

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# H

## HALAR

See "Ethylene Chlorotrifluoroethylene."

## HALOGENATED POLYESTER RESINS

Also see "Polymers" and "Thermoset Polymers." These consist of either chlorinated or brominated polyesters. Excellent resistance is exhibited in contact with oxidizing acids and solutions, such as 35% nitric acid at elevated temperatures and 70% nitric acid at room temperature, 40% chromic acid, chlorine water, wet chlorine, and 15% hypochlorites. They are also resistant to neutral and acid salts, nonoxidizing acids, organic acids, mercaptans, ketones, alcohols, glycols, organic esters, and fats and oils.

These polyesters are not resistant to highly alkaline solutions of sodium hydroxide; concentrated sulfuric acid; alkaline solutions with pH greater than 10; aliphatic, primary, and aromatic amines; amides and other alkaline organics; phenol; and acid halides. Refer to Table H.1 for the compatibility of halogenated polyesters with selected corrodents. Reference 1 provides the compatibility of halogenated resins with a wider range of corrodents.

See also Refs. 2–4.

## HASTELLOY

Hastelloy is the trademark of Haynes International Inc. and is prefixed to a series of high-nickel alloys designed for corrosion resistance. These alloys include Hastelloy C-276, Hastelloy B and B-2, Hastelloy (G, G-3, and G-30, Hastelloy alloy X. Hastelloy C-2000, and Hastelloy alloy No. 230.

Refer to the specific alloy for detailed information.

## HASTELLOY ALLOY C-2000

Hastelloy C-2000 is a nickel–chromium–molybdenum–copper alloy containing 23% chromium, 1.6% molybdenum, 1.6% copper, 0.01% carbon (max.), 008% silicon (max.), and the remainder nickel. It has the unique property of possessing outstanding resistance to oxidizing media with superior resistance to reducing environments. In addition, the alloy also exhibits pitting resistance and crevice corrosion resistance superior to C-276 alloy.

In contact with a 0–60 weight percent of hot sulfuric acid, alloy C-2000 has better corrosion resistance than alloy C-276. When exposed to boiling hydrochloric acid



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**Table H.1** Compatibility of Halogenated Polyester with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | x | x | Benzene sulfonic acid 10% | 120 | 49 |
| Acetic acid 10% | 140 | 60 | Benzoic acid | 250 | 121 |
| Acetic acid 50% | 90 | 32 | Benzyl alcohol | x | x |
| Acetic acid, glacial | 110 | 43 | Benzyl chloride | x | x |
| Acetic anhydride | 100 | 38 | Borax | 190 | 88 |
| Acetone | x | x | Boric acid | 180 | 82 |
| Acetyl chloride | x | x | Bromine gas, dry | 100 | 38 |
| Acrylic acid | x | x | Bromine gas, moist | 100 | 38 |
| Acrylonitrile | x | x | Bromine liquid | x | x |
| Adipic acid | 220 | 104 | Butyl acetate | 80 | 27 |
| Allyl alcohol | x | x | Butyl alcohol | 100 | 38 |
| Allyl chloride | x | x | *n*-Butylamine | x | x |
| Alum 10% | 200 | 93 | Butyl phthalate | 100 | 38 |
| Aluminum chloride, aqueous | 120 | 49 | Butyric acid 20% | 200 | 93 |
| Aluminum fluoride 10% | 90 | 32 | Calcium bisulfide | x | x |
| Aluminum hydroxide | 170 | 77 | Calcium bisulfite | 150 | 66 |
| Aluminum nitrate | 160 | 71 | Calcium carbonate | 210 | 99 |
| Aluminum oxychloride | | | Calcium chlorate | 250 | 121 |
| Aluminum sulfate | 250 | 121 | Calcium chloride | 250 | 121 |
| Ammonia gas | 150 | 66 | Calcium hydroxide, sat. | x | x |
| Ammonium carbonate | 140 | 60 | Calcium hypochlorite 20% | 80 | 27 |
| Ammonium chloride 10% | 200 | 93 | Calcium nitrate | 220 | 104 |
| Ammonium chloride 50% | 200 | 93 | Calcium oxide | 150 | 66 |
| Ammonium chloride, sat. | 200 | 93 | Calcium sulfate | 250 | 121 |
| Ammonium fluoride 10% | 140 | 60 | Caprylic acid | 140 | 60 |
| Ammonium fluoride 25% | 140 | 60 | Carbon bisulfide | x | x |
| Ammonium hydroxide 25% | 90 | 32 | Carbon dioxide, dry | 250 | 121 |
| Ammonium hydroxide, sat. | 90 | 32 | Carbon dioxide, wet | 250 | 121 |
| Ammonium nitrate | 200 | 93 | Carbon disulfide | x | x |
| Ammonium persulfate | 140 | 60 | Carbon monoxide | 170 | 77 |
| Ammonium phosphate | 150 | 66 | Carbon tetrachloride | 120 | 49 |
| Ammonium sulfate 10–40% | 200 | 93 | Carbonic acid | 160 | 71 |
| Ammonium sulfide | 120 | 49 | Cellosolve | 80 | 27 |
| Ammonium sulfite | 100 | 38 | Chloracetic acid, 50% water | 100 | 38 |
| Amyl acetate | 190 | 85 | Chloracetic acid 25% | 90 | 32 |
| Amyl alcohol | 200 | 93 | Chlorine gas. dry | 200 | 93 |
| Amyl chloride | x | x | Chlorine gas, wet | 220 | 104 |
| Aniline | 120 | 49 | Chlorine liquid | x | x |
| Antimony trichloride 50% | 200 | 93 | Chlorobenzene | x | x |
| Aqua regia 3:1 | x | x | Chloroform | x | x |
| Barium carbonate | 250 | 121 | Chlorosulfonic acid | x | x |
| Barium chloride | 250 | 121 | Chromic acid 10% | 180 | 82 |
| Barium hydroxide | x | x | Chromic acid 50% | 140 | 60 |
| Barium sulfate | 180 | 82 | Chromyl chloride | 210 | 99 |
| Barium sulfide | x | x | Citric acid 15% | 250 | 121 |
| Benzaldehyde | x | x | Citric acid, concentrated | 250 | 121 |
| Benzene | 90 | 32 | Copper acetate | 210 | 99 |

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**Table H.1** Compatibility of Halogenated Polyester with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Copper chloride | 250 | 121 | Nitrous acid, concentrated | 90 | 32 |
| Copper cyanide | 250 | 121 | Oleum | x | x |
| Copper sulfate | 250 | 121 | Perchloric acid 10% | 90 | 32 |
| Cresol | x | x | Perchloride acid 70% | 90 | 32 |
| Cyclohexane | 140 | 60 | Phenol 5% | 90 | 32 |
| Dichloroacetic acid | 100 | 38 | Phosphoric acid 50–80% | 250 | 121 |
| Dichloroethane (ethylene dichloride) | x | x | Picric acid | 100 | 38 |
| Ethylene glycol | 250 | 121 | Potassium bromide 30% | 230 | 110 |
| Ferric chloride | 250 | 121 | Salicylic acid | 130 | 54 |
| Ferric chloride 50% in water | 250 | 121 | Sodium carbonate 10% | 190 | 88 |
| Ferric nitrate 10–50% | 250 | 121 | Sodium chloride | 250 | 121 |
| Ferrous chloride | 250 | 121 | Sodium hydroxide 10% | 110 | 43 |
| Ferrous nitrate | 160 | 71 | Sodium hydroxide 50% | x | x |
| Hydrobromic acid, dilute | 200 | 93 | Sodium hydroxide, concentrated | x | x |
| Hydrobromic acid 20% | 160 | 71 | Sodium hypochlorite 20% | x | x |
| Hydrobromic acid 50% | 200 | 93 | Sodium hypochlorite, concentrated | x | x |
| Hydrochloric acid 20% | 230 | 110 | Sodium sulfide to 50% | x | x |
| Hydrochloric acid 38% | 180 | 82 | Stannic chloride | 80 | 27 |
| Hydrocyanic acid 10% | 150 | 66 | Stannous chloride | 250 | 121 |
| Hydrofluoric acid 30% | 120 | 49 | Sulfuric acid 10% | 260 | 127 |
| Hypochlorous acid I0% | 100 | 38 | Sulfuric acid 50% | 200 | 93 |
| Lactic acid 25% | 200 | 93 | Sulfuric acid 70% | 190 | 88 |
| Lactic acid, concentrated | 200 | 93 | Sulfuric acid 90% | x | x |
| Magnesium chloride | 250 | 121 | Sulfuric acid 98% | x | x |
| Malic acid 10% | 90 | 32 | Sulfuric acid 100% | x | x |
| Methyl chloride | 80 | 27 | Sulfuric acid, fuming | x | x |
| Methyl ethyl ketone | x | x | Sulfurous acid 10% | 80 | 27 |
| Methyl isobutyl ketone | 80 | 27 | Thionyl chloride | x | x |
| Muriatic acid | 190 | 88 | Toluene | 110 | 43 |
| Nitric acid 5% | 210 | 99 | Trichloroacetic acid 50% | 200 | 93 |
| Nitric acid 20% | 80 | 27 | White liquor | x | x |
| Nitric acid 70% | 80 | 27 | Zinc chloride | 200 | 93 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable.

*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. VoIs. 1–3. New York: Marcel Dekker, 1995.

(weight percent of 1 to 15), alloy C-276 exceeds a corrosion rate of 20 mpy, while alloy C-2000 provides good resistance up to a concentration of 3 weight percent. Excellent resistance is also displayed in oxidizing media such as nitric acid and solutions containing ferric ions, cupric ions, or dissolved oxygen.

Hastelloy and alloy C-2000 are trademarks of Haynes International Inc.

See Refs. 5 and 6.

## HEAT-AFFECTED ZONE (HAZ)

A heat-affected zone is an area of a section of metal in which the mechanical properties and/or the microstructure has been changed by the heat of welding or thermal cutting.

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**Table H.2** Mechanical and Physical Properties of High Silicon Iron

| Property | Duriron | Durichlor |
|---|---|---|
| Modulus of elasticity $\times 10^6$, psi | 23 | 23 |
| Tensile strength $\times 10^3$, psi | 16 | 17 |
| Elongation in 2 in., % | nil | nil |
| Hardness. Brinell | 520 | 520 |
| Density, lb/in.$^3$ | 0.255 | 0.255 |
| Specific gravity | 7.0 | 7.0 |
| Specific heat at 32–212°F, Btu/lb °F | 0.13 | 0.13 |
| Coefficient of thermal expansion $\times 10^{-6}$, Btu/ft$^2$ h/°F/in. | | |
| at 32–212°F | | 7.2 |
| at 68–392°F | 7.4 | |

For most welds in carbon and low-alloy steels, the heat affected zone is a band, usually approximately $\frac{1}{8}$ in. (3 mm) wide, adjacent to the fusion line of the weld. In austenitic stainless steels, there may be generated a secondary HAZ some distance from the fusion line as a result of welding-induced sensitization.

## HIGH-SILICON IRON

There are two high-silicon iron alloys that are of value in the corrosion field, both of which are manufactured by the Duriron Company. The first alloy, known as Duriron, contains nominally 14.5% silicon and 1% carbon, with the balance iron. When 4% chromium is added, the product is known as Durichlor. These are cast alloys.

The high-silicon content improves corrosion resistance, but it also lowers some of the mechanical properties as compared with gray iron. Silicon irons are hard and brittle and therefore do not stand up well under shock and impact. Because of their hardness high silicon irons are good for combined corrosion–erosion service. These alloys cannot withstand any substantial stressing or impact, and they cannot be subjected to sudden fluctuations in temperature. Refer to Table H.2 for the mechanical and physical properties.

High-silicon irons have excellent corrosion resistance to a wide range of chemicals. One of the major applications is in handling sulfuric acid. It is resistant to all concentrations of sulfuric acid, up to and including the normal boiling point. This alloy will handle nitric acid above 30% to the boiling point. Below 30% the temperature is limited to about 180°F (27°C). Refer to Table H.3 for the compatibility of high-silicon iron with selected corrodents.

Refer to Ref. 1 for a broader range of the compatibility of high-silicon iron with selected corrodents.

See also Ref. 7

## HIGH-TEMPERATURE CORROSION

High-temperature environments may be oxidizing or reducing, in a manner analogous to aqueous corrosion. There is even an electron transfer involved and an "electrolyte" (i.e., the semiconductive layer of corrosion products). There is a migration of ions and

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**Table H.3** Compatibility of High-Silicon Iron[a] with Selected Corrodents[b]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | 90 | 32 | Bromine gas, dry | x | x |
| Acetic acid 10% | 200 | 93 | Bromine gas, moist | 80 | 27 |
| Acetic acid 50% | 200 | 93 | Butyl alcohol | 80 | 27 |
| Acetic acid 80% | 260 | 127 | Butyl phthalate | 80 | 27 |
| Acetic acid, glacial | 230 | 110 | Butyric acid | 80 | 27 |
| Acetic anhydride | 120 | 49 | Calcium bisulfite | x | x |
| Acetone | 80 | 27 | Calcium carbonate | 90 | 32 |
| Acetyl chloride | 80 | 27 | Calcium chlorate | 80 | 27 |
| Acrylonitrile | 80 | 27 | Calcium chloride | 210 | 99 |
| Adipic acid | 80 | 27 | Calcium hydroxide, sat. | 200 | 93 |
| Allyl alcohol | 80 | 27 | Calcium hypochlorite | 80 | 27 |
| AlIyl chloride | 90 | 32 | Calcium sulfate | 80 | 27 |
| Alum | 240 | 116 | Caprylic acid | 90 | 32 |
| Aluminum acetate | 200 | 93 | Carbon bisulfide | 210 | 99 |
| Aluminum fluoride | x | x | Carbon dioxide, dry | 570 | 299 |
| Aluminum hydroxide | 80 | 27 | Carbon dioxide, wet | 80 | 27 |
| Aluminum nitrate | 80 | 27 | Carbon tetrachloride | 210 | 99 |
| Aluminum sulfate | 80 | 27 | Carbonic acid | 80 | 27 |
| Ammonium bifluoride | x | x | Cellosolve | 90 | 32 |
| Ammonium carbonate | 200 | 93 | Chloracetic acid, 50% water | 80 | 27 |
| Ammonium chloride 10% | | | Chloracetic acid | 90 | 32 |
| Ammonium chloride 50% | 200 | 93 | Chlorobenzene | 80 | 27 |
| Ammonium fluoride 10% | x | x | Chloroform | 90 | 32 |
| Ammonium fluoride 25% | x | x | Chromic acid 10% | 200 | 93 |
| Ammonium hydroxide 25% | 210 | 99 | Chromic acid 50% | 200 | 93 |
| Ammonium nitrate | 90 | 32 | Chromyl chloride | 210 | 99 |
| Ammonium persulfate | 80 | 27 | Citric acid, concentrated | 200 | 93 |
| Ammonium phosphate | 90 | 32 | Copper chloride | x | x |
| Ammonium sulfate 10–40% | 80 | 27 | Copper cyanide | 80 | 27 |
| Amyl acetate | 90 | 32 | Copper sulfate | 100 | 38 |
| Amyl alcohol | 90 | 32 | Cyclohexane | 80 | 27 |
| Amyl chloride | 90 | 32 | Cyclohexanol | 80 | 27 |
| Aniline | 250 | 121 | Dichloroethane (ethylene dichloride) | 80 | 27 |
| Antimony trichloride | 80 | 27 | Ethylene glycol | 210 | 99 |
| Aqua regia 3:1 | x | x | Ferric chloride | x | x |
| Barium carbonate | 80 | 27 | Ferric nitrate 10–50% | 90 | 32 |
| Barium chloride | 80 | 27 | Ferrous chloride | 100 | 38 |
| Barium sulfate | 80 | 27 | Fluorine gas, dry | x | x |
| Barium sulfide | 80 | 27 | Hydrobromic acid, dilute | x | x |
| Benzaldehyde | 120 | 49 | Hydrobromic acid 50% | x | x |
| Benzene | 210 | 99 | Hydrochloric acid 20%[c] | 80 | 27 |
| Benzene sulfonic acid 10% | 90 | 32 | Hydrocyanic acid 10% | x | x |
| Benzoic acid | 90 | 32 | Hydrofluoric acid 30% | x | x |
| Benzyl alcohol | 80 | 27 | Hydrofluoric acid 70% | x | x |
| Benzyl chloride | 90 | 32 | Hydrofluoric acid 100% | x | x |
| Borax | 90 | 32 | Ketones, general | 90 | 32 |
| Boric acid | 80 | 27 | Lactic acid 25% | 90 | 32 |

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**Table H.3** Compatibility of High-Silicon Iron[a] with Selected Corrodents[b] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Lactic acid, concentrated | 90 | 32 | Sodium chloride to 30% | 150 | 66 |
| Magnesium chloride 30% | 250 | 121 | Sodium hydroxide 10% | 170 | 77 |
| Malic acid | 90 | 32 | Sodium hydroxide 50% | x | x |
| Methyl ethyl ketone | 80 | 27 | Sodium hydroxide. concentrated | x | x |
| Methyl isobutyl ketone | 80 | 27 | Sodium hypochlorite 20% | 60 | 16 |
| Nitric acid 5% | 180 | 82 | Sodium hypochlorite, concentrated | | |
| Nitric acid 20% | 180 | 82 | Sodium sulfide to 50% | 90 | 32 |
| Nitric acid 70% | 186 | 86 | Stannic chloride | x | x |
| Nitric acid, anhydrous | 150 | 66 | Stannous chloride | x | x |
| Nitrous acid, concentrated | 80 | 27 | Sulfuric acid 10% | 212 | 100 |
| Oleum | x | x | Sulfuric acid 50% | 295 | 146 |
| Perchloric acid 10% | 80 | 27 | Sulfuric acid 70% | 386 | 197 |
| Perchloric acid 70% | 80 | 27 | Sulfuric acid 90% | 485 | 252 |
| Phenol | 100 | 38 | Sulfuric acid 98% | 538 | 281 |
| Phosphoric acid 50–80% | 210 | 99 | Sulfuric acid 100% | 644 | 340 |
| Picric acid | 80 | 27 | Sulfurous acid | x | x |
| Potassium bromide 30% | 100 | 38 | Trichloracetic acid | 80 | 27 |
| Salicylic acid | 80 | 27 | | | |

[a]Resistance applies to Duriron unless otherwise noted.
[b]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable when compatible corrosion rate is < 20 mpy.
[c]Resistance applies only to Durichlor.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed Vols. 1–3. New York: Marcel Dekker, 1995.

electrons between the metal, corrosion product layer, and environment. The overall nature of the corrosion is dependent upon the ratio of the specific gases, vapors, or molten materials present. The common materials encountered in gaseous media are as in the table.

| Oxidizing | Reducing |
|---|---|
| Oxygen | Hydrogen |
| Steam | Hydrogen sulfide |
| Sulfurous oxides ($SO_2$, $SO_3$) | Carbon disulfide |
| Sulfur | Carbon monoxide |
| Carbon dioxide | Carbon |
| Chlorine | Hydrocarbons |
| Oxides of nitrogen | Hydrogen chloride |
| | Ammonia |

Molten metals can cause chemical reactions, whereas molten salts can be either oxidizing or reducing.

As with aqueous corrosion, a protective oxide film is formed. The rate at which the metal oxidizes will depend on the stability of the film.

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If the film is stable and remains in place, the rate will he logarithmic, diminishing with time. Cycling temperatures will tend to spall off the surface film, leading to a stepwise oxidation of the alloy.

Although most high-temperature corrosion is considered to be oxidation, there are other forms that are also encountered such as oxidation–reduction, sulfidation, fuel-ash corrosion, carburization, and nitridation.

### Oxidation–Reduction

An environment of hot air, oxygen, steam, carbon dioxide, etc., will tend to oxidize a metal, while an environment of hydrogen, hydrogen-rich gases, or carbon monoxide is reducing and tends to convert the oxides back to the metallic state. In mixtures, the ratio of carbon monoxide to carbon dioxide determines the carburization or decarburization conditions. The same analogy holds for other combinations of oxidizing and reducing species such as hydrogen and water vapor, nitric oxides and ammonia, and sulfurous oxides with hydrogen sulfide. Further complicating the situation is the fact that one atmosphere may be reducing to one component such as nickel but oxidizing to another such as chromium or silicon.

### Sulfidation

Sulfidation is analogous to oxidation insofar as a sulfide film is formed on the surface of the metal. However, sulfide films are less protective than the corresponding oxide films.

### Carburization

Carburizing is not a specific type of corrosion, but it does reduce the efficiency of a prior oxide film by the formation of chromium carbides, which deplete the matrix of chromium. The most common corrosion phenomenon associated with carburization is general absorption. Another form of attack is metal dusting, where under alternating oxidizing and reducing conditions localized high-carbon areas are burned out during the oxidation period.

### Nitriding

Nitriding takes place when active nitrogen reacts with hot surfaces. Because elements like chromium, aluminum, and titanium readily form nitrides, the integrity of the protective oxide film is at risk,

Whenever the oxide film is damaged or removed, the metal becomes subject to corrosion.

### Fuel-Ash Corrosion

Fuel-ash corrosion is the result of the dissolving of the protective oxide film by the alkaline and sulfur constituents present in some heavier liquid petroleum and solid fuels.

While many of the austenitic stainless steels and high-nickel alloys can be utilized at elevated temperatures, there are some instances where these materials are not suitable.

### Alloys for High-Temperature Corrosion

Alloys that are designed to resist high-temperature corrosion are basically oxidation-resistant materials, since all forms of attack at elevated temperatures are considered to be

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oxidation. As with aqueous corrosion, a protective oxide film is formed. The rate at which the metal will oxidize will depend upon the stability of the film. If the film is stable and remains in place, the rate will be logarithmic, diminishing with time.

Cycling temperatures will tend to spall off the surface film, leading to a stepwise oxidation of the alloy. Changes in the environment can also have the same effect.

Although all high-temperature corrosion is considered to be oxidation, there are other terms that are also encountered, such as oxidation/reduction, sulfidation, fuel-ash corrosion, carburization, and nitridation, to mention a few.

While many of the high-nickel alloys previously discussed can be utilized at elevated temperatures, there are some instances where these materials are not satisfactory. Consequently, other alloys have been developed to overcome these shortcomings.

### *Haynes Alloy No. 556*

The presence of 18% cobalt in this alloy provides greater resistance to sulfidation than many nickel-based alloys such as alloy X or alloy 800H. In pure oxidation, alloy 556 shows good resistance, but it is superseded in performance by other alloys, such as alloys N and 214.

In chloride-bearing oxidizing environments, the alloy shows better resistance than alloys 800H and X but not as good as alloy 214.

In carburizing environments, the alloy is better than 310 stainless steel and some nickel-based alloys such as alloy X and 617 but not as good as the aluminum-containing alloys such as alloy 214.

Typical applications include internals of municipal waste incinerators and refractory anchors in a refinery train-gas-burning unit.

### *Haynes Alloy No. 214*

This alloy possesses the highest oxidation resistance of any of the nickel-based alloys to both static and dynamic environments. Alloy 214 develops a tenacious aluminum oxide layer at the surface. The aluminum film also provides superior resistance to carburizing environments containing chlorine and oxygen.

As is typical of many high-temperature alloys, this alloy does not have good resistance to aqueous chloride solutions, so dew point conditions must be avoided.

Typical applications of this alloy include mesh belts for supporting chinaware while being heated in a kiln, strand annealing tubes for making medical-grade stainless wire, and honeycomb seals in turbine engines.

### *Hastelloy Alloy No. 230*

The outstanding feature of this alloy is its superior nitridation resistance. This property, with its high creep strength, has enabled use of the alloy as a catalyst support grid in the manufacture of nitric acid. It also exhibits good resistance to carburization. However, the alloy does not possess adequate resistance to sulfidizing environments

Reference 1 provides an extensive listing of the compatibility of high-nickel alloys with various corrodents.

### *Hastelloy Alloy X*

Hastelloy alloy X possesses a combination of high strength and excellent oxidation resistance. Its oxidation resistance is due to the formation of a complex chromium oxide

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spinel that provides good resistance up to temperatures of 2150°F (1177°C). The high-temperature strength and resistance to warpage and distortion provide outstanding performance as distributor plates and catalyst grid supports.

Typical applications in the process industries are as distributor plates in the production of magnesium chloride and grid supports in the manufacture of nitric acid. Alloy X is a major material of construction in the hot section of gas turbine engines for such parts as burner cans and transition ducts.

## HYDROGEN DAMAGE

The degradation of physical and mechanical properties resulting from the action of hydrogen is known as hydrogen damage. The hydrogen may be initially present in the metal or it may be accumulated through absorption. In most cases, the damage is associated with residual or applied stresses. The damage may be in the form of

1. Loss of ductility and/or tensile strength.
2. Sustained propagation of defects at stresses well below those required for mechanical fracture.
3. Internal damage due to defect formation.
4. Macroscopic damage, such as internal flaking, blistering, fissuring, and cracking.

Hydrogen damage has occurred in many metals and alloys. High-strength steels are particularly vulnerable, and there have been many incidents of failure of oil drilling and other equipment made of high-strength steels working in "sour" oil fields as a result of hydrogen damage. All types of stainless steels; aluminum, nickel, copper, and their alloys; titanium and zirconium alloys; and refractory metals such as tungsten, niobium, vanadium, and tantalum are subject to hydrogen damage.

### Sources of Hydrogen

Metals are capable of absorbing hydrogen from various sources. Atomic hydrogen, rather than molecular hydrogen, is considered to be responsible for the damage. However, atomic hydrogen may be absorbed from a molecular hydrogen gas atmosphere. Hydrogen is readily available in environments such as water, water vapor, moist air, acids, hydrocarbons, hydrogen sulfide, and various liquids and gases utilized in chemical process operations.

Hydrogen may be introduced during several stages of equipment manufacture, even before the equipment is placed into service. Hydrogen can be introduced into the lattice of the metal during welding, heat treating in hydrogen-containing furnace atmospheres, acid pickling, or electroplating operations.

Underbead cracking is an embrittlement phenomenon associated with hydrogen pickup during welding operations. Hydrogen entry into metal results from moisture in electrode coating, high humidity in the atmosphere, and organic contaminants on the surface of prepared joints. Upon rapid cooling of the weld, entrapped hydrogen can produce internal fissuring and other damages.

During acid pickling or electroplating, and as a result of corrosion in service, atomic hydrogen is generated on the metal surface as a cathodic reduction product that diffuses in the bulk material. When the material is stressed, the diffusion rate is particularly high. In the pickling of steel, the level of hydrogen absorption is dependent on both the bath temperature and the nature of the acid.

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Liquids or gases containing hydrogen sulfide can embrittle certain high-strength steels. Wet hydrogen sulfide environments are considered to be one of the most effective in promoting hydrogen entry. In these cases, hydrogen sulfide reacts with the steel to form atomic hydrogen:

$$Fe + H_2S \rightarrow FeS + 2H$$

The chemisorbed sulfur partially poisons the hydrogen recombination reaction and promotes hydrogen absorption. When the pH of the solution is above 8, a protective iron sulfide film forms on the metal surface, which protects the steel and stops the corrosion. If cyanides are present, the protective film will be destroyed. The unprotected steel corrodes rapidly, and hydrogen damage results. Only a few ppm of hydrogen sulfide is sufficient to cause embrittlement or cracking in steel. Hydrogen stress cracking is a serious problem in petrochemical equipment used to store and handle the sour or hydrogen sulfide–containing fuels.

Exposure to process fluids containing hydrogen, as in catalytic cracking, can result in hydrogen entry into the material. Exposure to hydrogen gas or molecular hydrogen under high pressure and temperature enhances hydrogen entry and induces damage in iron alloys, nickel alloys, and titanium alloys. Hydrogen gas even at one atmosphere is capable of causing cracking in high-strength steel.

Regardless of the source of the hydrogen, the effect on the metal is the same.

## Types of Hydrogen Damage

The specific types of hydrogen damage are as follows:

1. Hydrogen embrittlement, which may be further divided as
   a. loss in tensile ductility
   b. hydrogen stress cracking
   c. hydrogen environment embrittlement
   d. embrittlement due to hydride formation
2. Hydrogen blistering
3. Flakes, fish eyes, and shatter cracks
4. Hydrogen attack

## Hydrogen Embrittlement

### *Loss of Ductility*

The entry of hydrogen into a metal results in decreases in elongation and reduction in area without the formation of any visible defects, chemical products, or cracking. The loss of ductility is only observed during slow-strain rate testing and conventional tensile tests. Tensile strength is also affected, but there is no loss in impact strength. Consequently, impact tests cannot be used to determine whether or not embrittlement is present. The degree of loss of ductility is a function of hydrogen content of the metal, as seen in Fig. H.1.

The loss of ductility is temporary and can be reversed by driving the hydrogen out of the metal by heating the metal. The rate of recovery depends on time and temperature. The higher the temperature, the shorter the time period required. However, the temperature should not exceed 598°F (315°C) because of the risk of high-temperature hydrogen attack.

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### *Hydrogen Stress Cracking*

Hydrogen stress cracking (HSC) refers to the brittle fracture of a normally ductile alloy under a sustained level in the presence of hydrogen. Carbon and low-alloy steels, stainless steels, nickel alloys, and aluminum alloys are susceptible to HSC. Hydrogen stress cracking is also referred to as hydrogen-induced cracking (HIC), hydrogen-assisted cracking (HAC), delayed fracture, and static fatigue. The cracking of high-strength steels in hydrogen sulfide environment, known as sulfide stress cracking, is a special case of HSC.

The cracking of embrittled metal is caused by static external stresses, transformation stresses, (e.g., as a result of welding), internal stresses, cold working, and hardening. In the absence of a sharp initial crack, the hydrogen-induced fracture often starts at subsurface sites where triaxial stress is highest. If a sharp crack is present, the hydrogen cracking may start at the tip of the preexisting crack. High hydrogen concentration ahead of the crack tip helps the crack to grow. A total hydrogen content as low as 0.1–10 ppm is sufficient to induce cracking. However, local concentrations of hydrogen are usually greater than average bulk values.

A feature of HSC is that the occurrence of the fracture is delayed, indicating that hydrogen diffusion in the metal lattice is important for the build-up of sufficient hydrogen concentration at the regions of triaxial stresses for crack nucleation or at the crack tip for its propagation. The susceptibility to cracking therefore depends on hydrogen gas pressure and temperature, factors that influence the diffusion process. Increasing the hydrogen pressure reduces the threshold stress intensity for crack propagation and increases the crack growth rate for specific stress intensity value. The threshold stress intensity and crack growth rate are a function of the specific hydrogen environment.

The susceptibility of steels to embrittlement depends to a large extent on their microstructure. A highly tempered martensitic structure with equiaxial ferritic grains and spheroidized carbides evenly distributed throughout the matrix have maximum resistance to embrittlement compared with normalized steels at equivalent strength levels. The resistance also increases with decreasing prior austenitic grain size. The presence of retained austenite is helpful because it either absorbs hydrogen or slows down crack growth. The effects of individual alloying elements on cracking susceptibility are associated with their effects on the heat treatment, microstructure, and strength of the steels. In general, carbon, phosphorus, sulfur, manganese, and chromium increase susceptibility and titanium decreases the sensitivity to HSC by decreasing the amount of hydrogen available for cracking.

The behavior of stainless steels in hydrogen environments is dependent upon their strength levels. Because of the low hardness of ferritic stainless steels, they are extremely resistant to HSC. However, in the as-welded or cold-worked condition they are susceptible. As a result of the higher strength of the martensitic and precipitation-hardening stainless steels, they are the most susceptible to HSC. In the annealed or highly cold-worked condition, the austenitic stainless steels are highly resistant to hydrogen cracking.

Although hydrogen stress cracking and stress corrosion cracking (SCC) are similar, there are certain distinguishing features between the two cracking processes:

1. The "specific ion" effect necessary for SCC is absent in HSC.
2. The application of cathodic potential or current, which retards or stops SCC, increases the intensity of HSC.

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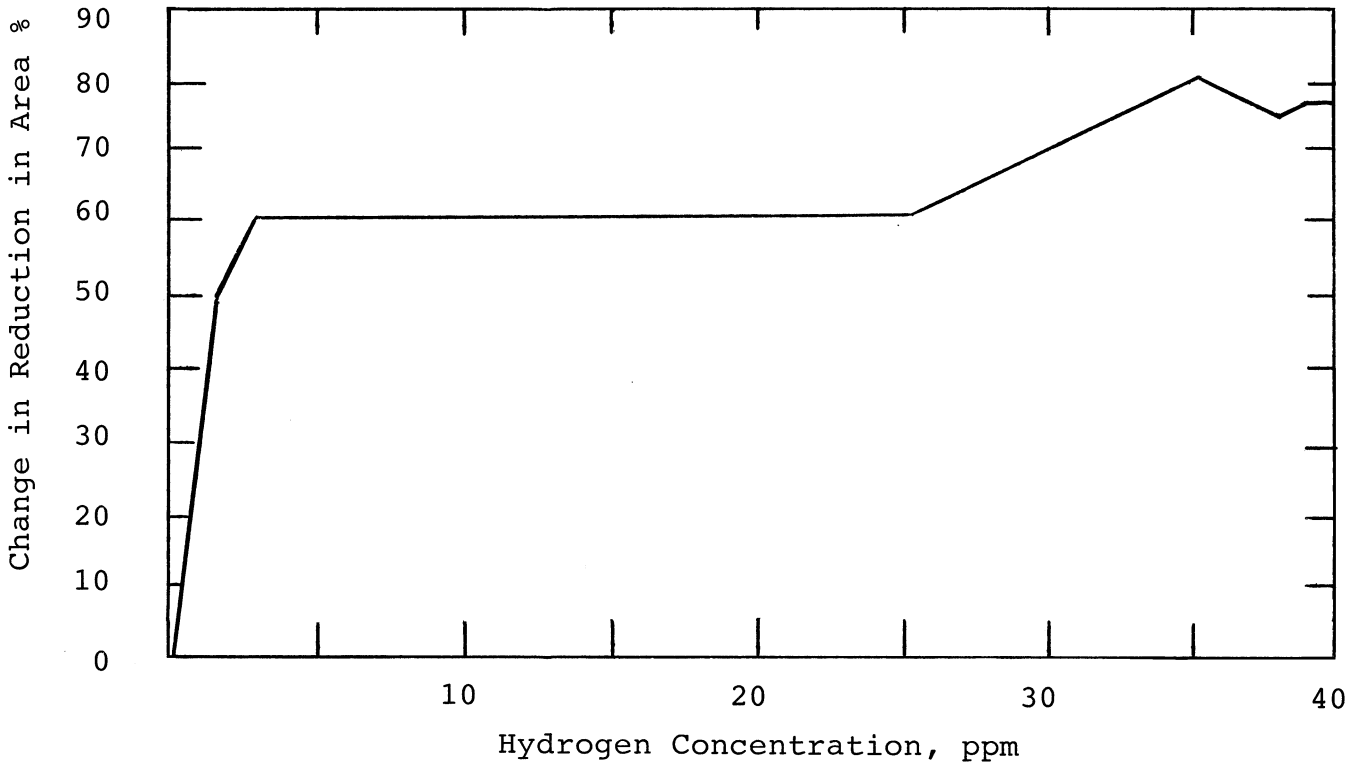



**Figure H.1** Loss of ductility in steel as a function of hydrogen content.



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3. Stress corrosion cracks generally originate at the surface, while hydrogen embrittlement failures originate internally.
4. HSC usually produces sharp singular cracks in contrast to the branching of cracks observed in SCC.

### *Hydrogen Environment Embrittlement*

Hydrogen environment embrittlement is the embrittlement encountered in an essentially hydrogen-free material when it is plastically deformed or mechanically tested in gaseous hydrogen. This phenomenon has been observed in ferritic steels, nickel alloys, aluminum alloys, titanium alloys, and some metastable stainless steels in hydrogen gas pressures ranging from 35 to 70 MPa. Embrittlement appears to be most severe at room temperatures. The degree of embrittlement is maximum at low strain rates and when the gas purity is high. These characteristics are the same as those observed for HSC. Because of this, there is some question as to whether or not this should be treated as a separate class of embrittlement. However, there is one exception. While nickel alloys are very susceptible to hydrogen environment embrittlement, they are relatively insusceptible to HSC.

### *Embrittlement Due to Hydride Formation*

Embrittlement and cracking of titanium, zirconium, tungsten, vanadium, tantalum, niobium, uranium, thorium, and their alloys are the result of hydride formation. Significant increases in strength and large losses in tensile ductility and impact strength are found. The brittleness is associated with the fracture of the hydride particle or its interface.

The solubility of hydrogen in these metals is $10^3$–$10^4$ times greater than that of iron, copper, nickel, and aluminum and increases with a decrease in temperature. The solubility tends toward saturation at low temperature, and at atmospheric pressure the composition of the solution approaches that of a finite compound hydride or a pseudo-hydride. The crack either gets stopped at the ductile matrix or continues to grow by ductile rupture of the regions between the hydrides. For some metal–hydrogen systems, the application of stress increases hydride formation. In these cases, the stress-induced hydride formation at the crack tip leads to a continued brittle fracture propagation. Titanium and zirconium form stable hydrides under ambient conditions when hydrogen is absorbed in excess of 150 ppm. Absorption of hydrogen by these metals increases rapidly if the protective oxide film normally present on the metal is damaged mechanically or by chemical reduction. Surface contaminants (e.g., iron smears) enhance hydrogen intake, and the absorption is accelerated at temperatures exceeding 160°F (70°C). Hydrogen is readily picked up during melting or welding, and hydride formation takes place during subsequent cooling. When sufficient hydrogen is present, the cracking is attributed to the strain-induced formation of hydrides.

## Hydrogen Blistering

This type of damage is prevalent in low-strength unhardened steels as a result of the pressure generated by the combination of atomic hydrogen into molecular hydrogen.

Hydrogen blistering literally means the formation of surface bulges resembling a blister. The generation of hydrogen gas in voids or other defect sites located near the surface can lead to such a condition. The blisters often rupture, producing surface cracks. Internal hydrogen blistering along grain boundaries (fissures) can lead to hydrogen-induced stepwise cracking.

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Killed steels are more susceptible to blistering than semikilled steels because of greater hydrogen intake after deoxidation, but the nature and size of inclusion are overriding factors. Rimmed steels are highly susceptible because of the inherent presence of voids. Sulfur-bearing steels are also especially prone because sulfur favors the hydrogen entry by acting as a cathodic poison.

Hydrogen blistering is encountered mostly during acid pickling operations. Corrosion-generated hydrogen causes blistering of steel in oil well equipment and petroleum storage and refining equipment.

## Flakes, Fish Eyes, and Shatter Cracks

Flaking refers to small internal fissures that occur in steels when cooled from temperatures on the order of 2012°F (1100°C) in hydrogen atmospheres. These are also described as fish eyes, shatter cracks, or snowflakes and are common hydrogen damage found on forgings, weldments, and castings.

The extent of damage is dependent on the time of exposure in a hydrogen-containing environment. The cracks produced are readily detectable by radiographic or ultrasonic inspection or by visual and microscopic observation of traverse sections.

## Hydrogen Attack

Hydrogen attack is a form of damage that occurs in carbon and low-alloy steels exposed to high-pressure gas at high temperatures for extended time. The damage may result in the formation of cracks and fissures or loss in strength of the alloy. This condition is prevalent above 392°F (200°C). The reaction takes place between absorbed hydrogen and the iron carbide or the carbon in solution forming hydrocarbons:

$$2H + Fe_3 \rightarrow CH_4 + 3Fe$$

The methane produced does not dissolve in the iron lattice, and internal gas pressures lead to the formation of fissures or cracks. The strength and ductility of the steel may be lowered by the generated defects of the decarburization, which may take place internally or at the surface. In the latter case, the decarburized layer grows to increasing depths as the reaction continues. Cracking may develop in the metal under tensile stress. Temperature and hydrogen partial pressures determine the extent of the damage. Surface decarburization takes place at temperatures above 1004°F (540°C) and internal decarburization above 342°F (200°C). Hydrogen attack can take several forms within the metal structure depending upon the severity of the attack, stress, and the presence of inclusions in the steel. When stress is absent, a component may undergo a general surface attack. Areas of high-stress concentrations are often the initiation point of hydrogen attack. Isolated decarburized and fissured areas are often found adjacent to weldments. Severe hydrogen attack may also result in laminations and the formation of blisters.

The stability of carbides determines the resistance of steels to hydrogen attack. Alloying with carbide-stabilizing elements such as chromium, molybdenum, vanadium, and titanium has beneficial effects. Austenitic stainless steels are not subject to hydrogen attack.

See Refs. 8 through 11.

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## HYDROGEN PROBES

Hydrogen probes are used to detect the penetration of atomic or nascent hydrogen into metal pipes and vessels. There are three basic types of hydrogen probes. For more details, refer to "Monitoring Corrosion."

## HYDROLYSIS

Hydrolysis is a reaction of a salt with water to form an acid and a base; it is also the chemical reaction of any compound with water. It also refers to a decomposition process in the presence of water, particularly of coatings or paints.

## HYLAR

See "Polyvinylidene Fluoride."

## HYPALON

See "Chlorosulfonated Polyethylene Rubber."

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# I

## IMMERSION COATINGS

Immersion coatings are coatings for marine service. The most common formulations are coal tar epoxies and straight epoxies. These coatings resist moisture absorption, moisture transfer, and electroendosmosis (electrochemically induced diffusion of moisture through the coating).

Cathodic protection is usually used in conjunction with these coatings to supplement the protection supplied by the immersion coating.

## IMPERVIOUS GRAPHITE

Graphite is a crystalline form of carbon produced from carbon particles bonded with materials that carbonize when produced at processing temperatures in excess of 3600°F (1980°C). The normal fine-grain graphite is porous. By impregnating with organic resins such as phenolic or furan prior to the final heat treatment, the graphite is made impervious.

Impervious graphite has a wide range of chemical resistance. Its stability depends upon the impregnating resin. A phenolic resin provides chemical resistance to most acids, salt solutions, and organic compounds. A furan resin imparts resistance against alkaline and oxidizing media. The normal maximum operating temperature is 338°F (170°C), depending upon the corrosive media. Higher temperatures can be achieved by impregnating with PTFE.

Table I.1 shows the compatibility of impervious graphite with selected corrodents. Additional data are available in Refs. 1 and 2.

## IMPINGEMENT CORROSION ATTACK

Impingement corrosion is a localized pitting type of erosion corrosion resulting from the impinging or turbulent flow of liquids. See "Forms of Corrosion."

## INHIBITORS

See "Corrosion Inhibitors."

## INORGANIC COATINGS

See "Coatings" also.



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**Table I.1** Compatibility of Impervious Graphite with Selected Corrodents[a]

| Chemical | Resin | Max. temp. °F | Max. temp. °C |
|---|---|---|---|
| Acetaldehyde | phenolic | 460 | 238 |
| Acetamide | phenolic | 460 | 238 |
| Acetic acid 10% | furan | 400 | 204 |
| Acetic acid 50% | furan | 400 | 204 |
| Acetic acid 80% | furan | 400 | 204 |
| Acetic acid, glacial | furan | 401 | 204 |
| Acetic anhydride | furan | 400 | 204 |
| Acetone | furan | 400 | 204 |
| Acetyl chloride | furan | 460 | 238 |
| Acrylic acid | | | |
| Acrylonitrile | furan | 400 | 204 |
| Adipic acid | furan | 460 | 238 |
| Allyl alcohol | | x | x |
| Aluminum chloride, aqueous | phenolic | 120 | 49 |
| Aluminum chloride, dry | furan | 460 | 238 |
| Aluminum fluoride | furan | 460 | 238 |
| Aluminum hydroxide | furan | 250 | 121 |
| Aluminum nitrate | furan | 460 | 238 |
| Aluminum sulfate | phenolic | 460 | 238 |
| Ammonium bifluoride | phenolic | 390 | 199 |
| Ammonium carbonate | phenolic | 460 | 238 |
| Ammonium chloride 10% | phenolic | 400 | 204 |
| Ammonium hydroxide 25% | phenolic | 400 | 204 |
| Ammonium hydroxide, sat. | phenolic | 400 | 204 |
| Ammonium nitrate | furan | 460 | 238 |
| Ammonium persulfate | furan | 250 | 121 |
| Ammonium phosphate | furan | 210 | 99 |
| Ammonium sulfate 10–40% | phenolic | 400 | 204 |
| Amyl acetate | furan | 460 | 238 |
| Amyl alcohol | furan | 400 | 204 |
| Amyl chloride | phenolic | 210 | 99 |
| Aniline | furan | 400 | 204 |
| Aqua regia 3:1 | | x | x |
| Barium chloride | furan | 250 | 121 |
| Barium hydroxide | phenolic | 250 | 121 |
| Barium sulfate | phenolic | 250 | 121 |
| Barium sulfide | phenolic | 250 | 121 |
| Benzaldehyde | furan | 460 | 238 |
| Benzene | furan | 400 | 204 |
| Benzene sulfonic acid 10% | phenolic | 460 | 238 |
| Borax | furan | 460 | 238 |
| Boric acid | phenolic | 460 | 238 |
| Bromine gas, dry | | x | x |

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**Table I.1** Compatibility of Impervious Graphite with Selected Corrodents[a] (Continued)

| Chemical | Resin | Max. temp. °F | Max. temp. °C |
|---|---|---|---|
| Bromine gas, moist | | x | x |
| Butadiene | furan | 460 | 238 |
| Butyl acetate | furan | 460 | 238 |
| Butyl alcohol | furan | 400 | 204 |
| *n*-Butylamine | phenolic | 210 | 99 |
| Butyric acid | furan | 460 | 238 |
| Calcium bisulfate | furan | 460 | 238 |
| Calcium carbonate | phenolic | 460 | 238 |
| Calcium chloride | furan | 460 | 238 |
| Calcium hydroxide 10% | furan | 250 | 121 |
| Calcium hydroxide, sat. | furan | 250 | 121 |
| Calcium hypochlorite | furan | 170 | 77 |
| Calcium nitrate | furan | 460 | 238 |
| Calcium oxide | | | |
| Calcium sulfate | furan | 460 | 238 |
| Carbon bisulfide | furan | 400 | 204 |
| Carbon dioxide, dry | phenolic | 460 | 238 |
| Carbon dioxide, wet | phenolic | 460 | 238 |
| Carbon disulfide | furan | 400 | 204 |
| Carbon monoxide | phenolic | 460 | 238 |
| Carbon tetrachloride | furan | 400 | 204 |
| Carbonic acid | phenolic | 400 | 204 |
| Cellosolve | furan | 460 | 238 |
| Chloracetic acid, 50% water | furan | 400 | 204 |
| Chloracetic acid | furan | 400 | 204 |
| Chlorine gas, dry | furan | 400 | 204 |
| Chlorine liquid | phenolic | 130 | 54 |
| Chlorobenzene | phenolic | 400 | 204 |
| Chloroform | furan | 400 | 204 |
| Chlorosulfonic acid | | x | x |
| Chromic acid 10% | | x | x |
| Chromic acid 50% | | x | x |
| Citric acid 15% | furan | 400 | 204 |
| Citric acid, conc. | furan | 400 | 204 |
| Copper chloride | furan | 400 | 204 |
| Copper cyanide | furan | 460 | 238 |
| Copper sulfate | phenolic | 400 | 204 |
| Cresol | furan | 400 | 204 |
| Cupric chloride 5% | furan | 400 | 204 |
| Cupric chloride 50% | furan | 400 | 204 |
| Cyclohexane | furan | 460 | 238 |
| Ethylene glycol | furan | 330 | 166 |
| Ferric chloride 60% | phenolic | 210 | 99 |
| Ferric chloride 50% in water | furan | 260 | 127 |

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**Table I.1** Compatibility of Impervious Graphite with Selected Corrodents[a] (Continued)

| Chemical | Resin | Max. temp. °F | Max. temp. °C |
|---|---|---|---|
| Ferric nitrate 10–50% | furan | 210 | 99 |
| Ferrous chloride | furan | 400 | 204 |
| Fluorine gas, dry | phenolic | 300 | 149 |
| Fluorine gas, moist | | x | x |
| Hydrobromic acid, dilute | furan | 120 | 49 |
| Hydrobromic acid 20% | furan | 250 | 121 |
| Hydrobromic acid 50% | furan | 120 | 49 |
| Hydrochloric acid 20% | phenolic | 400 | 204 |
| Hydrochloric acid 38% | phenolic | 400 | 204 |
| Hydrocyanic acid 10% | furan | 460 | 238 |
| Hydrofluoric acid 30% | phenolic | 460 | 238 |
| Hydrofluoric acid 70% | | x | x |
| Hydrofluoric acid 100% | | x | x |
| Iodine solution 10% | phenolic | 120 | 49 |
| Ketones, general | furan | 400 | 204 |
| Lactic acid 25% | furan | 400 | 204 |
| Lactic acid, concentrated | furan | 400 | 204 |
| Magnesium chloride | furan | 170 | 77 |
| Manganese chloride | furan | 460 | 238 |
| Methyl chloride | phenolic | 460 | 238 |
| Methyl ethyl ketone | furan | 460 | 238 |
| Methyl isobutyl ketone | furan | 460 | 238 |
| Muriatic acid | phenolic | 400 | 204 |
| Nitric acid 5% | phenolic | 220 | 104 |
| Nitric acid 20% | phenolic | 220 | 104 |
| Nitric acid 70% | | x | x |
| Nitric acid, anhydrous | | x | x |
| Nitrous acid, concentrated | | x | x |
| Oleum | | x | x |
| Phenol | furan | 400 | 204 |
| Phosphoric acid 50–80% | phenolic | 400 | 204 |
| Potassium bromide 30% | furan | 460 | 238 |
| Salicylic acid | furan | 340 | 171 |
| Sodium carbonate | furan | 400 | 204 |
| Sodium chloride | phenolic | 400 | 204 |
| Sodium hydroxide 10% | furan | 400 | 204 |
| Sodium hydroxide 50% | furan | 400 | 204 |
| Sodium hydroxide, concentrated | | x | x |
| Sodium hypochlorite 20% | | x | x |
| Sodium hypochlorite, concentrated | | x | x |
| Stannic chloride | furan | 400 | 204 |
| Sulfuric acid 10% | phenolic | 400 | 204 |
| Sulfuric acid 50% | phenolic | 400 | 204 |

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**Table I.1** Compatibility of Impervious Graphite with Selected Corrodents[a] (Continued)

| Chemical | Resin | Max. temp. °F | Max. temp. °C |
|---|---|---|---|
| Sulfuric acid 70% | phenolic | 400 | 204 |
| Sulfuric acid 90% | phenolic | 400 | 204 |
| Sulfuric acid 98% | | x | x |
| Sulfuric acid 100% | | x | x |
| Sulfuric acid, fuming | | x | x |
| Sulfurous acid | phenolic | 400 | 204 |
| Thionyl chloride | phenolic | 320 | 160 |
| Toluene | furan | 400 | 204 |
| Trichloroacetic acid | furan | 340 | 171 |
| Zinc chloride | phenolic | 400 | 204 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

Inorganic coatings are coatings (paint) employing inorganic binders or vehicles such as silicates or phosphates, which are usually pigmented with metallic zinc. Unlike organic coatings, in which the pigment is secondary to the resistance of the organic binders, the role of the zinc pigment in the zinc-rich coating predominates, and the high amount of zinc dust metal in the dried film determines the coating's basic property, galvanic protection.

This term also refers to cold-applied ceramic coatings, which are not as dense or glossy as a fused ceramic coating.

## INTERGRANULAR CORROSION

This is a localized form of attack taking place at the grain boundaries of a metal with little or no attack on the grain boundaries themselves. This results in loss of strength and ductility. The attack is often rapid, penetrating deeply into the metal and causing failure.

In the case of austenitic stainless steels, the attack is the result of carbide precipitation during welding operations. Carbide precipitation can be prevented by using alloys containing less than 0.03% carbon, by using alloys that have been stabilized with columbium or titanium, or by specifying solution heat treatment followed by a rapid quench that will keep the carbides in solution. The most practical approach is to use either a low carbon content or stabilized austenitic stainless steel.

Nickel-based alloys can also be subjected to carbide precipitation and precipitation of intermetallic phases when exposed to temperatures lower than their annealing temperatures. As with the austenitic stainless steels, low carbon content alloys are recommended to delay precipitation of carbides. In some alloys, such as alloy 625, niobium, tantalum, or titanium is added to stabilize the alloy against precipitation of chromium or molybdenum carbides. These elements combine with carbon instead of chromium or molybdenum.

See Refs. 3–7. See also "Forms of Corrosion."

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## ISO

See "Polyvinylidene Fluoride."

## ISOCORROSION DIAGRAM

An isocorrosion diagram is a chart or graph showing constant corrosion behavior with changing conditions such as temperature, solution concentration, or other environment composition. The isocorrosion diagram for Monel 400 in hydrofluoric acid is shown in Fig. I.1.

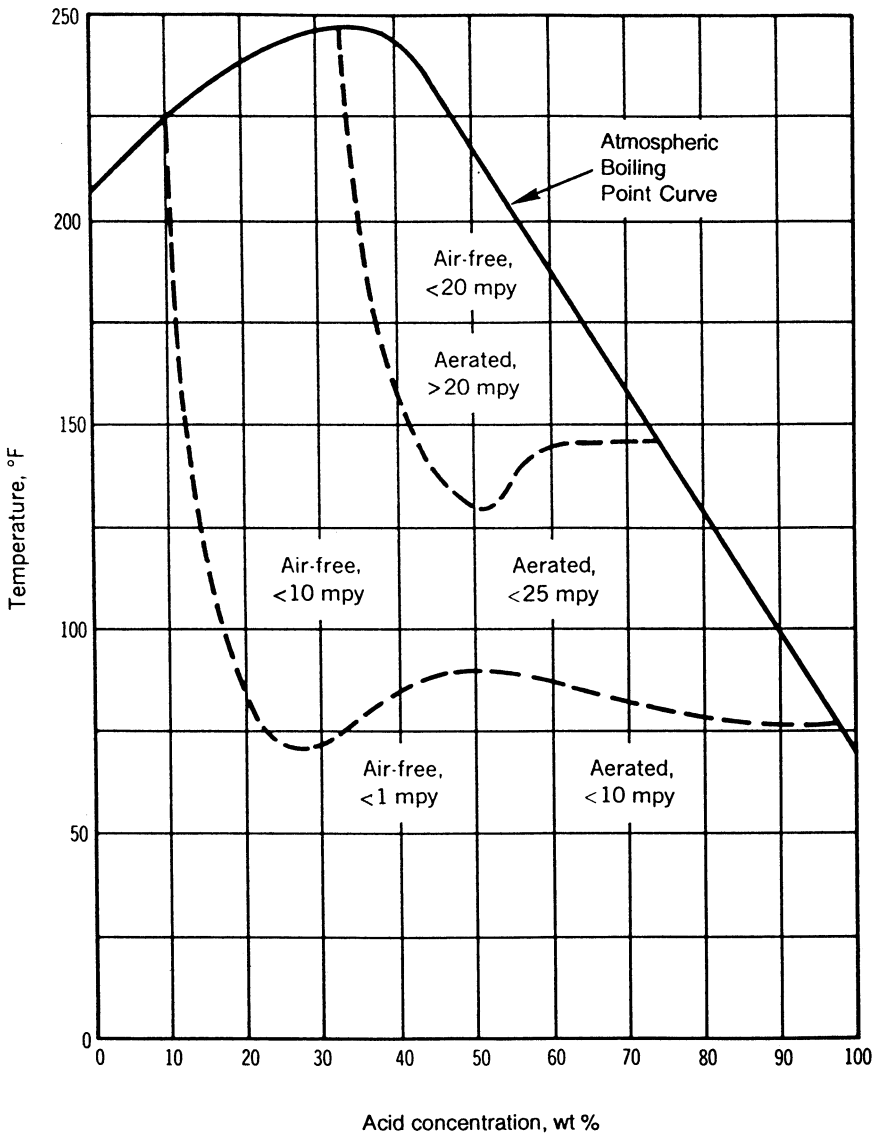



**Figure I.1** Isocorrosion diagram for Monel 400.

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## ISOPHTHALIC ESTERS

Also see "Polymers" and "Thermoset Polymers."

The isophthalic esters have a relatively wide range of corrosion resistance. They are satisfactory for use up to 125°F (52°C) in such acids as 10% acetic, benzoic, boric, citric, oleic, 25% phosphoric, tartaric, 10–25% sulfuric, and fatty acids. Most inorganic salts are also compatible with the isophthalic esters. Solvents such as amyl alcohols, ethylene glycol, formaldehyde, gasoline, kerosene, and naphtha are also compatible.

The isophthalic resins are not resistant to acetone, amyl acetate, benzene, carbon disulfides, solutions of alkaline salts of potassium and sodium, hot distilled water, or higher concentrations of oxidizing acids. Refer to Table I.2 for the compatibility of the isophthalic resins with selected corrodents. Refer to Ref. 1 for a wider range of compatibility of the isophthalic esters with selected corrodents.

Also see Refs. 8–10.

## ISOPRENE RUBBER (IR)

Chemically, natural rubber is natural *cis*-polyisoprene. The synthetic form of natural rubber, synthetic *cis*-polyisoprene, is called isoprene rubber. The physical and mechanical

**Table I.2** Compatibility of Isophthalic Polyester with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetaldehyde | x | x | Ammonium fluoride 25% | 90 | 32 |
| Acetic acid 10% | 180 | 82 | Ammonium hydroxide 25% | x | x |
| Acetic acid 50% | 110 | 43 | Ammonium hydroxide, sat. | x | x |
| Acetic acid 80% | x | x | Ammonium nitrate | 160 | 71 |
| Acetic acid, glacial | x | x | Ammonium persulfate | 160 | 71 |
| Acetic anhydride | x | x | Ammonium phosphate | 160 | 71 |
| Acetone | x | x | Ammonium sulfate 10% | 180 | 82 |
| Acetyl chloride | x | x | Ammonium sulfide | x | x |
| Acrylic acid | x | x | Ammonium sulfite | x | x |
| Acrylonitrile | x | x | Amyl acetate | x | x |
| Adipic acid | 220 | 104 | Amyl alcohol | 160 | 71 |
| Allyl alcohol | x | x | Amyl chloride | x | x |
| Allyl chloride | x | x | Aniline | x | x |
| Alum | 250 | 121 | Antimony trichloride | 160 | 71 |
| Aluminum chloride, aqueous | 180 | 82 | Aqua regia 3:1 | x | x |
| Aluminum chloride, dry | 170 | 77 | Barium carbonate | 190 | 88 |
| Aluminum fluoride 10% | 140 | 60 | Barium chloride | 140 | 60 |
| Aluminum hydroxide | 160 | 71 | Barium hydroxide | x | x |
| Aluminum nitrate | 160 | 71 | Barium sulfate | 160 | 71 |
| Aluminum sulfate | 180 | 82 | Barium sulfide | 90 | 32 |
| Ammonia gas | 90 | 32 | Benzaldehyde | x | x |
| Ammonium carbonate | x | x | Benzene | x | x |
| Ammonium chloride 10% | 160 | 71 | Benzene sulfonic acid 10% | 180 | 82 |
| Ammonium chloride 50% | 160 | 71 | Benzoic acid | 180 | 82 |
| Ammonium chloride, sat. | 180 | 82 | Benzyl alcohol | x | x |
| Ammonium fluoride 10% | 90 | 32 | Benzyl chloride | x | x |

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**Table I.2** Compatibility of Isophthalic Polyester with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Borax | 140 | 60 | Cupric chloride 50% | 170 | 77 |
| Boric acid | 180 | 82 | Cyclohexane | 80 | 27 |
| Bromine gas, dry | x | x | Dichloroacetic acid | x | x |
| Bromine gas, moist | x | x | Dichloroethane (ethylene dichloride) | x | x |
| Bromine liquid | x | x | Ethylene glycol | 120 | 49 |
| Butyl acetate | x | x | Ferric chloride | 180 | 82 |
| Butyl alcohol | 80 | 27 | Ferric chloride 50% in water | 160 | 71 |
| *n*-Butylamine | x | x | Ferric nitrate 10–50% | 180 | 82 |
| Butyric acid 25% | 120 | 49 | Ferrous chloride | 180 | 82 |
| Calcium bisulfide | 160 | 71 | Ferrous nitrate | 160 | 71 |
| Calcium bisulfite | 150 | 66 | Fluorine gas, dry | x | x |
| Calcium carbonate | 160 | 71 | Fluorine gas, moist | x | x |
| Calcium chlorate | 160 | 71 | Hydrobromic acid, dilute | 120 | 49 |
| Calcium chloride | 180 | 82 | Hydrobromic acid 20% | 140 | 60 |
| Calcium hydroxide 10% | 160 | 71 | Hydrobromic acid 50% | 140 | 60 |
| Calcium hydroxide, sat. | 160 | 71 | Hydrochloric acid 20% | 160 | 71 |
| Calcium hypochlorite 10% | I20 | 49 | Hydrochloric acid 38% | 160 | 71 |
| Calcium nitrate | 140 | 60 | Hydrocyanic acid 10% | 90 | 32 |
| Calcium oxide | 160 | 71 | Hydrofluoric acid 30% | x | x |
| Calcium sulfate | 160 | 71 | Hydrofluoric acid 70% | x | x |
| Caprylic acid | 160 | 71 | Hydrofluoric acid 100% | x | x |
| Carbon bisulfide | x | x | Hypochlorous acid | 90 | 32 |
| Carbon dioxide, dry | 160 | 71 | Ketones, general | x | x |
| Carbon dioxide, wet | 160 | 71 | Lactic acid 25% | 160 | 71 |
| Carbon disulfide | x | x | Lactic acid, concentrated | 160 | 71 |
| Carbon monoxide | 160 | 71 | Magnesium chloride | 180 | 82 |
| Carbon tetrachloride | x | x | Malic acid | 90 | 32 |
| Carbonic acid | 160 | 71 | Methyl ethyl ketone | x | x |
| Cellosolve | x | x | Methyl isobutyl ketone | x | x |
| Chloracetic acid, 50% water | x | x | Muriatic acid | 160 | 71 |
| Chloracetic acid to 25% | 150 | 66 | Nitric acid 5% | 120 | 49 |
| Chlorine gas, dry | 160 | 71 | Nitric acid 20% | x | x |
| Chlorine gas. wet | 160 | 71 | Nitric acid 70% | x | x |
| Chlorine liquid | x | x | Nitric acid, anhydrous | x | x |
| Chlorobenzene | x | x | Nitrous acid, concentrated | 120 | 49 |
| Chloroform | x | x | Oleum | x | x |
| Chlorosulfonic acid | x | x | Perchloric acid 10% | x | x |
| Chromic acid 10% | x | x | Perchloric acid 70% | x | x |
| Chromic acid 50% | x | x | Phenol | x | x |
| Chromyl chloride | 140 | 60 | Phosphoric acid 50–80% | 180 | 82 |
| Citric acid 15% | 160 | 71 | Picric acid | x | x |
| Citric acid, concentrated | 200 | 93 | Potassium bromide 30% | 160 | 71 |
| Copper acetate | 160 | 71 | Salicylic acid | 100 | 38 |
| Copper chloride | 180 | 82 | Sodium carbonate 20% | 90 | 32 |
| Copper cyanide | 160 | 71 | Sodium chloride | 200 | 93 |
| Copper sulfate | 200 | 93 | Sodium hydroxide 10% | x | x |
| Cresol | x | x | Sodium hydroxide 50% | x | x |
| Cupric chloride 5% | 170 | 77 | Sodium hydroxide, concentrated | x | x |

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**Table I.2** Compatibility of Isophthalic Polyester with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Sodium hypochlorite 20% | x | x | Sulfuric acid 98% | x | x |
| Sodium hypochlorite, concentrated | x | x | Sulfuric acid 100% | x | x |
| Sodium sulfide to 50% | x | x | Sulfuric acid, fuming | x | x |
| Stannic chloride | 180 | 82 | Sulfurous acid | x | x |
| Stannous chloride | 180 | 82 | Thionyl chloride | x | x |
| Sulfuric acid 10% | 160 | 71 | Toluene | 110 | 43 |
| Sulfuric acid 50% | 150 | 66 | Trichloroacetic acid 50% | 170 | 77 |
| Sulfuric acid 70% | x | x | White liquor | x | x |
| Sulfuric acid 90% | x | x | Zinc chloride | 180 | 82 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable.

properties of isoprene rubber are similar to the physical and mechanical properties of natural rubber, the one major difference being that isoprene does not have an odor. This feature permits the use of isoprene rubber in certain food-handling applications.

Isoprene rubber can he compounded, processed, and used in the same manner as natural rubber. Other than the lack of odor, isoprene rubber has no advantages over natural rubber. See "Natural Rubber."

See Refs. 11 and 1.

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# K

## KALREZ

Kalrez is the trademark of E.I. DuPont for their perfluoroelastomer that has the chemical resistance of Teflon. When comparing the corrosion and fluid resistance of Kalrez with Teflon, certain differences should be kept in mind. Kalrez is an amorphous, low-modulus rubber, whereas Teflon is a crystalline, high-modulus plastic. In fluid environments where high permeation occurs, Kalrez will probably swell to a greater extent than Teflon, even though the polymer is not attacked. This is most noticeable in fully halogenated solvents. As with all elastomers, Kalrez perfluoroelastomer is compounded with fillers and curatives in order to produce desired mechanical properties. In a limited number of environments, the additives may interact with the environment.

Refer to Table K.1 for the compatibility of Kalrez with selected corrodents.

## KEVLAR

Kevlar is an ararnid fiber (trademark of E. I. DuPont de Nemours) used as reinforcing in laminates. See "Thermoset Reinforcing Materials."

## KILLED CARBON STEEL

Raw liquid steel contains oxygen as iron oxides or as dissolved gas. Carbon is also contained in the liquid steel. The oxygen and carbon can react to form carbon monoxide. This reaction can cause violent boiling during pouring and the solidification process. The excess oxygen can be removed as slag by adding an oxygen scavenger such as silicon to the molten steel prior to pouring. The resulting material does not boil during pouring and cooling, thereby producing a more homogeneous "killed steel." These steels are cleaner and contain fewer defects than "unkilled" or "wild" steels.

Steels can also be killed with a combination of silicon and aluminum or with aluminum alone. Silicon, when used alone to deoxidize the steel, tends to produce a coarse grain structure. These steels have a relatively high brittle-ductile transition temperature. This precludes their use for applications requiring low-temperature toughness. However, the coarse-grained steels are more resistant to creep, graphitization, and some forms of corrosion.

When the steel is deoxidized with a combination of silicon and aluminum or with aluminum alone, a fine austenitic grain size is produced. These steels are used for applications requiring low-temperature toughness.



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**Table K.1** Compatibility of Kalrez with Selected Corrodents

Kalrez is suitable for use with the following corrodents up to a temperature of 212°F/100°C.

| | | |
|---|---|---|
| Acetone | Chromic acid | Maleic acid |
| Acetonitrile | Coke oven gas | Maleic anhydride |
| Acetophenone | Cresol | Methyl acetate |
| Acetyl chloride | Cresylic acid | Methyl acrylate |
| Acetylene | Cumene | Methyl butyl ketone |
| Aluminum acetate | Cyclohexanol | Methyl cellosolve |
| Aluminum bromate | Cyclohexanone | Methyl chloride |
| Aluminum chloride | Diacetone | Methyl formate |
| Aluminum fluoride | Diacetone alcohol | Methyl isobutyl ketone |
| Ammonium acetate | Dibenzyl ether | Methyl methacrylate |
| Ammonium bisulfite | Dibutyl ether | Methyl salicylate |
| Ammonium bromide | Dibutyl phthalate | Methylene chloride |
| Ammonium chloride | o-Dichlorobenzene | Mineral oil |
| Amyl acetate | Diethyl amine | Monochlorobenzene |
| Amyl alcohol | Diethyl benzene | Naphtha |
| Aniline dyes | Diethyl ether | Nitrobenzene |
| Aniline hydrochloride | Dinitrotoluene | Nitroethane |
| Aqua regia | Dioxane | Nitromethane |
| Arsenic trisulfide | Dipentene | *n*-Octane |
| Benzaldehyde | Ethyl acetate | Octyl alcohol |
| Benzene | Ethyl acrylate | Oleic acid |
| Benzene sulfonic acid | Ethyl ether | Oleum |
| Benzoic acid | Ethylene chloride | Paint thinner |
| Benzoyl chloride | Ethylene dichloride | Perchloroethylene |
| Benzyl alcohol | Ethylene oxide | Petroleum above 250°F |
| Benzyl chloride | Ethylene trifluoride | Phenol |
| Bromine, aqueous | Fatty acids | Phenyl benzene |
| Bromobenzene | Fluorobenzene | Phosphoric acid 20% |
| Butadiene | Furan | Phosphoric acid 40% |
| Butyl acetate | Gallic acid | Phosphorus, molten |
| Butyl acrylate | Gasoline | Phosphorus oxychloride |
| Butyl benzoate | Hydrobromic acid 40% | Phosphorus trichloride |
| Butyl carbitol | Hydrochloric acid 37% | Phthalic acid |
| Butyl cellosolve | Hydrocyanic acid | Picric acid |
| Calcium acetate | Hydrofluoric acid, anhy. | Piperdine |
| Calcium bisulfite | Hydrofluoric acid, conc. | Potassium acetate |
| Calcium hypochlorite | Hydrogen peroxide 90% | Potassium hydroxide |
| Carbamate | Hydroquinone | Propyl acetate |
| Carbon bisulfide | Isophorone | Propyl acetone |
| Carbon tetrachloride | Isopropyl acetate | Propyl nitrate |
| Cellosolve | Isopropyl chloride | Propylene |
| Chlorine, dry | Isopropyl ether | Propylene oxide |
| Chloroacetone | Lactic acid | Pyridine |
| Chlorobenzene | Lavender oil | Silicate esters |
| Chloroform | Lead acetate | Sodium acetate |

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**Table K.1** Compatibility of Kalrez with Selected Corrodents (Continued)

| Kalrez is suitable for use with the following corrodents up to a temperature of 212°F/100°C. | | |
|---|---|---|
| Sodium fluorosilicate | Sulfur dioxide, wet | Tributyl phosphate |
| Sodium hydroxide | Sulfur trioxide | Trichloroethane |
| Sodium hypochlorite | Sulfuric acid, conc. | Trichloroethylene |
| Sodium trichloride, wet | Sulfuric acid, dil. | Turbine oils |
| Stearic acid | Sulfurous acid | Varnish |
| Sulfite liquors | Tetrohydrofuran | Vinyl chloride |
| Sulfur | Thionyl chloride | Xylene |
| Sulfur chloride | Titanium tetrachloride | |
| Sulfur dioxide, dry | Toluene | |

Using an oxygen scavenger is the primary method of deoxidation. A less common method is vacuum degassing. Vacuum degassing not only controls oxidizing gasses such as oxygen and carbon dioxide but also will help to limit nonoxidizing gasses such as nitrogen and hydrogen. This treatment substantially decreases the number of nonmetallic inclusions in the steel and is used for bearings and other high-quality steel.

When steel cools in a mold, shrinkage of the steel on solidifying causes "piping." The cavity of a "pipe" is usually found in the upper portion of the ingot. To minimize this condition, a large-end-up mold is used together with a refractory "hot top" that supplies molten steel to the main body of the ingot while solidification takes place. This minimizes the quantity of metal that has to be discarded because of piping.

To reduce the large percentage of metal that must be discarded when making steel for structural purposes, the steel is not fully oxidized. This results in blowholes in the steel on solidification. These blowholes minimize the piping by distributing small voids throughout the ingot instead of having one large one in the upper center of the ingot. As long as the blowholes are not exposed on the surface, they will weld together during rolling. Steel deoxidized in this manner is called semikilled steel.

If the molten steel is deoxidized still less, a reaction takes place during solidification in which the oxygen and carbon react to form carbon monoxide, which is freely evolved from the ingot. This evolution affects the structure of the ingot. When the reaction is allowed to go to completion, the product is called "rimmed steel." If the reaction is stopped in a mechanical manner after a short period of time preventing further evolution of the gas from the top of the ingot, the product is called "capped steel."

Rimmed steel ingots have an outer skin that is clean and very low in carbon. In capped steel the skin is thinner and there is less segregation or concentration of impurities than in rimmed steel.

## KNIFE-LINE ATTACK

Knife-line attack is a highly localized form of intergranular corrosion. Titanium or columbium is added to the type 300 stainless steels to prevent the precipitation of chromium carbide by permitting the alloy to precipitate titanium or columbium carbide, instead of chromium carbide.

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There are two problems with this approach. Titanium will lose much of its effectiveness in multipass welding or cross-welding (intercepting horizontal and vertical welds). Columbium does not react in this manner, but the columbium carbides, as well as the titanium carbides, can be redissolved by the heat of welding, particularly with alloys of higher nickel content. Because of this, cross-welding or multiple-pass welding can first redissolve titanium or columbium carbides and then allow chromium carbide precipitation in the "fusion zone" and not the heat-affected zone. This results in knife-line attack at the "fusion zone." The alloys most subject to this form of attack are type 347 stainless steel and alloy 825. See "Forms of Corrosion."

## KYNAR

See "Polyvinylidene Fluoride."

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# L

## LAMELLAR CORROSION

See "Exfoliation Corrosion."

## LAYER CORROSION

Layer corrosion is a localized attack of a metal surface. The attack is in thin parallel layers oriented to the direction of metal processing and leads to unattached metal layers being released like pages in a hook. See "Forms of Corrosion."

## LEAD AND LEAD ALLOYS

Lead is a weak metal, unable to support its own weight; therefore, alloys have been developed to improve its physical and mechanical properties.

Chemical lead is lead with traces of copper and silver left from the original ore. It is not economical to recover the copper and silver. The copper content is believed to improve the general corrosion resistance and to add stiffness.

### Corrosion Resistance

The corrosion resistance of lead is due primarily to the protective film formed by the insolubility of some of its corrosion products.

Lead is resistant to atmospheric exposures, particularly atmospheres in which a protective $PbSO_4$ film forms.

Being amphotoric, lead is attacked by both acids and alkalies under certain conditions. Lead is corroded by alkalies at moderate or high rates depending on aeration, temperature, and concentration. In caustics lead is limited to concentrations of 10% maximum up to 195°F (90°C). It will resist cold strong amines but is attacked by dilute aqueous amine solutions.

Lead will be attacked by hydrochloric acid and nitric acid as well as organic acids if they are dilute or if they contain oxidizing agents. It is resistant to sulfuric, sulfurous, chromic, and phosphoric acids and cold hydrofluoric acid.

Lead is also subject to attack by soft aggressive waters, but is resistant to most natural waters. Because of the toxicity of lead salts, lead should not be used to handle potable (drinking) water.

Initially, lead is anodic to more highly alloyed materials, but due to a film of insoluble corrosion products on its surface, it may become cathodic in time. There have been



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instances where alloy 20 valves have undergone accelerated attack in lead piping systems handling sulfuric acid services. In such applications it is necessary to electrically isolate the valves from the piping to prevent galvanic action.

Because of the toxicity problems associated with lead burning (joining process), applications of lead have been greatly reduced in modern practice.

Refer to Table L.1 for the compatibility of lead with selected corrodents.

**Table L.1** Compatibility of Lead with Selected Corrodents[a]

| Corrodent | °F/°C | Corrodent | °F/°C |
|---|---|---|---|
| Acetic acid | U | Hydrocyanic acid | U |
| Acetic anhydride | 80/27 | Hydrofluoric acid to 50% | 100/38 |
| Acetone | 190/88 | Hydrofluoric acid 70% | U |
| Acetone 50% water | 212/100 | Hydrogen peroxide | U |
| Acetophenone | 140/60 | Hydrogen sulfide, wet | U |
| Allyl alcohol | 220/104 | Hypochlorous acid | U |
| Allyl chloride | U | Jet fuel, JP-4 | 170/77 |
| Aluminum chloride | U | Kerosene | 170/77 |
| Ammonium nitrate | U | Lactic acid | U |
| Arsenic acid | U | Lead acetate | U |
| Barium hydroxide | U | Lead sulfate | 150/66 |
| Barium sulfide | U | Magnesium chloride | U |
| Boric acid | 130/54 | Magnesium hydroxide | U |
| Butyric acid | U | Magnesium sulfate | 150/66 |
| Calcium bisulfite | U | Mercuric chloride | U |
| Calcium chloride | U | Methyl alcohol | 150/66 |
| Calcium hydroxide | U | Methyl ethyl ketone | 150/66 |
| Calcium hypochlorite | U | Methyl isobutyl ketone | 150/66 |
| Carbon bisulfide | 170/77 | Monochlorobenzene | U |
| Carbon dioxide, dry | 170/77 | Nickel nitrate | 212/100 |
| Carbon dioxide, wet | 180/82 | Nickel sulfate | 212/100 |
| Carbonic acid | U | Nitric acid | U |
| Chlorobenzene | 150/66 | Oleic acid | U |
| Chloroform | 140/60 | Oleum | 80/27 |
| Chromic acid 10–50% | 212/100 | Oxalic acid | U |
| Citric acid | U | Phenol | 90/32 |
| Copper sulfate | 140/60 | Phosphoric acid to 80% | 150/66 |
| Cresylic acid | U | Picric acid | U |
| Dichloroethane | 150/66 | Potassium carbonate | U |
| Ethyl acetate | 212/100 | Potassium cyanide | U |
| Ethyl chloride | 150/66 | Potassium dichromate to 30% | 130/54 |
| Ferric chloride | U | Potassium hydroxide | U |
| Ferrous chloride | U | Potassium nitrate | 80/27 |
| Fluorine gas | 200/93 | Potassium permanganate | U |
| Formic acid 10-85% | U | Potassium sulfate10% | 80/27 |
| Hydrobromic acid | U | Propane | 80/27 |
| Hydrochloric acid | U | Pyridine | 100/38 |

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**Table L.1** Compatibility of Lead with Selected Corrodents[a] (Continued)

| Corrodent | °F/°C | Corrodent | °F/°C |
|---|---|---|---|
| Salicylic acid | 100/38 | Sodium nitrate | U |
| Silver nitrate | U | Sodium perborate | U |
| Sodium bicarbonate | 80/27 | Stannic chloride | U |
| Sodium bisulfate | 90/32 | Stannous chloride | U |
| Sodium bisulfite | 90/32 | Stearic acid | U |
| Sodium carbonate | U | Sulfite liquors | 100/38 |
| Sodium chloride to 30% | 212/100 | Sulfur dioxide, dry | 180/82 |
| Sodium cyanide | U | Sulfur dioxide, wet | 160/71 |
| Sodium hydroxide to 50% | U | Sulfuric acid to 50% | 212/100 |
| Sodium hydroxide 70% | 120/49 | Sulfuric acid 60–70% | 180/82 |
| Sodium hypochlorite | U | Sulfuric acid 80–100% | 100/38 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by a U. When compatible, the corrosion rate is less than 20 mpy.
*Source:* Ref. 6.

### Lead Alloys

Antimonial lead (also called hard lead) is an alloy containing from 2% to 6% antimony to improve the mechanical properties. It is used in places where greater strength is needed. Hard lead can be used in services up to 200°F (93°C). Above this temperature strength and corrosion resistance are reduced. Cast lead–antimony alloys containing 6% to 14% antimony have a tensile strength of 7000 to 8000 psi with elongation decreasing from 24% to 10%. The lead–antimony alloys in the range of 2% to 8% antimony are susceptible to heat treatment, which increases their strength; however, this treatment is rarely employed.

Tellurium lead is a lead alloy containing a fraction of 1% of tellurium. This alloy has better resistance to fatigue failure caused by vibration because of its ability to work harden under strain.

There are also a number of proprietary alloys to which copper and other elements have been added to improve corrosion resistance and creep resistance.

## LININGS, SHEET

See "Sheet Linings."

## LIQUID APPLIED LININGS

Of the various coating applications the most critical is that of a tank lining. The coating must be resistant to the corrodent and be free of pinholes through which the corrosive could penetrate and reach the substrate. The severe attack that many corrosives have on the bare tank emphasizes the importance of using the correct procedure in lining a tank to obtain a perfect coating. It is also essential that the tank be designed and constructed in the proper manner to permit a perfect lining to be applied.

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Liquid applied linings or coatings may be troweled on or spray applied. In a lined tank there are usually four areas of contact with the stored material. Each area has the potential of developing a different form of corrosive attack. These areas are the bottom of the tank (where moisture and other contaminants of greater density may settle), the liquid phase (the area constantly immersed), the interphase (the area where the liquid phase meets the vapor phase), and the vapor phase (the area above the liquid). Each of these areas can be more severely attacked than the rest at one time or another. The type of material contained, the nature of impurities that may be present, and the amount of water and oxygen present are all factors affecting the attack. In view of this it is necessary to understand the corrosion resistance of the lining material under each condition and not only the immersed condition.

Other factors that have an effect on the performance of the lining material are vessel design, vessel preparation prior to lining, application techniques of the coating, curing of the coating, inspection, operating instructions, and temperature limitations.

## Vessel Design

All vessels to be lined should be of welded construction. Riveted tanks will expand or contract, thus damaging the liner and causing leakage. Butt welding is preferred, but lap welding can be used, providing a fillet weld is used and all sharp edges are ground smooth. Butt welds need not be ground flush but they must be ground to a smooth rounded contour. All weld splatter must be removed. Any sharp prominence may result in a spot where the film thickness will be inadequate and noncontinuous, thus causing premature failure. Other design considerations are as follows:

1. Do not use construction that will result in the creation of pockets or crevices that will not drain or that cannot be properly sandblasted and lined.
2. All joints must be continuous and solid welded. All welds must be smooth with no porosity, holes, high spots, lumps or pockets.
3. All sharp edges must be ground to a minimum of $1\frac{1}{8}$ in. radius.
4. Outlets must be flanged or pad type rather than threaded.
5. Stiffening members should be on the outside of the vessel.
6. Tanks larger than 25 feet in diameter may require three manways for working entrances. Usually two are located at the bottom (180° apart) and one at the top. The minimum opening diameter should he 20 in., but 30 in. openings are preferable.

Concrete tanks should be located above the water table. Unless absolutely necessary, expansion joints should be avoided. Small tanks do not normally require expansion joints. Larger tanks can make use of a chemical resistant joint such as polyvinyl chloride (PVC). Any concrete curing compound used must be compatible with the lining material or removed before coating. Form joints must be made as smooth as possible. Adequate steel reinforcement must be used in a strong, dense, concrete mix to reduce movement and cracking. The coating manufacturer should be consulted for special instructions.

## Vessel Preparation

In order for the lining material to obtain maximum adhesion to the substrate surface it is essential that the surface be absolutely clean. All steel surfaces to be coated must be abrasive

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blasted to a white metal in accordance with SSPC specification SP5-63 or NACE specification 1. A white metal blast is defined as removing all rust, scales, paints, and so on, to a clean white metal that has a uniform gray-white appearance. No streaks or stains of rust or any other contaminants are allowed. At times a near white, blast-cleaned surface equal to SSPC SP-10 may be used. If this is permitted by the manufacturer of the lining material, it should be used as it is less expensive.

All dust and spent abrasive must be removed from the surface by vacuum cleaning or brushing. After blasting, all workers coming into contact with the clean surface should wear clean, protective gloves and clothing to prevent contamination of the cleaned surface. Any contamination may cause premature failure by osmotic blistering or adhesion loss. The first coat must be applied before the surface starts to rust.

Concrete surfaces must be clean, dry, and properly cured before applying the lining. All protrusions and form joints must be removed. All surfaces must be toughened by sand blasting to remove all loose, weak, or powdery concrete to open all voids and provide the necessary profile for mechanical adhesion of the coating. All dust must be removed by brushing or vacuuming. The coating manufacturer should be contacted for special priming and caulking methods.

## Lining Selection

In order to properly specify a lining material it is necessary to know specifically what is being handled and under what conditions. The following information must be known about the material being handled:

1. What are the primary chemicals to be handled and at what concentrations?
2. Are there any secondary chemicals, and if so at what concentrations?
3. Are there any trace impurities or chemicals?
4. Are there any solids present, and if so what are the particle sizes and concentrations?
5. Will there be any agitation?
6. What are the fluid purity requirements?

The answers to these questions will narrow the selection to those coatings that are compatible. However, the answers to the next set of questions will narrow the selection down to those materials that are compatible as well as to those coatings that have the required mechanical and/or physical properties.

1. What is the normal operating temperature and temperature range?
2. What peak temperatures can be reached during shutdown, startup, process upset, etc.?
3. Will any mixing areas exist where exothermic or heat of mixing temperatures may develop?
4. What is the normal operating pressure?
5. What vacuum conditions and range are possible during operation, startup, shutdown, and upset conditions?
6. Is grounding necessary?

Other factors must also be considered before the final decision can be made as to which coating to use. After the previous questions have been answered, there will still be several potential materials from which to choose.

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Service life expectation must be considered. Different protective coating options afford different degrees of protection for different periods of time at a variety of costs. Such factors as maintenance cycle, operating cycles, and reliability of the coating must all be considered. Can the facility tolerate any downtime for inspection and maintenance? If so, how often and for how long?

When these questions have all been answered, an appropriate decision can be made as to which coating material will he used.

## Lining Application

In lining a vessel the primary concern is to deposit a void-free film of the specified thickness on the surface. Any area that is considerably less than the specified thickness may have a noncontinuous film. In addition, pinholes in the coating may cause premature failure.

If the film is too thick, there is always the danger of solvents being entrapped, which can lead to bad adhesion, excessive brittleness, improper cure, and subsequent poor performance. Dry spraying of the coating should be avoided because it causes the coating to be porous. Poor film formation may be caused if thinners other than those recommended by the coating manufacturer are used. Do not permit application to take place below the temperature recommended by the manufacturer.

During application the film thickness should be checked. This can be accomplished by use of an Elcometer or Nordsen wet film thickness gauge. If the wet film thickness meets specifications, in all probability the dry film will also be within specification limits.

All gauges used to measure dry film thickness must be calibrated before use, following the manufacturer's recommended procedure. Readings should be taken at random locations on a frequent basis. Special attention should be given to hard-to-coat areas.

## Inspection

Proper inspection requires that the inspector be involved with the job from the beginning. An understanding of the design criteria of the vessel and the reasons for the specific design configuration is helpful. The inspector should participate in the prework meeting, prejob inspection, and coating application inspection. Daily inspection reports should be prepared along with a final acceptance report.

Before the coating is applied, the inspector should verify that the vessel has been properly prepared for lining. Welds must be ground smooth with a rounded contour. It is not necessary that they be ground flush. Sharp protrusions should be rounded and weld crevices opened up manually so that the coating can penetrate. If this is not possible, the projection should be removed by grinding. Back-to-back angles, tape, or stitch welding and so forth cannot be properly cleaned and coated. They should be sealed with caulking to prevent crevice corrosion.

Once the vessel has been sand blasted the inspector should work quickly so that the application of the coating to the surface is not delayed.

The inspector should examine coatings during and after application. It is important to check for porosities. The first visual inspection is mandatory to detect pinholing and provide recoat instructions. Visual inspections are performed either with the unaided eye or by the use of a magnifying glass.

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After repairs of visible defects, inspection should be done using low-voltage (75 V or less) holiday detectors that ring, buzz, or light up to show electrical contact through a porosity within the coating to the metal surface. This check should he performed after the primer or second coat, so that these areas can be touched up and made free of porosities before the final top coat. These visual techniques permit the inspector to identify areas that have been missed, damaged areas, or thin areas. In some instances white primers have been used to spot areas of low film thickness or inadequate coverage of the substrate. The final test employing instruments will provide the inspector with an accurate appraisal as to whether the proper film thickness has been met.

The inspector should also he involved in the selection of the applicator. Since a tank lining requires nearly perfect application, a knowledgeable and conscientious contractor is required. The lowest bidder is not necessarily the best choice. Evaluate the applicator before awarding the contract to ensure that the tank lining contractor is experienced in applying the specified lining. Before placing a contractor on the bidders list, review his qualifications. Inquire as to what jobs he has done using the selected lining material and follow up with those particular applications. If possible, visit his facilities and inspect his workmanship. An experienced inspector is helpful during this evaluation. Taking these steps will help to ensure installation of a tank lining that will provide the desired performance.

## Curing

Proper curing is essential if the lining is to provide the corrosion protection for which it was selected. Each coat must be cured using proper air circulation techniques. Fresh air over 50°F (10°C) and having a relative humidity of less than 89% should be supplied to an opening at the top of the vessel with an exhaust at the bottom. The air flow should be by forced-air fans and should be downward because the solvents used in coatings are usually heavier than air. This is why proper exhaustion can only be obtained with downward flow.

To prevent solvent entrapment between coats and to ensure a proper final cure, the curing time and temperature must be in accordance with the manufacturer's instructions for the specific coating material. A warm forced-air cure between coats and as a final cure will provide a dense film and tighter cross-linking, which provides superior resistance to solvents and moisture permeability. Before placing the vessel in service, the lining should be washed down with water to remove any loose overspray.

Linings must be allowed sufficient time to obtain a full cure before being placed in service. This usually requires 3–7 days. Do not skimp on this time.

When the tank is placed in service, operating instructions should be prepared and should include the maximum temperature to be used. The outside of the tank should be labeled: "Do not exceed x°F (x°C). This tank has been lined with _____. It is to be used only for _____ service."

## Properties of Lining Materials

A wide variety of lining materials are available. Information as to the corrosion resistance of specific lining materials is available from the manufacturer, If data on the resistance of a lining material to a specific corrodent are not available, then tests should be conducted by evaluating sample panels of several coating systems for at least 90 days. A six-month test would be preferable. The tests should simulate as closely as possible the actual operating

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conditions to which the coating will be subjected. This should include maximum operating temperatures, any temperature cycling, washing cycles, and whatever other conditions the coating will be exposed to.

Table L.2 lists the more common lining materials and their general area of application. Because most of these coatings are formulated products, their performance will be based on their formulation. Therefore, the resistance of these generic coatings may vary between manufacturers. If a generic coating is selected, resistance should be verified with the manufacturer.

By the same token, any testing done should be with material supplied by several manufacturers.

See Refs. 1–6.

**Table L.2** Corrosion Resistance of Lining Materials

| Type of coating | Use |
|---|---|
| Baked phenolic | Most widely used lining material. Has dry heat resistance of 400°F (204°C). Excellent resistance to acids, solvents, food products, beverages, water. Compared with other coatings its flexibility is poor. |
| Air-dried phenolic | Can be formulated for excellent resistance to alkalies, solvents, fresh water, de-ionized water; mild acid resistance. Excellent for dry products. Has dry heat resistance of 150°F (65°C). |
| Vinyl ester | Excellent resistance to strong acids. Resistant up to 400°F (204°C) depending upon thickness. |
| Vinyl polyester | Excellent resistance to acids, alkalies, solvents, and water. Resistant up to 400°F (204°C) for short duration. Continuous maximum temperature of 220°F (104°C). |
| Polyester unsaturated | Excellent resistance to strong mineral and organic acids and oxidizing materials. Very poor aromatic solvent and alkali resistance. |
| Epoxy (amine catalyst) | Good alkali resistance, fair to good resistance to mild acids, solvents, and dry food products. Widely used for covered hopper-car linings and nuclear containment facilities. Maximum temperature 275°F (135°C). |
| Baked epoxy | Excellent resistance to acids, alkalies, solvents, inorganic salts, and water. Maximum continuous temperature 325°F (163°C). |
| Epoxy polyamide | Poor acid resistance, fair alkali resistance, good resistance to water and brines. Used in storage tanks and nuclear containment facilities. |
| Epoxy polyester | Poor solvent resistance, good abrasion resistance. Used for covered hopper-car linings. |
| Coal tar | Excellent water resistance. Used for water tanks. |
| Coal tar epoxy | Excellent resistance to salt water, fresh water, mild acids, mild alkalies. Poor solvent resistance. Used for crude oil storage tanks, sewage disposal plants, and water works. |
| Asphalts | Good water and acid resistance. |
| Modified polyvinyl chloride (polyvinyl chloracetates) air-cured | Excellent resistance to strong mineral acids and water, Poor solvent resistance. Used in water immersion service, potable and marine. Used extensively for water storage tanks (beverage processing). |
| Polyvinyl chloride (PVC) plastisols | Popular acid-resistant lining. Must be heat cured. |
| Chlorinated rubber | Excellent water resistance. Poor solvent resistance. |
| Hypalon | Chemical salts. |
| Neoprene | Good acid and flame resistance. Chemical processing. |

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**Table L.2** Corrosion Resistance of Lining Materials (Continued)

| Type of coating | Use |
|---|---|
| Polysulfide | Good solvent resistance and water resistance. Used for lining jet fuel tanks. |
| Butyl rubber | Good resistance to strong acids, alkalies, aggressive salts, and oxidizing agents. Flexible coating absorbs vibration, resists wear/abrasion. |
| ECTFE | Excellent resistance to mineral and organic acids at moderate temperatures. |
| PFA | Recommended where severe corrosion is a problem. Can withstand full vacuum at 300°F (149°C). Ideal for high-purity applications. |
| Styrene-butadiene polymers | Food and beverage processing, concrete tanks. |
| Urethanes | Excellent resistance to strong mineral acids and alkalies. Fair solvent resistance. Used to line dishwashers and washing machines. |
| Rubber latex | Excellent alkali resistance. Used to line 50% and 73% caustic tanks 180–250°F (82–121°C). |
| Inorganic zinc | Jet fuel storage tanks, petroleum products. |
| Inorganic zinc solvent-based self-curing | Excellent resistance to most organic solvents (i.e., aromatic, ketones, and hydrocarbons), excellent water resistance, difficult to clean. Often sensitive to decomposition products in tanks. |
| Alkyds, epoxy esters, oleoresinous primers | Water immersion service. Primers for other top coats. |

## LIQUID METAL EMBRITTLEMENT

The failure of a solid metal under stress in contact with a liquid metal is known as liquid metal embrittlement (LME). It is also known as liquid metal cracking. The loss of ductility of a normally ductile metal is manifested as a reduction in fracture stress, strain, or both. Normally there is a change in the fracture mode from ductile to brittle intergranular or brittle transgranular (cleavage)

The failure resulting from LME may be instantaneous or it may take place after a lapse of time following the exposure of the stressed metal to a liquid metal environment. The former is the "classical" LME while the latter is often referred to as "delayed failure" or "static fatigue." In either, the presence of stress is necessary. The stress may be shear, tensile, or tortional in nature, but not compressive. LME and SCC are similar in that stress must be present; however, the propagation of fracture is much faster in LME than in SCC. If sufficient time is allowed, intergranular penetration of liquid metal may render a solid metal brittle even if stress is absent.

The elongation and reduction in area of the metal or alloy are lowered as the result of LME. The fracture stress is also reduced and in cases of severe embrittlement may be less than the yield stress of the material. However, there is no change in the yield strength and strain hardening behavior of the solid metal. The liquid metal acts only to limit the total ductility before fracture or the stress at fracture if failure occurs below the normal yield point. The failure of mild steel in molten lithium occurs at only 2–3% elongation, but the lower yield point, upper yield point, and the yield point elongation remain unaffected.

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As with SSC, all liquid metals do not embrittle all solid metals. For example, liquid mercury embrittles zinc but not cadmium; liquid gallium embrittles aluminum but not magnesium. Table L.3 lists the known embrittlement combinations.

**Table L.3** Summary of Embrittlement Combinations

| | | Liquid metal | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Solid | | Hg | | Cs | Ga | | Na | In | | Li | Sn | | Bi | | Ti | Cd | Pb | | Zn | Te | Sb | Cu | | | | | | | | |
| metal | | P | A | P | P | A | P | P | A | P | P | A | P | A | P | P | P | A | P | P | P | P | | | | | | | | | |
| Sn | P | x | | | x | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bi | P | x | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cd | P | | | x | x | x | | | | | | | | | | | | | | | | | | | | | | | | | |
| Zn | P | x | x | | x | x | | x | x | | x | | | | | | x | | | | | | | | | | | | | | |
| Mg | CA | | | | | | x | | | | | | | | | | | | x | | | | | | | | | | | | |
| Al | P | x | x | | x | | | x | | | | x | x | | | x | x | | | | | | | | | | | | | | |
| | CA | x | x | | x | | x | x | | | x | | x | x | | | x | | x | | | | | | | | | | | | |
| Ge | P | | | | x | | | x | | | x | | x | | x | x | x | | | | x | | | | | | | | | |
| Ag | P | x | x | | x | x | | | | x | | | | | | | | | | | | | | | | | | | | | |
| Cu | CP | x | x | | | | x | | | x | | | x | x | | | x | | | | | | | | | | | | | | |
| | CA | x | x | | x | | | x | x | x | x | | x | | | | x | | | | | | | | | | | | | | |
| Ni | P | x | | | | | | | | x | | | | | | | x | | | | | | | | | | | | | | |
| | CA | | | | | | | | | | x | | | | | | | | | | | | | | | | | | | | |
| Fe | P | | | | | | | | | | | | | | | | | | | | | x | | | | | | | | | |
| | CA | | | | | | | x | | x | x | | | | | x | x | x | x | x | x | x | | | | | | | | | |
| Pd | P | | | | | | | | | x | | | | | | | | | | | | | | | | | | | | | |
| Ti | CA | | x | | | | | | | | | | | | | x | | | | | | | | | | | | | | | |

P = Normally pure element
A = Alloy
C = Commercial
x = Embrittlement combination

## Requirements for Embrittlement

The general requirements for LME to occur in a ductile metal are as follows:

1. There must be wetting or intimate contact of the solid metal by the liquid metal.
2. The solid metal must be stressed to the point of producing plastic deformation.
3. There must be an adequate supply of liquid metal.

The most critical condition for LME is intimate contact between the solid metal and the liquid metal. This is required in order to initiate embrittlement and guarantee the presence of liquid metal at the tip of the propagating crack to cause brittle failure. An adequate supply of liquid metal is necessary to adsorb at the propagating crack tip. The total amount need not be large; a few monolayers of liquid atoms are necessary for LME. Even a few micrograms of liquid can cause LME.

## Factors Influencing LME

### *Grain Size*

The yield stress and the fracture stress of a metallic material normally bear a linear relationship with the inverse square root of grain diameter. The same relationship holds true

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for LME. A linear decrease of fracture strength as a function of the square root of the average grain diameter has been observed for copper and iron in molten lithium, 70-30 brass in mercury, and zinc in mercury, indicating that coarser-grained materials are more susceptible to LME. The grain size dependence of LME is indicative of a reduction in cohesive strength of the material rather than an effect of the penetration or dissolution of liquid into the grain boundary.

### *Temperature*

Except for the few cases of embrittlement caused by the vapor phase, LME takes place at temperatures above the melting point of the liquid metal. In the vicinity of the melting point of the liquid metal, LME is relatively temperature insensitive. At higher temperatures, a brittle-to-ductile transition occurs in many systems over a temperature range, and the ductitility is restored.

The brittle-to-ductile transition temperature is dependent on the presence of notch, grain size, and strain rate. The transition temperature is raised in the presence of notches. An increase in strain rate and a decrease in grain size increase the transition temperature.

### *Strain Rate*

In addition to its effect on brittle-to-ductile transition temperature, the strain rate may be an important factor for the occurrence of LME. The effect of strain rate appears to be related to the increase in yield strength, and this corresponds to an increase in LME susceptibility.

### *Alloying*

Some metals are embrittled in their pure state, such as zinc by mercury and aluminum by liquid gallium. On the other hand, pure iron is not embrittled by mercury and pure copper is relatively immune in liquid mercury (coarse-grained copper is embrittled). However, iron becomes susceptible to embrittlement in mercury when alloyed with more than 2% silicon, 4% aluminum, or 8% nickel. When copper is alloyed with zinc, aluminum, silicon, or gallium, its susceptibility to LME is increased greatly. The same occurs when zinc is alloyed with a small amount of copper or gold in mercury. The increase in yield strength of the material on alloying is considered responsible for the increased susceptibility. The high-strength alloys are more severely embrittled than low-strength alloys based on the same metal.

In iron, a nickel addition greater than 8% gives rise to martensite with coarse slip lines. In precipitation-hardening aluminum and copper alloys, maximum susceptibility to LME coincides with the peak strength of the alloys. All of these point to the generation of stress concentrations as a result of alloying.

## Delayed Failure

Delayed failure refers to those failures taking place under a sustained load after a period of time. In liquid metal environments the embrittlement and failure of some metals are time dependent.

Aluminum-copper and copper-beryllium alloys in liquid mercury exhibit delayed failure, as does AISI 4130 steel in molten lithium. Age-hardenable alloys exhibit the lowest time of fracture in the maximum hardened state. The susceptibility increases with prior strain or cold work.

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## Preventive Measures

Liquid metal embrittlement may be prevented or a reduction in occurrence may be achieved by the following measures:

1. Introduction of impurity atoms in the solid metal. Examples are the addition of phosphorus to Monel to reduce embrittlement in liquid mercury, or the addition of lanthanides to leaded steels.
2. In some cases, the addition of a second metal to the embrittling liquid decreases the embrittlement.
3. An effective barrier between the solid metal and the liquid metal. This may be a ceramic or covalent material coating.
4. Cladding with a soft, high-purity metal such as zircaloy clad with pure zirconium to resist embrittlement in liquid cadmium.
5. Elimination of the embrittling metal.
6. Reduction in the level of applied or residual stress below the static endurance limit.

## Corrosion by Liquid Metals

Because of their excellent heat transfer properties, liquid metals are being used extensively in nuclear power generation plants and in heat transfer systems making use of heat pipes containing liquid metals. Examples are liquid sodium in fast-breeder reactors, and lithium, sodium, or sodium-potassium liquid metals as the working fluid in heat transfer systems.

Liquid metal corrosion can take place through any one or a combination of the following processes:

1. Direct dissolution
2. Corrosion product formation
3. Elemental transfer
4. Alloying

### *Direct Dissolution*

Direct dissolution is the release of atoms of the containment material into the molten metal. As the liquid metal becomes saturated with the dissolving metal, the dissolution reaction decreases or stops altogether. However, in a nonisothermal liquid metal system this may not occur because of the convection from hotter to colder regions. Under this condition the dissolved metal from the "hot leg" is carried to the "cold leg," where it gets deposited. Plugging of coolant pipes result. The dissolution may be uniform or selective. The selective leaching may proceed to such an extent that voids are left in the steel.

### *Corrosion Product Formation*

At times the corrosion or reaction products form protective layers on the containment metal surface, reducing further attack. For example, the addition of aluminum or silicon to steel helps in forming such a protective layer. The addition of zirconium to liquid bismuth or mercury has an inhibiting effect on the corrosion of steel in these liquid metals. The nitrogen present in steel forms a surface layer of ZrN, a very stable compound and an effective diffusion barrier.

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### *Elemental Transfer*

Elemental transfer refers to the net transfer of impurities to or from a liquid metal. In such a case the liquid metal atoms do not react with the atoms of the containment metal atoms. Carburization of refractory metals and of austenitic stainless steels has been observed in liquid sodium contaminated with carbon. Decarburization of iron-chromium-molybdenum steels in liquid sodium or lithium is another example of element transfer.

### *Alloying*

An alloying action can be observed between the atoms of the liquid metals and the constituents of the material. Systems that form alloys or stable intermetallic compounds (nickel in molten aluminum) should be avoided.

See Refs. 7–9.

## LOCAL CORROSION CELL

Corrosion in metals is caused by the flow of electricity from one metal to another metal or a recipient of some kind; or from one part of the surface of one piece of metal to another part of the same metal, when conditions permit the flow of electricity. A moist conductor or electrolyte must be present.

A local corrosion cell is formed when one area or region on a metal surface has a negative charge relative to a second area which has a positive charge in opposition, and an electrolyte is present. These cells can be formed by surface imperfections, grain orientation, lack of homogeneity of the metal, variation in the environment, localized shear and torque during manufacture, mill scale, and existing red iron oxide rust. The result is usually a pitting type of corrosion.

The rate of corrosion depends not only on charge transfer kinetics and on mass transport conditions at the anode and the cathode, but also on the resistivity of the electrolyte and the geometry of the cell that determines the internal resistance. This is illustrated in Fig.L.l.

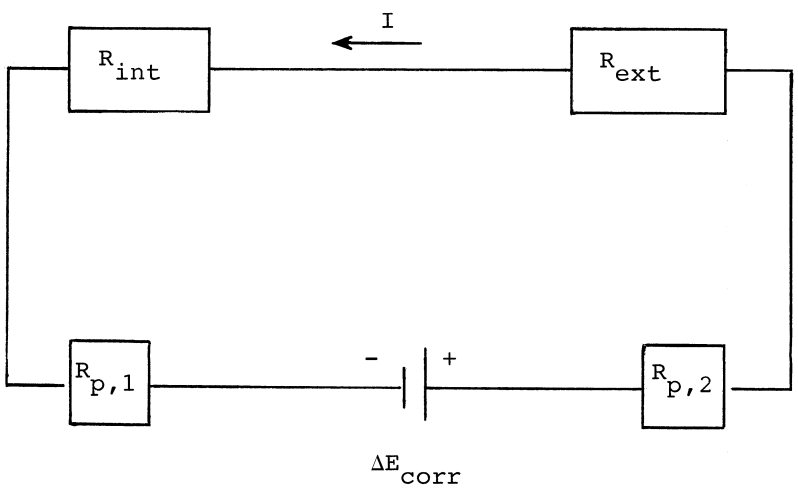



**Figure L.1** Electrical analogue of a corrosion cell, including a voltage source $\Delta E_{corr}$; the polarization resistances at the anode and the cathode $R_{p1}$ and $R_{p2}$, respectively; the internal cell resistance $R_{\Omega int}$; and the external resistance $R_{\Omega ext}$.

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The voltage source corresponds to the difference in corrosion potentials,

$$\Delta E_{\text{corr}} = E_{\text{cor2}} - E_{\text{corr1}}$$

The nonohmic resistances $R_{p1}$ and $R_{p2}$ represent the polarization resistances of the anode and the cathode, respectively. Because the electrode potential usually varies in a nonlinear way with current density, the values of the polarization resistances $R_{p1}$ and $R_{p2}$ vary as a function of current density. The ohmic resistances $R_{\Omega\text{int}}$ and $R_{\Omega\text{ext}}$ represent the internal cell resistance and the resistance of the external circuit, respectively. The latter term is usually negligible. It is seen from the figure that for a given potential difference $\Delta E_{\text{corr}}$, the current in the corrosion cell, and therefore the corrosion rate at the anode, depends on the values of all of the circuit elements present. A further complication arises in practice from the fact that in many corrosion cells the potential distribution on the electrodes is highly nonuniform. Typically, for a given geometry the potential at a given location on the anode varies with the distance from the cathode. In addition, the local corrosion rate may be influenced by nonuniform hydrodynamic conditions.

## LOCALIZED CORROSION

Localized corrosion is any form of corrosion that takes place at discrete sites. This includes pitting, crevice corrosion, intergranular attack, corrosion fatigue, and stress corrosion cracking.

See "Forms of Corrosion."

## LOW-ALLOY STEELS

There are two basic types of low-alloy steels: weathering steels and hardenable steels: weathering steels contain small additions of copper, chromium, and nickel to form a more adherent oxide during atmospheric exposure. A typical example is U.S. Steels Cor-Ten steel. Hardenable steels contain additions of chromium or molybdenum and possibly nickel. These steels offer higher strength and hardness after proper heat treatment. Typical examples are 4130 and 4340 steels.

See Ref. 10.

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# M

## MAGNESIUM ALLOYS

When strength-to-weight ratio is an important consideration, magnesium alloys compete with aluminum alloys. Magnesium has a density of 1.74 g/cm$^3$, which is 36% less than that of aluminum. However, aluminum is less expensive and has a greater corrosion resistance. The oxide film formed on magnesium provides only limited protection, unlike the adherent protective oxide film on aluminum.

Magnesium alloys have the best strength-to-weight ratio of the commonly die-cast metals, generally a better machinability, and often a higher production rate. The primary application for magnesium alloys are die-cast products.

Magnesium alloys are designated by a series of letters and numbers. Two letters indicate the two principal alloying elements, which are followed by two numbers that state the weight percentage of each element. The next letter in the sequence denotes the alloy developed; the letter C, e.g., indicates the third alloy of the series. AZ91C describes the third alloy standardized that contains normally 9% aluminum and 1% zinc.

Heat treatments are designated in a manner similar to that used for the aluminum alloys, i.e., H-10, slightly strain hardened; H-23 to H-26, strain hardened and partially annealed; and T-6, solution heat treated and artificially aged. Some letters used are different from the chemical symbols, e.g., E = rare earth, H = thorium, K = zirconium, and W = yttrium.

Magnesium resists corrosion in fresh water, hydrofluoric acid, pure chromic acid, fatty acids, dilute alkalies, aliphatic and aromatic hydrocarbons, pure halogenated organic compounds, dry fluorinated hydrocarbons, and ethylene glycol solutions.

Ambient-temperature dry gases, such as chlorine, iodine, bromine, and fluorine, do not attack magnesium.

In coastal atmospheres the high-purity alloys such as M11918 offer better corrosion resistance than steel or aluminum.

Magnesium is rapidly attacked by seawater, many salt solutions, most mineral acids, methanol and ethanol, most wet gases, and halogenated organic compounds when wet or hot.

Since magnesium is anodic to most metals, it is very often used as a sacrificial anode in cathodic protection systems.

Table M.1 lists the chemical composition of selected magnesium alloys.

## MALLEABLE IRON

Malleable iron is relatively expensive to produce in comparison to ductile iron, whose properties are similar. For this reason it is declining in popularity. In general, the corrosion



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**Table M.1** Chemical Composition of Selected Magnesium Alloys

| UNS no. | ASTM no. | Composition (wt%) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Mn | Zn | Cu | Zr | Al | RE | Y |
| M16710 | ZC71 | | 6.5 | 1.2 | | | | |
| | ZW3 | | 3.0 | | 6.0 | | | |
| M11312 | AZ31 | | 1 | | | 13 | | |
| M18410 | WE54A | | | | | | 2 | 5 |
| M16631 | ZC6356 | | 6 | 3 | | | | |
| M18430 | WE43A | | | | | | 3 | 4 |
| | AZM | | 1 | | | 6 | | |
| M11918T6 | | 0.3 | 0.7 | | | 9 | | |
| M10602F | | 0.2 | | | | 6 | | |
| M10100F | | 0.3 | | | | 10 | | |
| M11810T4 | | 0.3 | 1 | | | 8 | | |

resistance of malleable iron and gray iron are the same, as are the properties of ductile iron. See "Cast Irons."

See Ref. 1.

## MARINE COATINGS

Marine atmospheres include salt particles that attack steel substrate, saltwater spray and splashes, and immersion. Paint coatings used to protect against salt spray include chlorinated rubber, epoxy, and vinyl resin. For protection against seawater, zinc coatings are also effective. Each mil (0.03 mm) of zinc will provide protection against rusting for approximately one year. Epoxy coal tar will also provide protection. See "Coatings."

## MARINE ENVIRONMENT

Marine environment is an atmospheric exposure that is frequently wetted by salt mist but is not in direct contact with salt spray or splashing waves.

## MARTENSITE

When austenite is cooled rapidly, preventing the formation of ferrite, martensite is formed. Since martensite is a brittle material, it is normally tempered. The tempering is done to permit some carbon to diffuse from the martensite. Tempered martensite is considerably stronger and tougher than the parent ferritic alloy. A tempered material should never be stress relieved or postweld heat treated at a temperature in excess of the final tempering temperature.

The specific alloy will determine what procedure is required to effect cooling to produce martensite from austenite. Some heat-treatable alloys require quenching in water or some other liquid such as oil or a molten salt in order to obtain the cooling rate necessary. Some steels have sufficient alloying additions that quenching is not

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necessary to produce martensite. The martensitic microstructure can be produced in type 410 stainless steel by air cooling.

Heat-treated martensitic steels become brittle at low temperatures even though they have superior fracture toughness. Most martensitic steels are very sensitive to hydrogen embrittlement.

See "Austenite."

## MARTENSITIC STAINLESS STEELS

The martensitic grades are so named because when steel is heated above the critical temperature, 1600°F (870°C), and cooled rapidly, a metallurgical structure known as martensite is obtained. In the hardened condition the steel has very high strength and hardness, but to obtain the optimal corrosion resistance, ductility, and impact strength, the steel is given a stress-relieving or tempering treatment, usually in the range of 300–700°F (149–371°C). These alloys are hardenable because of the phase transformation from body-centered cubic to body-centered tetragonal. As with low-alloy steels, this transformation is thermally controlled.

Tempering at 800°F (425°C) does not reduce the hardness of the part, and in this condition these alloys show an exceptional resistance to fruit and vegetable acids, lye, ammonia, and other corrodents to which cutlery may be subject.

Moderate corrosion resistance, relatively high strength, and good fatigue properties after suitable heat treatment are the usual reasons for selecting the martensitic stainless steels.

### Type 410 (S41000)

Type 410 stainless steel is heat treatable and is the most widely used of the martensitic stainless steels. Its chemical composition is shown in Table M.2. Type 410 stainless has a maximum operating temperature of 1300°F (705°C) for continuous service, but for intermittent service it may be operated at a maximum of 1500°F (815°C). Table M.3 lists the mechanical and physical properties.

Type 410 stainless steel is used where corrosion is not severe, such as in air, fresh water, some chemicals, and food acids. Table M.4 provides the compatibility of type 410 stainless steel with selected corrodents.

**Table M.2** Chemical Composition of Type 410 Stainless Steel

| Chemical | Weight percent |
|---|---|
| Carbon | 0.15 |
| Manganese | 1.00 |
| Phosphorus | 0.040 |
| Sulfur | 0.030 |
| Silicon | 1.00 |
| Chromium | 11.50–13.50 |
| Iron | Balance |

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**Table M.3** Mechanical and Physical Properties of Alloy 410 Stainless Steel

| | |
|---|---|
| Modulus of elasticity $\times 10^6$, psi | 29 |
| Tensile strength $\times 10^3$, psi | |
| annealed | 75 |
| heat-treated | 150 |
| Yield strength 0.2% offset $\times 10^3$, psi | |
| annealed | 40 |
| heat-treated | 115 |
| Elongation in 2 in., % | |
| annealed | 30 |
| heat-treated | 15 |
| Hardness, Brinell | |
| annealed | 150 |
| heat-treated | 410 |
| Density, lb/in.$^3$ | 0.28 |
| Specific gravity | 7.75 |
| Specific heat, (32–212°F) Btu/lb °F | 0.11 |
| Thermal expansion coefficient (32–212°F), in./in. °F $\times 10^{-6}$ | 173 |

**Table M.4** Compatibility of Type 410 Stainless Steel with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetaldehyde | 60 | 16 | Ammonium sulfate, 10–40% | 60 | 16 |
| Acetamide | 60 | 16 | Ammonium sulfite | x | x |
| Acetic acid, 10% | 70 | 21 | Amyl acetate[b] | 60 | 16 |
| Acetic acid, 50% | 70 | 21 | Amyl alcohol | 110 | 43 |
| Acetic acid, 80% | 70 | 21 | Amyl chloride | x | x |
| Acetic acid, glacial | x | x | Aniline | 210 | 99 |
| Acetic anhydride | x | x | Antimony trichloride | x | x |
| Acetone | 210 | 99 | Barium carbonate, 10% | 210 | 99 |
| Acrylonitrile | 110 | 43 | Barium chloride[b] | 60 | 16 |
| Allyl alcohol | 90 | 27 | Barium hydroxide | 230 | 110 |
| Alum | x | x | Barium sulfate | 210 | 99 |
| Aluminum chloride, aqueous | x | x | Barium sulfide | 70 | 21 |
| Aluminum chloride, dry | 150 | 66 | Benzaldehyde | | |
| Aluminum fluoride | x | x | Benzene | 230 | 110 |
| Aluminum hydroxide | 60 | 16 | Benzoic acid | 210 | 99 |
| Aluminum nitrate | 210 | 99 | Benzyl alcohol | 130 | 54 |
| Aluminum oxychloride | x | x | Borax | 150 | 66 |
| Aluminum sulfate | x | x | Boric acid | 130 | 54 |
| Ammonium bifluoride | x | x | Bromine gas, dry | x | x |
| Ammonium carbonate | 210 | 99 | Bromine gas, moist | x | x |
| Ammonium chloride, 10%[b] | 230 | 110 | Bromine, liquid | x | x |
| Ammonium chloride, 50% | x | x | Butadiene | 60 | 16 |
| Ammonium chloride, sat. | x | x | Butyl acetate | 90 | 32 |
| Ammonium hydroxide, sat. | 70 | 21 | Butyl alcohol | 60 | 16 |
| Ammonium nitrate | 210 | 99 | Butyric acid | 150 | 66 |
| Ammonium persulfate, 5% | 60 | 16 | Calcium bisulfite | x | x |
| Ammonium phosphate, 5% | 90 | 32 | Calcium carbonate | 210 | 99 |

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**Table M.4** Compatibility of Type 410 Stainless Steel with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | Maximum temp. °C | Chemical | Maximum temp. °F | Maximum temp. °C |
|---|---|---|---|---|---|
| Calcium chloride[b] | 150 | 66 | Hydrofluoric acid, 30% | x | x |
| Calcium hydroxide, 10% | 210 | 99 | Hydrofluoric acid, 70% | x | x |
| Calcium hypochlorite | x | x | Hydrofluoric acid, 100% | x | x |
| Calcium sulfate | 210 | 99 | Ketones, general | 60 | 16 |
| Carbon bisulfide | 60 | 16 | Lactic acid, 25% | 60 | 16 |
| Carbon dioxide, dry | 570 | 299 | Lactic acid, conc. | 60 | 16 |
| Carbon dioxide, wet | 570 | 299 | Magnesium chloride, 50% | 210 | 99 |
| Carbon disulfide | 60 | 16 | Malic acid | 210 | 99 |
| Carbon monoxide | 570 | 299 | Methyl chloride, dry | 210 | 99 |
| Carbon tetrachloride[b] | 210 | 99 | Methyl ethyl ketone | 60 | 16 |
| Carbonic acid | 60 | 16 | Muriatic acid | x | x |
| Chloracetic acid | x | x | Nitric acid, 5% | 90 | 32 |
| Chloride gas, wet | x | x | Nitric acid, 20% | 160 | 71 |
| Chloride, liquid | x | x | Nitric acid, 70% | 60 | 16 |
| Chlorine gas, dry | x | x | Nitric acid, anhydrous | x | x |
| Chlorobenzene, dry | 60 | 16 | Nitrous acid, conc. | 60 | 16 |
| Chloroform | 150 | 66 | Perchloric acid, 10% | x | x |
| Chlorosulfonic acid | x | x | Perchloric acid, 70% | x | x |
| Chromic acid, 10% | x | x | Phenol[b] | 210 | 99 |
| Chromic acid, 50% | x | x | Phosphoric acid, 50–80% | x | x |
| Citric acid, 15% | 210 | 99 | Picric acid | 60 | 16 |
| Citric acid, 50% | 140 | 60 | Potassium bromide, 30% | 210 | 99 |
| Copper acetate | 90 | 32 | Salicylic acid | 210 | 99 |
| Copper carbonate | 80 | 27 | Silver bromide, 10% | x | x |
| Copper chloride | x | x | Sodium carbonate, 10–30% | 210 | 99 |
| Copper cyanide | 210 | 99 | Sodium chloride[b] | 210 | 99 |
| Copper sulfate | 210 | 99 | Sodium hydroxide, 10% | 210 | 99 |
| Cupric chloride, 5% | x | x | Sodium hydroxide, 50% | 60 | 16 |
| Cupric chloride, 50% | x | x | Sodium hypochlorite, 20% | x | x |
| Cyclohexane | 80 | 27 | Sodium hypochlorite, conc. | x | x |
| Cyclohexanol | 90 | 32 | Sodium sulfide, to 50% | x | x |
| Ethylene glycol | 210 | 99 | Stannic chloride | x | x |
| Ferric chloride | x | x | Stannous chloride | x | x |
| Ferric chloride, 50% in water | x | x | Sulfuric acid, 10% | x | x |
| Ferric nitrate, 10–50% | 60 | 16 | Sulfuric acid, 50% | x | x |
| Ferrous chloride | x | x | Sulfuric acid, 70% | x | x |
| Fluorine gas, dry | 570 | 299 | Sulfuric acid, 90% | x | x |
| Fluorine gas, moist | x | x | Sulfuric acid, 98% | x | x |
| Hydrobromic acid, dilute | x | x | Sulfuric acid, 100% | x | x |
| Hydrobromic acid, 20% | x | x | Sulfurous acid | x | x |
| Hydrobromic acid, 50% | x | x | Toluene | 210 | 99 |
| Hydrochloric acid, 20% | x | x | Trichloroacetic acid | x | x |
| Hydrochloric acid, 38% | x | x | Zinc chloride | x | x |
| Hydrocyanic acid, 10% | 210 | 99 | | | |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. When compatible, the corrosion rate is <20 mpy.
[b]Material is subject to pitting.
*Source:* Ref. 11.

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Applications include valve and pump parts, fasteners, cutlery, turbine parts, bushings, and heat exchangers.

Type 410 double tempered is a quenched and double-tempered variation conforming to NACE and API specifications for parts used in hydrogen sulfide service. Type 410S has a lower carbon content (0.8%) and a nitrogen content of 0.6%.

## Type 414 (S41400)

Type 414 stainless is a nickel-bearing chromium stainless steel. The chemical composition is shown in Table M.5. By adding nickel the chromium content can be increased, which leads to improved corrosion resistance. Refer to Table M.6 for the mechanical and physical properties.

**Table M.5** Chemical Composition of Type 414 Stainless Steel

| Chemical | Weight percent |
|---|---|
| Carbon | 0.15 |
| Manganese | 1.00 |
| Phosphorus | 0.040 |
| Sulfur | 0.030 |
| Silicon | 1.00 |
| Chromium | 11.50–13.50 |
| Nickel | 1.25–2.50 |
| Iron | Balance |

**Table M.6** Mechanical and Physical Properties of Type 414 Stainless Steel

| | |
|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 29 |
| Tensile strength $\times 10^3$ (psi) | |
| annealed | 70 |
| heat-treated | 200 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | |
| annealed | 45 |
| heat-treated | 150 |
| Elongation in 2 in. (%) | |
| annealed | 25 |
| heat-treated | 17 |
| Density (lb/in.$^3$) | 0.28 |
| Specific gravity | 7.75 |
| Specific heat (32–212°F) (Btu/lb °F) | 0.11 |
| Thermal expansion coefficient $\times 10^{-6}$ (in./in. °F) | |
| at 32–212°F | 6.1 |
| Thermal conductivity (Btu/ft$^2$/hr/°F/in.) | 173 |
| Rockwell hardness | |
| annealed | C-22 |
| heat-treated | C-44 |

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Type 414 stainless steel is resistant to mild atmospheric corrosion, fresh water, and mild chemical exposures. Applications include high-strength nuts and bolts.

## Type 416 (S41600)

Type 416 stainless steel is a low-carbon class martensitic alloy, a free-machining variation of type 410 stainless steel. The chemical composition is shown in Table M.7. It has a maximum continuous-service operating temperature of 1250°F (675°C) and an intermittent maximum operating temperature of 1400°F (760°C). See Table M.8 for mechanical and physical properties.

**Table M.7** Chemical Composition of Type 416 Stainless Steel

| Chemical | Weight percent |
|---|---|
| Carbon | 0.15 |
| Manganese | 1.25 |
| Phosphorus | 0.060 |
| Silicon | 1.00 |
| Chromium | 12.00–14.00 |
| Molybdenum | 0.60[a] |
| Iron | Balance |

[a]May be added at manufacturer's option.

**Table M.8** Mechanical and Physical Properties of Type 416 Stainless Steel

| | |
|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 29 |
| Tensile strength $\times 10^3$ (psi) | |
| annealed | 75 |
| heat-treated | 150 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | |
| annealed | 40 |
| heat-treated | 115 |
| Elongation in 2 in. (%) | |
| annealed | 30 |
| heat-treated | 15 |
| Toughness (ft-lb) | |
| annealed | 33 |
| heat-treated | 49 |
| Density (lb/in.$^3$) | 0.276 |
| Specific gravity | 7.74 |
| Specific heat (32–212°F) (Btu/lb °F) | 0.11 |
| Rockwell hardness | |
| annealed | B-82 |
| heat-treated | C-43 |

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**Table M.9** Chemical Composition of Type 4l6Se Stainless Steel

| Chemical | Weight percent |
|---|---|
| Carbon | 0.15 |
| Manganese | 1.25 |
| Phosphorus | 0.060 |
| Sulfur | 0.060 |
| Silicon | 1.00 |
| Chromium | 12.00–14.00 |
| Selenium | 0.15 min. |
| Iron | Balance |

**Table M.10** Mechanical and Physical Properties of Type 416Se Stainless Steel

| | |
|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 29 |
| Tensile strength $\times 10^3$ (psi) | |
| annealed | 75 |
| heat-treated | 150 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | |
| annealed | 40 |
| heat-treated | 115 |
| Elongation in 2 in. (%) | |
| annealed | 30 |
| heat-treated | 15 |
| Density (lb/in.$^3$) | 0.28 |
| Specific gravity | 7.75 |
| Specific heat (32–212°F) (Btu/lb °F) | 0.11 |
| Rockwell hardness | |
| annealed | B-82 |
| heat-treated | C-43 |

Type 416Se has selenium added to the composition and the sulfur quantity reduced to improve the machinability and physical properties. Refer to Table M.9.

These alloys exhibit useful corrosion resistance to natural food acids, basic salts, water, and most natural atmospheres. The physical and mechanical properties are shown in Table M.10.

## Type 420 (S42000)

Type 420 stainless steel is a hardenable 12% chrome stainless steel with higher strength, hardness, and wear resistance than type 410. Table M.11 shows the chemical composition. This alloy is used for cutlery, surgical instruments, magnets, molds, shafts, valves, and other products. Refer to Table M.12 for the mechanical and physical properties.

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**Table M.11** Chemical Composition of Type 420 Stainless Steel

| Chemical | Weight percent |
|---|---|
| Carbon | 0.15 min. |
| Manganese | 1.50 |
| Phosphorus | 0.040 |
| Sulfur | 0.030 |
| Silicon | 1.50 |
| Chromium | 12.00–14.00 |
| Iron | Balance |

**Table M.12** Mechanical and Physical Properties of Type 420 Stainless Steel

| | |
|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 29 |
| Tensile strength $\times 10^3$ (psi) | |
| annealed | 95 |
| heat-treated | 250 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | |
| annealed | 50 |
| heat-treated | 200 |
| Elongation in 2 in. (%) | |
| annealed | 25 |
| heat-treated | 8 |
| Toughness, heat treated (ft-lb) | 15 |
| Density (lb/in.$^3$) | 0.28 |
| Specific gravity | 7.75 |
| Specific heat (32–212°F) (Btu/lb °F) | 0.11 |
| Coefficient of thermal expansion $\times 10^{-6}$ (in./in. °F) | |
| at 32–212°F | 5.7 |
| Thermal conductivity (Btu/ft$^2$/hr/°F/in.) | 173 |
| Rockwell hardness | |
| annealed | B-92 |
| heat-treated | C-54 |

Type 420F (S42020) stainless is a free-machining version of type 420. The chemical composition is shown in Table M.13. See Table M.14 for the mechanical and physical properties.

## Type 422 (S42200)

This alloy is designed for service temperatures to 1200°F (649°C). It is a high-carbon martensitic alloy whose composition is shown in Table M.15. It exhibits good resistance to scaling and oxidation in continuous service at 1200°F (649°C) with high strength and toughness. Refer to Table M.16 for its mechanical and physical properties.

Type 422 stainless is used in steam turbines for blades and bolts.

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**Table M.13** Chemical Composition of Type 420F (S42020) Stainless Steel

| Chemical | Weight percent |
|---|---|
| Carbon | 0.15 min. |
| Manganese | 1.25 |
| Phosphorus | 0.060 |
| Sulfur | 0.15 min. |
| Silicon | 1.00 |
| Chromium | 12.00–14.00 |
| Molybdenum | 0.60 |
| Iron | Balance |

**Table M.14** Mechanical and Physical Properties of Type 420F (42020) Stainless Steel

| | |
|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 29 |
| Tensile strength $\times 10^3$ (psi) | |
| annealed | 95 |
| heat-treated | 250 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | |
| annealed | 55 |
| heat-treated | 200 |
| Elongation in 2 in. (%) | |
| annealed | 22 |
| heat-treated | 8 |
| Toughness, heat treated (ft-lb) | |
| Density (lb/in.$^3$) | 0.28 |
| Specific gravity | 7.75 |
| Specific heat (32–212°F) (Btu/lb °F) | 0.11 |
| Coefficient of thermal expansion $\times 10^{-6}$ (in./in. °F) | |
| at 32–212°F | 5.7 |
| Rockwell hardness | |
| annealed | B-92 |
| heat-treated | C-54 |

## Type 431 (S43100)

The addition of nickel to type 431 provides improved corrosion resistance and impact strength. Table M.17 shows the chemical composition. This alloy finds application in fasteners and fittings for structural components exposed to marine atmospheres, and for highly stressed aircraft components. Table M.18 provides the mechanical and physical properties of type 431 stainless steel.

## Type 440A (S44002)

This is a high-carbon chromium steel providing stainless properties with excellent hardness. Because of its high carbon content, type 440A exhibits lower toughness than type 410. The chemical composition is shown in Table M.19. Type 440A has a lower carbon

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content than 440B or 440C and consequently is characterized by a lower hardness but a greater toughness. The mechanical and physical properties are shown in Table M.20.

### Type 440B (S44003)

When heat treated, this high-carbon chromium steel attains a hardness of Rockwell C-58, intermediate between types 440A and 440C. Table M.21 shows the chemical composition. Table M.22 shows the mechanical and physical properties.

Type 440B has been used for cutlery, hardened balls, and similar parts.

**Table M.15** Chemical Composition of Type 422 Stainless Steel

| Chemical | Weight percent |
|---|---|
| Carbon | 0.2–0.25 |
| Manganese | 1.00 |
| Phosphorus | 0.025 |
| Sulfur | 0.025 |
| Silicon | 0.75 |
| Chromium | 11.00–13.00 |
| Nickel | 0.5–1.00 |
| Molybdenum | 0.75–1.25 |
| Vanadium | 0.15–0.30 |
| Tungsten | 0.75–1.25 |
| Iron | Balance |

**Table M.16** Mechanical and Physical Properties of Type 422 Stainless Steel

| | |
|---|---|
| Tensile strength, heat-treated, $\times 10^3$ (psi) | 145 |
| Yield strength 0.2% offset, heat-treated, $\times 10^3$ (psi) | 125 |
| Elongation in 2 in., heat-treated (%) | 16 |
| Specific heat (32–212°F) (Btu/lb °F) | 0.11 |
| Brinnell hardness, heat-treated | 320 |

**Table M.17** Chemical Composition of Type 431 Stainless Steel

| Chemical | Weight percent |
|---|---|
| Carbon | 0.20 |
| Manganese | 1.00 |
| Phosphorus | 0.040 |
| Sulfur | 0.030 |
| Silicon | 1.00 |
| Chromium | 15.00–17.00 |
| Nickel | 1.25–2.50 |
| Iron | Balance |

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**Table M.18** Mechanical and Physical Properties of Type 431 Stainless Steel

| | |
|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 29 |
| Tensile strength $\times 10^3$ (psi) | |
| annealed | 125 |
| heat-treated | 196 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | |
| annealed | 95 |
| heat-treated | 150 |
| Elongation in 2 in. (%) | |
| annealed | 25 |
| heat-treated | 20 |
| Toughness, heat-treated (ft-lb) | 25 |
| Density (lb/in.$^3$) | 0.28 |
| Specific gravity | 7.75 |
| Specific heat (32–212°F) (Btu/lb °F) | 0.11 |
| Coefficient of thermal expansion $\times 10^{-6}$ (in./in. °F) | |
| at 32–212°F | 6.5 |
| Thermal conductivity (Btu/ft$^2$/hr/°F/in.) | 140 |
| Rockwell hardness | |
| annealed | C-24 |
| heat-treated | C-41 |

**Table M.19** Chemical Composition of Type 440A Stainless Steel

| Chemical | Weight percent |
|---|---|
| Carbon | 0.60–0.75 |
| Manganese | 1.00 |
| Phosphorus | 0.040 |
| Sulfur | 0.030 |
| Silicon | 1.00 |
| Chromium | 16.00–18.00 |
| Molybdenum | 0.75 |
| Iron | Balance |

**Table M.20** Mechanical and Physical Properties of Type 440A Stainless Steel

| | |
|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 29 |
| Tensile strength $\times 10^3$ (psi) | |
| annealed | 105 |
| heat-treated | 260 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | |
| annealed | 60 |
| heat-treated | 240 |

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**Table M.20** Mechanical and Physical Properties of Type 440A Stainless Steel (Continued)

| | |
|---|---|
| Elongation in 2 in. (%) | |
| annealed | 20 |
| heat-treated | 5 |
| Toughness, heat treated (ft-lb) | 8 |
| Specific heat (32–212°F) (Btu/lb °F) | 0.11 |
| Rockwell hardness | |
| annealed | B-95 |
| heat-treated | C-56 |

**Table M.21** Chemical Composition of Type 440B Stainless Steel

| Chemical | Weight percent |
|---|---|
| Carbon | 0.75–0.95 |
| Manganese | 1.00 |
| Phosphorus | 0.040 |
| Sulfur | 0.030 |
| Silicon | 1.00 |
| Chromium | 16.00–18.00 |
| Molybdenum | 0.75 |
| Iron | Balance |

**Table M.22** Mechanical and Physical Properties of Type 440B Stainless Steel

| | |
|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 29 |
| Tensile strength $\times 10^3$ (psi) | |
| annealed | 107 |
| heat-treated | 280 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | |
| annealed | 62 |
| heat-treated | 270 |
| Elongation in 2 in. (%) | |
| annealed | 18 |
| heat-treated | 3 |
| Specific heat (32–212°F) (Btu/lb °F) | 0.11 |
| Rockwell hardness | |
| annealed | B-96 |
| heat-treated | C-55 |

## Type 440C (S44004)

Type 440C stainless steel is a high-carbon chromium steel that can attain the highest hardness (Rockwell C-60) of the 440 series stainless steels. In the hardened and stress-relieved condition, type 440C has maximum hardness together with high strength and

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corrosion resistance. It also has good abrasion resistance. The chemical composition is shown in Table M.23.

This stainless steel is used principally in bearing assemblies, including bearing balls and races. Refer to Table M.24 for the mechanical and physical properties of type 440C stainless steel.

### Alloy 440-XH

This alloy is produced by Carpenter Technology, with a nominal composition as follows:

| Chemical | Weight percent |
|---|---|
| Carbon | 1.50 |
| Manganese | 0.50 |
| Silicon | 0.40 |
| Chromium | 16.00 |
| Nickel | 0.35 |
| Molybdenum | 0.80 |
| Vanadium | 0.95 |
| Iron | Balance |

This is a high-chromium, high-carbon, corrosion-resistant alloy that can be described as either a high-hardness type 440C stainless steel or a corrosion-resistant D2 tool steel. It possesses corrosion resistance equivalent to type 440C stainless steel but can attain a maximum hardness of Rockwell C-64, approaching that of tool steel.

### Type 440F or 440F-Se

This high-carbon chromium steel is designed to provide stainless properties with maximum hardness, approximately Rockwell C-60 after heat treatment. However, the addition of sulfur to type 440F, or the addition of selenium to type 440Se, makes these two grades free machining. Either of these two types should be considered for machined parts that require higher hardness values than are possible with other free-machining grades.

**Table M.23** Chemical Composition of Type 440C Stainless Steel

| Chemical | Weight percent |
|---|---|
| Carbon | 0.95–1.2 |
| Manganese | 1.00 |
| Phosphorus | 0.040 |
| Sulfur | 0.030 |
| Silicon | 1.00 |
| Chromium | 16.00–18.00 |
| Molybdenum | 0.75 |
| Iron | Balance |

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**Table M.24** Mechanical and Physical Properties of Type 440C Stainless Steel

| | |
|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 29 |
| Tensile strength $\times 10^3$ (psi) | |
| annealed | 110 |
| heat-treated | 285 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | |
| annealed | 65 |
| heat-treated | 275 |
| Elongation in 2 in. (%) | |
| annealed | 14 |
| heat-treated | 2 |
| Toughness, heat treated (ft-lb) | |
| Specific heat (32–212°F) (Btu/lb °F) | 0.11 |
| Rockwell hardness | |
| annealed | B-97 |
| heat-treated | C-60 |

### 13Cr-4N (F6NM)

F6NM is a high-nickel, low-carbon martensitic stainless steel with higher toughness and corrosion resistance than type 410 and superior weldability. It has been used in the oil fields as a replacement for type 410. F6NM has a chemical composition as follows:

| Chemical | Weight percent |
|---|---|
| Carbon | 0.05 |
| Manganese | 0.50–1.00 |
| Phosphorous | 0.030 |
| Sulfur | 0.030 |
| Silicon | 0.30–0.60 |
| Chromium | 12.00–14.00 |
| Nickel | 3.50–4.50 |
| Molybdenum | 0.40–0.70 |
| Iron | Balance |

See Refs. 2–4.

## MEASURING CORROSION

See "Monitoring Corrosion" and "Corrosion Testing."

## MEMBRANE

A membrane is any sheet or layer that acts as a barrier to prevent the passage of corrodents, specifically a sheet installed between the brick or masonry lining of a vessel and the vessel substrate. Membranes can be classified as either rigid or nonrigid. Included under the classification of rigid are baked epoxy, phenolic, and furan resin coatings and glass linings. Coatings are not really true membranes. Also included in the rigid classification are

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unplasticized PVC, fiberglass-reinforced built-up resin linings, and glass flake–filled sprayed polyester resin coatings.

Under the classification of nonrigid membranes are materials such as natural rubber sheet, neoprene, plasticized PVC, butyl rubber, polyisobutylene sheet, and polyurethane.

Natural rubber and neoprene are the most commonly used with a steel substrate. If oxidizing agents are present, plasticized PVC is the better choice. For higher-temperature applications butyl rubber can be used, but it will be damaged if petroleum products are present. For strong oxidizing conditions, polyisobutylene sheet is recommended.

At times, rubber, neoprene, and polyurethane have been employed in multicoat built-up membrane applications.

## MERCURY CORROSION

See "Liquid Metal Embrittlement."

## METAL DUSTING

Also see "High-Temperature Corrosion." Metal dusting is a form of high-temperature corrosion in which, under alternating oxidizing and reducing conditions, localized high-carbon areas are burned out during the oxidation period.

## METALLIC COATINGS

The development of new and improved coatings and linings has been increasing over the past several years. New technologies have evolved that have expanded the usage of these materials. By incorporating these coatings and linings with a substrate having the required physical and mechanical properties, it is possible to obtain the desired strength and the optimum corrosion resistance at an economical cost.

Some of the materials can be used as either coatings or linings. The terminology of coating or lining is usually associated with the specific material and is not necessarily indicative of its actual usage.

There are several methods by which metallic coatings may he applied:

1. Brief immersion in a molten bath of metal, called hot dipping
2. Electroplating from an aqueous electrolyte
3. Spraying in which a gun is used that simultaneously melts and propels small droplets of metal onto the surface to be coated, similar to spray painting
4. Cementation, in which the material to be coated is tumbled in a mixture of metal powder and an appropriate flux at elevated temperatures, which allows the metal to diffuse into the base metal
5. Gas phase reaction
6. Chemical reduction of metal-salt solutions, the precipitated metal forming an overlay on the base metal (nickel coatings of this type are referred to as "electroless" nickel plate)

Coatings from a corrosion viewpoint are classified as either noble or sacrificial. All metal coatings contain some degree of porosity. Coating performance is therefore determined by the degree of galvanic action that takes place at the base of a pore, scratch, or other imperfection in the coating.

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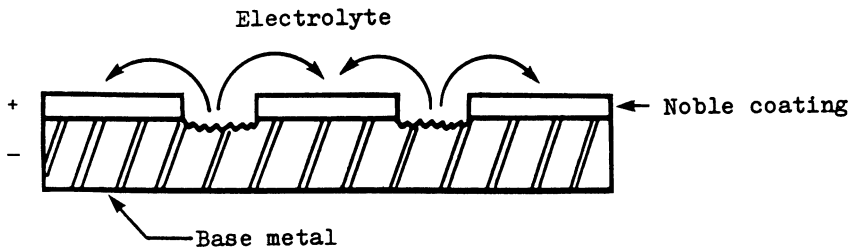



**Figure M.1** Galvanic action with a noble coating.

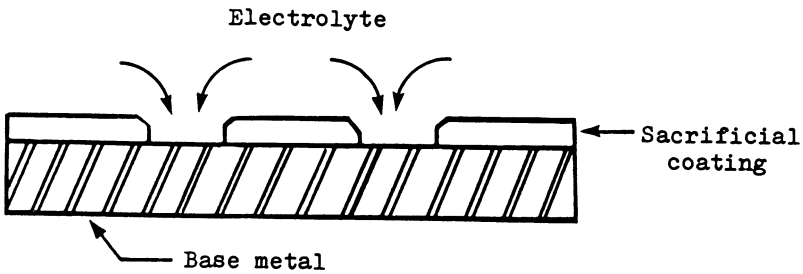



**Figure M.2** Galvanic action with a sacrificial coating.

Noble coatings, consisting of nickel, silver, copper, lead, or chromium on steel, are noble in the galvanic series with respect to steel, resulting in galvanic current attack at the base of the pores of the base metal and eventually undermining the coating (see Fig. M.1).

In order to reduce this rate of attack, it is important that this type of coating be prepared with a minimum number of pores and that any pores present be as small as possible. This can be accomplished by increased coating thickness.

In sacrificial coatings consisting of zinc, cadmium, and in certain environments aluminum and tin on steel, the base metal is noble in the galvanic series to the coating material, resulting in cathodic protection to the base metal and attack on the coating material (see Fig. M.2).

As long as sufficient current flows and the coating remains in electrical contact, the base metal will be protected from corrosion. Contrary to noble coatings, the degree of porosity of sacrificial coatings is relatively insignificant. However, the thicker the coating, the longer cathodic protection will be provided to the base metal.

For information on other metallic coatings refer to the specific metal (e.g., "Tin Coatings," "Nickel Coatings," etc.)

See Refs. 5 and 6.

## MICROALLOYED STEELS

Microalloyed steels are killed steels that have been alloyed with small amounts of vanadium, titanium, or niobium. The total of such alloying ingredients is usually less than 0.1 weight percent. The purpose of these elements is to modify the microstructure and refine the grain size, which results in a relatively small and uniform grain size.

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The addition of these elements improves toughness and strength. Applications for these steels exist where section thickness or gross weight is a concern as in large-diameter, long pipelines, where pipe tonnage is a major cost factor. At times these steels are selected for use in applications where improved toughness is a requirement. Most such applications are for plate steels used for improved piping and vessel toughness.

Microalloyed steels require some care in selecting weld joint geometries and welding procedures since they have a tendency to produce an excessively hard heat-affected zone. These heat-affected zones make the steel more susceptible to various forms of hydrogen stress cracking. The hard heat-affected zone is of no concern if the intended service does not involve the threat of hydrogen stress cracking. Double-sided welds are more likely to produce a hard heat-affected zone than single-side welds. In multiple-pass single-side welds, the previously deposited bead weld is tempered by the following bead(s). Because of this, pipe welds are less likely to retain hard heat-affected zones.

These steels are sometimes referred to as high-strength, low-alloy steels or HSLA steels.

## MICROBIAL CORROSION

The term microorganism covers a wide variety of life forms, including bacteria, blue-green cyanobacteria, algae, lichens, fungi, and protozoa All microorganisms may be involved in the biodeterioration of materials. Pure cultures never occur under natural conditions; rather, mixed cultures prevail. Of the mixed cultures, only a few may actually be actively involved in the process of corrosion. The other organisms support the active ones by adjusting the environmental conditions in such a manner as to support their growth. For example, in the case of metal corrosion caused by sulfate-reducing bacteria (SRB), the accompanying organisms remove toxic oxygen and produce simple carbon compounds like acetic and/or lactic acid as nutrients for the SRB.

### Bacteria

Bacteria are the smallest living organisms on this planet. Some can live with and others without oxygen. Some can adapt to changing conditions and live either aerobically or anaerobically. There is a wide diversity with regard to their metabolism. They are classified as to their source of metabolic energy as indicated in the table.

| Energy Source | Classification |
|---|---|
| Light | Phototrophs |
| Chemical reactions | Chemotrophs |
| Inorganic hydrogen donators | Lithotrophs |
| Organic hydrogen donators | Organotrophs |
| Carbon dioxide (cell source) | Autotrophs |
| Organic molecules (cell source) | Heterotrophs |

These six terms may be combined to describe easily the nutritional requirements of a bacterium. For example, if energy is derived from inorganic hydrogen donators and biomass is derived from organic molecules, they are called mirotrophs (chemolitho-organotrophs).

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An important feature of microbial life is the ability to degrade any naturally occurring compound. Exceptions to this rule are a few man-made materials such as highly polymerized and halogenated compounds.

In addition to energy and carbon sources, nitrogen, phosphorus, and trace elements are needed by microorganisms. Nitrogen compounds may he inorganic ammonium nitrate as well as organically bound nitrogen (e.g.. amino acids, nucleotides). With the help of an enzyme called nitrogenase, bacteria are able to fix nitrogen from atmospheric nitrogen, producing ammonia, which is incorporated in cell constituents.

Phosphorus is taken up as inorganic phosphate or as organically bound phosphoxylated compounds such as phosphorus-containing sugars and lipids. Phosphorus in the form of adenosine triphosphate (ATP) is the main energy storage compound.

For many metabolic purposes, trace elements are needed. Cobalt aids in the transfer of methyl groups from/to organic or inorganic molecules (vitamin $B_{12}$, cobalamin, is involved in the methylation of heavy metals such as mercury); iron as $Fe^{2+}$ or $Fe^{3+}$ is required for the electron transport system, where it acts as an oxidizable/reducible central atom in cytochromes or in nonheme iron sulfur proteins; magnesium acts in a similar manner in the chlorophyll molecule; copper is an essential part of a cytochrome, which at the terminal end of the electron transport system is responsible for the reduction of oxygen to water.

Since life cannot exist without water, water is an essential requirement for microbial life and growth. Different microorganisms have different requirements as to the amount of water needed. A solid material is surrounded by three types of water: hygroscopic, pellicular, and gravitational. Only pellicular and gravitational water are biologically available and can be used by microorganisms. The biologically available water is usually measured as the water activity $a_w$ of a sample:

$$a_w = \frac{\text{vapor pressure of a solution}}{\text{vapor pressure of pure water}} = \frac{V_s}{P_w}$$

at the same temperature. Most bacteria require an $a_w$ value in excess of 0.90.

Hydrogen ion concentration is another important factor affecting growth. Microorganisms are classified as to their ability to grow under acidic, neutral, or alkaline conditions, being given such titles as acidophiles, neutrophiles, and alkalophiles. Most microorganisms thrive in a neutral pH range of 6–8.

Microbial growth is also affected by redox potential. Under standard conditions, hydrogen is assumed to have a redox potential of −421 mV, and oxygen has a redox potential of +820 mV. Metabolism can take place within this range.

Available oxygen is another factor that influences microbial growth. Microbial growth is possible under well-aerated as well as under totally oxygen-free conditions. Those organisms living with the amount of oxygen contained in the air are called aerobes, while those that perform their metabolism without any free oxygen are called anaerobes. These latter are able to use only bound oxygen (sulfate, carbon dioxide) or to ferment organic compounds.

Temperature is another important factor affecting microbial growth. Microbial life is possible within the temperature range of −5°C to +110°C. Microorganisms are also classified as to the temperature range in which they thrive as given in the table.
Most of the organisms live in the mesophilic range of 20°C to 45°C, which corresponds to the usual temperature on the surface of the earth.

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| Microorganism | Temperature range |
|---|---|
| Psychrophiles | –5°C to +20°C |
| Psychotrophes | 5°C to 30°C |
| Mesophiles | 20°C to 45°C |
| Moderate thermophiles | 40°C to 55°C |
| Thermophiles | 55°C to 85°C |
| Extreme thermophiles | Up to 110°C |

## Corrosion of Specific Materials

Microbially induced corrosion (MIC) may occur for metallic materials in many industrial applications. MIC has been reported in the following industrial applications.

| Industry | Location of MIC |
|---|---|
| Chemical processing industry | Pipelines, stainless steel tanks, flanged joints, welded areas, after hydrotesting with natural river or well waters |
| Nuclear power generation | Copper-nickel, stainless steel, brass, and aluminum-bronze cooling water pipes, carbon and stainless steel piping and tanks |
| Underground pipeline industry | Water-saturated clay-type soils of near neutral pH with decaying organic matter and a source of sulfur-reducing bacteria |
| Metalworking industry | Increased wear from breakdown of machinery oils and emulsions |
| Onshore and offshore oil and gas industries | Mothballed and water-flooded systems, oil- and gas-handling systems, particularly in environments soured by sulfate-reducing bacteria–produced sulfides |
| Water treatment industry | Heat exchanges and piping. |
| Sewage handling and treatment industry | Concrete and reinforced concrete structures |
| Highway maintenance industry | Culvert piping |
| Aviation industry | Aluminum integral wing tanks and fuel storage tanks |

MIC of metallic materials is not a new form of corrosion. The methods by which microorganisms increase the rate of corrosion of metals and/or the susceptibility to localized corrosion in an aqueous environment are

1. *Production of corrosive metabolites.* Bacteria may produce inorganic acids, organic acids, sulfides, and ammonia, all of which may be corrosive to metallic materials.
2. *Destruction of protective layers.* Organic coatings may be attacked by various microorganisms, leading to the corrosion of the underlying metal.
3. *Hydrogen embrittlement.* By acting as a source of hydrogen and/or through the production of hydrogen sulfide, microorganisms may influence hydrogen embrittlement of metals.
4. *Formation of concentration cells at the metal surface and in particular oxygen concentration cells.* A concentration cell may be formed when a biofilm or bacterial

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growth develops heterogeneously on the metal surface. Some bacteria tend to trap heavy metals such as copper and cadmium within their extracellular polymeric substance, causing the formation of ionic concentration cells. These lead to localized corrosion.

5. *Modification of corrosion inhibitors.* Certain bacteria may convert nitrite corrosion inhibitors used to protect mild steel to nitrate, while other bacteria may convert nitrate inhibitors used to protect aluminum and aluminum alloys to nitrite and ammonia.
6. *Stimulation of electrochemical reactions.* An example of this type is the evolution of cathodic hydrogen from microbially produced hydrogen sulfide.

MIC can result from

1. Production of sulfuric acid by bacteria of the genus thiobacillus through the oxidation of various inorganic sulfur compounds. The concentration of the sulfuric acid may be as high as 10–12%.
2. Production of hydrogen sulfide by sulfate-reducing bacteria.
3. Production of organic acids.
4. Production of nitric acid.
5. Production of hydrogen sulfide.
6. Production of ammonia.

### Prevention

There are a number of approaches that may be used to prevent or minimize MIC. Among the choices are

1. Change or modify the material
2. Modify the environment or process parameters
3. Use of organic coatings
4. Cathodic protection
5. Use of biocides
6. Microbiological methods
7. Physical methods

Which approach to follow will depend upon the type of bacteria present. A technique that has gained importance in addition to the preventive methods is simulation of biogenic attack. By this method, a quick-motion effect can be produced that will allow materials to be tested for their compatibility for a specific application. In order to conduct the simulation properly, a thorough knowledge of all the processes and participating microorganisms is necessary. The situation may be modeled under conditions that are optimum for the microorganisms, resulting in a reduced time span for the corrosion to become detectable.

See Refs. 7–10.

## MILS PER YEAR (MPY)

This is an expression for the uniform corrosion rate of a metal. See "Uniform Corrosion" for more details.

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**Table M.25** Chemical Composition of Monel Alloys

| Chemical | Weight percent | | |
|---|---|---|---|
| | 400 (N04400) | 405 (N04405) | K-500 (N05500) |
| Carbon | 0.2 max. | 0.3 max. | 0.1 max. |
| Manganese | 2.0 max. | 2.0 max. | 0.8 max. |
| Silicon | 0.5 max. | 05 max. | 0.2 max. |
| Sulfur | 0.015 max. | 0.020–0.060 | — |
| Nickel | 63.0–70.0 | 63.0–70.0 | 63.0 min. |
| Iron | 2.50 max. | 2.50 max. | 1.0 |
| Copper | Balance | Balance | 27.0–33.0 |
| Columbium | — | — | 2.3–3.15 |
| Titanium | — | — | 0.35–0.85 |

## MONEL

The first nickel alloy, invented in 1905, was approximately two-thirds nickel and one-third copper. The present equivalent of that alloy, Monel alloy 400, remains one of the widely used nickel alloys. Refer to Table M.25 for the chemical composition.

Nickel-copper alloys offer somewhat higher strength than unalloyed nickel, with no sacrifice of ductility. The thermal conductivity of Monel, although lower than that of nickel, is significantly higher than that of nickel alloys containing substantial amounts of chromium or iron.

The alloy is readily fabricated and is virtually immune to chloride stress corrosion cracking in typical environments. Generally, its corrosion resistance is very good in reducing environments but poor in oxidizing conditions. Mechanical and physical properties of alloy 400 can be found in Table M.26.

The alloying of 30–33% copper with nickel, producing Monel 400, provides an alloy with many of the characteristics of chemically pure nickel, but with improvements on others.

The general corrosion resistance of Monel 400 in the nonoxidizing acids such as sulfuric, hydrochloric, and phosphoric is improved over that of pure nickel. The alloy is not resistant to oxidizing media such as nitric acid, ferric chloride, chromic acid, wet chlorine, sulfur dioxide, or ammonia.

Alloy 400 does have excellent resistance to hydrofluoric acid solutions at all concentrations and temperatures, as shown in Fig. M.3. Again, aeration or the presence of oxidizing salts increases the corrosion rate. This alloy is widely used in HF alkylation, is comparatively insensitive to velocity effects, and is widely used for critical parts such as bubble caps or valves that are in contact with flowing acid. Monel 400 is subject to stress corrosion cracking in moist, aerated hydrofluoric or hydrofluorosilicic acid vapor. However, cracking is unlikely if the metal is completely immersed in the acid.

Water handling, including seawater and brackish waters, is a major area of application. It gives excellent service under high-velocity conditions, as in propellers, propeller shafts, pump shafts, impellers, and condenser tubes. The addition of iron to the composition

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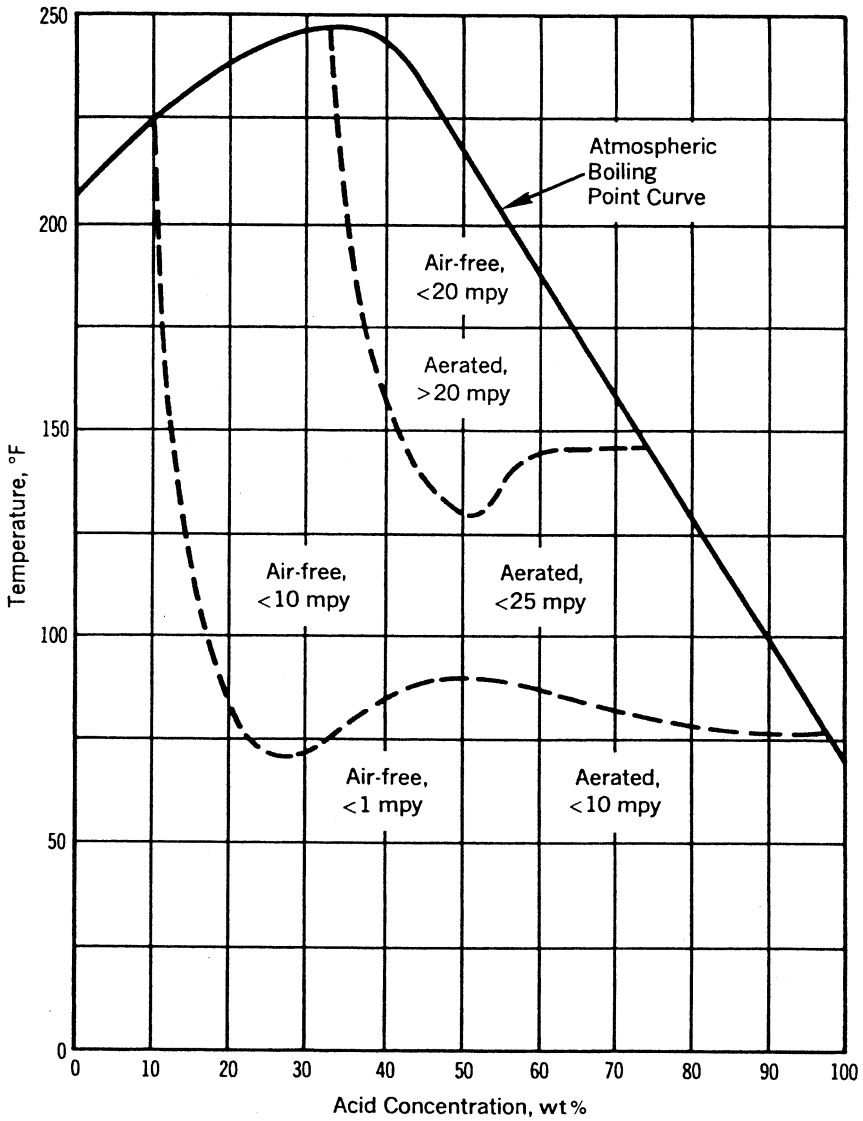



**Figure M.3** Isocorrosion diagram for alloy 400 in hydrofluoric acid (from Ref. 12).

improves the resistance to cavitation and erosion in condenser tube applications. Alloy 400 can pit in stagnant seawater, as does nickel 200; however, the rates are considerably lower. The absence of chloride stress corrosion cracking is also a factor in the selection of the alloy for this service.

Alloy 400 undergoes negligible corrosion in all types of natural atmospheres. Indoor exposures produce a very light tarnish that is easily removed by occasional wiping. Outdoor surfaces that are exposed to rain produce a thin gray-green patina. In sulfurous atmospheres a smooth, brown adherent film forms.

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**Table M.26** Mechanical and Physical Properties of Monel 400

| | |
|---|---|
| Modulus of elasticity $\times 10^6$ (psi) | 26 |
| Tensile strength $\times 10^3$ (psi) | 70 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | 25–28 |
| Elongation in 2 in. (%) | 48 |
| Brinell hardness | 130 |
| Density (lb/in.$^3$) | 0.318 |
| Specific gravity | 8.84 |
| Specific heat, at 32–212°F (Btu/lb °F) | 0.102 |
| Thermal conductivity (Btu/hr/ft$^2$/in./°F) | |
| at 70°F | 151 |
| at 200°F | 167 |
| at 500°F | 204 |
| Coefficient of thermal expansion $\times 10^{-6}$ (in./in.°F) | |
| at 70–200°F | 7.7 |
| at 70–400°F | 8.6 |
| at 70–500°F | 88 |
| at 70–1000°F | 9.1 |

Monel 400 exhibits stress corrosion cracking in high temperatures, in concentrated caustic, and in mercury. Refer to Table M.27 for the compatibility of Monel 400 with selected corrodents. A more detailed compilation will be found in Ref. 11.

**Table M.27** Compatibility of Monel 400 with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetaldehyde | 170 | 77 | Ammonia gas | x | x |
| Acetamide | 340 | 171 | Ammonium bifluoride | 400 | 204 |
| Acetic acid 10% | 80 | 27 | Ammonium carbonate | 190 | 88 |
| Acetic acid 50% | 200 | 93 | Ammonium chloride 10% | 230 | 110 |
| Acetic acid 80% | 200 | 93 | Ammonium chloride 50% | 170 | 77 |
| Acetic acid, glacial | 290 | 143 | Ammonium chloride sat. | 570 | 299 |
| Acetic anhydride | 190 | 88 | Ammonium fluoride 10% | 400 | 204 |
| Acetone | 190 | 88 | Ammonium fluoride 25% | 400 | 204 |
| Acetyl chloride | 400 | 204 | Ammonium hydroxide 25% | x | x |
| Acrylonitrile | 210 | 99 | Ammonium hydroxide sat. | x | x |
| Adipic acid | 210 | 99 | Ammonium nitrate | x | x |
| Ally alcohol | 400 | 204 | Ammonium persulfate | x | x |
| Allyl chloride | 200 | 93 | Ammonium phosphate 30% | 210 | 99 |
| Alum | 100 | 38 | Ammonium sulfate 10–40% | 400 | 204 |
| Aluminum acetate | 80 | 27 | Ammonium sulfite | 90 | 32 |
| Aluminum chloride, aqueous | x | x | Amyl acetate | 300 | 149 |
| Aluminum chloride, dry | 150 | 66 | Amyl alcohol | 180 | 82 |
| Aluminum fluoride | 90 | 32 | Amyl chloride | 400 | 204 |
| Aluminum hydroxide | 80 | 27 | Aniline | 210 | 99 |
| Aluminum sulfate | 210 | 99 | Antimony chloride | 350 | 177 |

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**Table M.27** Compatibility of Monel 400 with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Aqua regia 3:1 | x | x | Chromic acid 10% | 130 | 54 |
| Barium carbonate | 210 | 99 | Chromic acid 50% | x | x |
| Barium chloride | 210 | 99 | Chromyl chloride | 210 | 99 |
| Barium hydroxide | 80 | 27 | Citric acid 15% | 210 | 99 |
| Barium sulfate | 210 | 99 | Citric acid, concentrated | 80 | 27 |
| Barium sulfide | x | x | Copper acetate | x | x |
| Benzaldehyde | 210 | 99 | Copper carbonate | x | x |
| Benzene | 210 | 99 | Copper chloride | x | x |
| Benzene sulfonic acid 10% | 210 | 99 | Copper cyanide | x | x |
| Benzoic acid | 210 | 99 | Copper sulfate | x | x |
| Benzyl alcohol | 400 | 204 | Cresol | 100 | 38 |
| Benzyl chloride | 210 | 99 | Cupric chloride 5% | x | x |
| Borax | 90 | 32 | Cupric chloride 50% | x | x |
| Boric acid | 210 | 99 | Cyclohexane | 180 | 82 |
| Bromine gas, dry | 120 | 49 | Cyclohexanol | 80 | 27 |
| Bromine gas, moist | x | x | Dichloroethane (ethylene dichloride) | 200 | 93 |
| Butadiene | 180 | 82 | Ethylene glycol | 210 | 99 |
| Butyl acetate | 380 | 193 | Ferric chloride | x | x |
| Butyl alcohol | 200 | 93 | Ferric chloride 50% in water | x | x |
| Butyl phthalate | 210 | 99 | Ferric nitrate 10–50% | x | x |
| Butyric acid | 210 | 99 | Ferrous chloride | x | x |
| Calcium bisulfide | 60 | 16 | Ferrous nitrate | | |
| Calcium bisulfite | x | x | Fluorine gas, moist | x | x |
| Calcium carbonate | 200 | 93 | Fluorine gas. dry | 570 | 299 |
| Calcium chlorate | 140 | 60 | Hydrobromic acid, dilute | x | x |
| Calcium chloride | 350 | 177 | Hydrobromic acid 20% | x | x |
| Calcium hydroxide 10% | 210 | 99 | Hydrobromic acid 50% | x | x |
| Calcium hydroxide, sat. | 200 | 93 | Hydrochloric acid 20% | 80 | 27 |
| Calcium hypochlorite | x | x | Hydrochloric acid 38% | x | x |
| Calcium oxide | 90 | 32 | Hydrocyanic acid 10% | 80 | 27 |
| Calcium sulfate | 80 | 27 | Hydrofluoric acid 30%[c] | 400 | 204 |
| Caprylic acid[b] | 210 | 99 | Hydrofluoric acid 70%[c] | 400 | 204 |
| Carbon bisulfide | x | x | Hydrofluoric acid 100%[c] | 210 | 99 |
| Carbon dioxide, dry | 570 | 299 | Hypochlorous acid | x | x |
| Carbon dioxide, wet | 400 | 204 | Iodine solution 10% | x | x |
| Carbon disulfide | x | x | Ketones, general | 100 | 38 |
| Carbon monoxide | 570 | 299 | Lactic acid 25% | x | x |
| Carbon tetrachloride | 400 | 204 | Lactic acid, concentrated | x | x |
| Carbonic acid | x | x | Magnesium chloride 50% | 350 | 177 |
| Cellosolve | 210 | 99 | Malic acid | 210 | 99 |
| Chloracetic acid | x | x | Manganese chloride 40% | 100 | 38 |
| Chloracetic acid, 50% water | 180 | 82 | Methyl chloride | 210 | 99 |
| Chlorine gas, dry | 570 | 299 | Methyl ethyl ketone | 200 | 93 |
| Chlorine gas, wet | x | x | Methyl isobutyl ketone | 200 | 93 |
| Chlorine, liquid | 150 | 66 | Muriatic acid | x | x |
| Chlorobenzene, dry | 400 | 204 | Nitric acid 5% | x | x |
| Chloroform | 210 | 99 | Nitric acid 20% | x | x |
| Chlorosulfonic acid | 80 | 27 | Nitric acid 70% | x | x |

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**Table M.27** Compatibility of Monel 400 with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Nitric acid, anhydrous | x | x | Sodium hypochlorite, concentrated | x | x |
| Nitrous acid, concentrated | x | x | Sodium sulfide to 50% | 210 | 99 |
| Oleum | x | x | Stannic chloride | x | x |
| Perchloric acid 10% | x | x | Stannous chloride, dry | 570 | 299 |
| Perchloric acid 70% | x | x | Sulfuric acid 10% | x | x |
| Phenol | 570 | 299 | Sulfuric acid 50% | 80 | 27 |
| Phosphoric acid 50–80% | x | x | Sulfuric acid 70% | 80 | 27 |
| Picric acid | x | x | Sulfuric acid 90% | x | x |
| Potassium bromide 30%, air free | 210 | 99 | Sulfuric acid 98% | x | x |
| Salicylic acid | 210 | 99 | Sulfuric acid 100% | x | x |
| Silver bromide 10% | 80 | 27 | Sulfuric acid, fuming | x | x |
| Sodium carbonate | 210 | 99 | Sulfurous acid | x | x |
| Sodium chloride to 30% | 210 | 99 | Thionyl chloride | 300 | 149 |
| Sodium hydroxide 10%[c] | 350 | 177 | Toluene | 210 | 99 |
| Sodium hydroxide 50%[c] | 300 | I49 | Trichloroacetic acid | 170 | 77 |
| Sodium hydroxide, concentrated | 350 | 177 | White liquor | x | x |
| Sodium hypochlorite 20% | x | x | Zinc Chloride to 80% | 200 | 93 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable. When compatible the corrosion rate is < 20 mpy.
[b]Not for use with carbonated beverages
[c]Material subject to stress cracking.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols 1–3. New York: Marcel Dekker, 1995.

Monel alloy 405 is a higher-sulfur grade in which the sulfur content is increased over that of alloy 400 in order to improve machinability. Refer to Table M.25 for the chemical composition. The corrosion resistance of this alloy is essentially the same as that of alloy 400. Mechanical properties are shown in Table M.28.

Monel alloy K-500 (NO5500) is an age-hardenable alloy which combines the excellent corrosion resistance characteristics of alloy 400 with the added advantage of increased strength and hardness. Chemical composition will be found in Table M.25. Age hardening increases its strength and hardness; however, still higher properties can be achieved when the alloy is cold worked prior to the aging treatment. Alloy K-500 has good mechanical properties over a wide range of temperatures. Strength is maintained up to about 1200°F (649°C), and the alloy is strong, tough, and ductile at temperatures as low as −423°F (−235°C). It also has low permeability and is nonmagnetic to −210°F (−134°C). Refer to Table M.29 for mechanical and physical properties.

**Table M.28** Mechanical and Physical Properties of Monel Alloy 405

| | |
|---|---|
| Tensile strength $\times 10^3$ (psi) | 70 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | 25 |
| Elongation in 2 in. (%) | 28 |
| Brinell hardness | 110–140 |
| Density (lb/in.$^3$) | 0.318 |
| Specific gravity | 8.48 |

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**Table M.29** Mechanical and Physical Properties of Monel Alloy K-500

| | |
|---|---|
| Tensile strength $\times 10^3$ (psi) | 100 |
| Yield strength 0.2% offset $\times 10^3$ (psi) | 50 |
| Elongation in 2 in. (%) | 35 |
| Brinell hardness | 161 |
| Density (lb/in.$^3$) | 0.318 |
| Specific gravity | 8.48 |
| Specific heat (J/kgK) | 418 |
| Thermal conductivity (W/mK) | 17.4 |
| Coefficient of thermal expansion (m/mK) at 20–93 °C | 13.7 |

Typical applications include pump shafts, impellers, electronic components, doctor blades and scrapers, oil well drill collars and instruments, springs, and valve trim.

See Ref. 12.

## MONITORING CORROSION

There are many operating and environmental parameters that can affect the corrosion of a metal, changes in any of which can greatly affect the corrosion rate. When construction materials are initially selected, some compromise may be involved between hard-to-obtain alloys highly resistant to corrosion by the process under any conceivable operating conditions, and less expensive, more readily obtainable materials that offer corrosion resistance under normal operating conditions, but would have a high corrosion rate during process upsets. Under these conditions direct on-line monitoring systems are essential to detect and measure the effect of these changes. Without these data, costly and potentially hazardous damage can occur before corrections are made. Accurate and timely corrosion measurement is an essential part of almost all corrosion control programs.

To monitor the condition of process equipment, both onstream and offstream nondestructive testing must be relied upon. Nondestructive testing is testing to detect internal, external, and concealed flaws in materials by use of techniques that do not damage or destroy the items being tested. Nondestructive testing can be utilized as an early warning system to indicate when process equipment is approaching the end of its safe serviceability, or when changed process conditions have increased the corrosion rates.

Measurement of corrosion refers to any technique that can be used to determine the effects of corrosion. Monitoring refers to those measurement techniques that are suitable for use while the equipment is in operation. Included in nondestructive measurement techniques are the following:

1. *Radiography (x-ray).* Radiography is not normally used in continuous on-line monitoring since it cannot detect small changes in residual wall thickness due to accuracy limitations. It is suitable for detecting major flaws or severe corrosive attack.
2. *Ultrasonic measurement.* There are several types of ultrasonic equipment, primarily A-scan, B-scan, and C-scan. A-scan generally measures wall thickness but can be fooled by mid-wall flaws. B-scan is more powerful and produces cross-sectional images

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similar to x-rays, while C-scan produces a three-dimensional view of a surface using complex and expensive equipment. These units are used almost exclusively for measurement rather than monitoring.

**3.** *Visual inspection.* This can be performed only when the equipment is out of service during a plant shutdown. When possible, an internal inspection should be made to verify the results of any on-line monitoring program. Visual inspection will also permit detection of forms of corrosion not detectable by on-line monitoring equipment such as pitting or crevice corrosion.

**4.** *Coupons*. Coupons are the simplest device used for the monitoring of corrosion. They are small pieces of metal which are inserted into the process stream and removed after a period of time (at least 30 days) for study. Coupons are used to determine the average corrosion rate over the period of exposure. An advantage of coupons is their ability to indicate the forms of corrosion present. They can be examined for evidence of pitting and other forms of localized attack. Refer also to "Corrosion Testing."

**5.** *Hydrogen probes.* Hydrogen probes are used to detect the penetration of elemental hydrogen into metal such as pipe or vessel walls. There are three types of hydrogen probes. The most common hydrogen probe consists of a thin-walled carbon steel tube inserted into the flow stream with a solid rod inside the tube forming a small annular space. Hydrogen atoms small enough to permeate the carbon steel collect in the annular space and combine to form molecular hydrogen gas, which is too large to pass back into the process. Pressure in the annular space builds up as the gas collects and registers on an external pressure gauge.

Patch probes operate the same way, except that the patch is sealed to the outside of a pipe or vessel and collects the hydrogen atoms that penetrate the wall. The third type is the palladium foil type, which produces an electrical output proportional to the hydrogen evolution rate. These probes are used when hydrogen-induced corrosion is a concern, such as in cathodic reactions in acid solutions, particularly when hydrogen sulfide is present.

**6.** *Polarization studies.* Polarization studies are electrochemical techniques used to study corrosion phenomena, especially pitting. In the past these were primarily used in the laboratory, but with advances in computer technology some of these systems are now being used in the field. These studies can be conducted using a variety of methods and equipment such as those given in the table.

| | |
|---|---|
| Potentiostatic | Potential held constant |
| Galvanostatic | Current held constant |
| Potentiodynamic | a. Potential changed constantly at a specified rate |
| | b. Potential changed in steps and held constant at each step |
| Galvanodynamic | a. Current changed constantly at a specified rate |
| | b. Current changed in steps and held constant at each step |

Because of the high polarization potentials required, the results are less accurate than those gotten using linear polarization resistance.

**7.** *Electrical impedance spectroscopy.* Electrical impedance spectroscopy is a laboratory technique, but with the development of more rugged computers, some investigation of this work is being made in the field.

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One of the requirements of making impedance measurements is to have a common cell of known geometry, a reference electrode, and instrumentation capable of measuring and recording the electrical response of the test corrosion cell over a wide range of AC excitation frequencies.

**8.** *Electrochemical noise*. Electrochemical noise is a monitoring technique of current and electrochemical potential disturbances as a result of ongoing corrosion activity. It is not as quantitative as linear polarization resistance for corrosion rate calculations. Laboratory and field interpretation is still in the development stage.

**9.** *Electrical resistance*. Electrical resistance systems work by measuring the resistance of a thin metal probe. The probe is exposed to the gas or liquid stream. As the measuring element corrodes, the cross-section reduces and the electrical resistance increases. The thickness of the measuring element is directly proportional to a corrosion dial reading. With an automated system, continuous readings are made, and through the use of sophisticated data analysis techniques, detection of significant changes in corrosion rates can be made in as little as two hours.

The actual corrosion rate in mils per year (mpy) can be determined by

$$\text{mpy} = \frac{\text{dial reading}}{\text{time, in days}} \times 0.365 \times \text{probe multiplier}$$

**10.** *Linear polarization resistance.* Linear polarization resistance is an electrochemical technique that measures the DC current that flows between one or two electrodes of the material under study by application of a small electrical potential. The current is measured on a microammeter that has been converted to read the corrosion rate directly (in mils per year) of the test electrode. Measurements cannot be made in nonconductive fluids or fluids that contain compounds that coat the electrodes (e.g., crude oil).

See Refs. 13–15.

## MONOLITHIC SURFACINGS

See "Polymer Concretes."

## MONOMER

A monomer is a single molecule or a substance consisting of single molecules. It is relatively low-mass molecular structure that undergoes a polymerization reaction to form a polymer. A monomer is an organic molecule or compound capable of polymerizing or linking together with itself or with other monomers to form a dimer, trimer, or polymer.

## MORTARS

Mortar is used to bond brick or tile. It must have a heavy enough consistency to support the weight of the tile or brick without being squeezed from the joints while the joint is curing. Application is made by buttering each unit. Joints are usually $\frac{1}{8}$ in. (3 mm) wide.

Chemically resistant mortars and grouts are formulated using an inorganic binder or a liquid resin system; fillers such as silica, carbon, or combinations thereof; and a hardener or catalyst system.

Carbon is the most inert of the fillers, having a wide resistance to most chemicals; consequently, it is the filler most often used. It is resistant to strong alkalies, hydrochloric acid, and other fluorine chemicals. The general resistance of these fillers to acids, alkalies, and salts is shown in the table.

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| Corrodent at 20% concentration | Filler | | |
|---|---|---|---|
| | Carbon | Silica | Carbon-silica |
| Hydrochloric acid | R | R | R |
| Hydrofluoric acid | R | N | N |
| Sulfuric acid | R | R | R |
| Potassium hydroxide | R | N | N |
| Sodium hydroxide | R | N | N |
| Neutral salts | R | R | R |
| Solvents, conc. | R | R | N |

R = recommended, N = not recommended.

## Inorganic Mortars

The inorganic materials are the original mortars. These mortars are commonly referred to as acid-proof mortars, primarily because they are limited in application to a maximum pH of 7. They cannot be used in alkaline or alternate alkaline-acid service. There are two general types of inorganic mortars, the hot-pour sulfur and the ambiently mixed and applied silicate mortars.

### *Sulfur Mortars*

Sulfur mortars are hot-melt compounds, available in flake, powder, and ingot forms. They must be heated to a temperature of 250°F (120°C) and poured into the joints while hot. Sulfur mortars are particularly useful against oxidizing acids. When they are carbon filled, they are suitable for use against combinations of oxidizing acids and hydrofluoric acid. Chemical resistance to strong alkaline solutions and certain organic solvents is poor.

The sulfur mortars possess certain advantages over some of the resin mortars, primarily their resistance to oxidizing, nonoxidizing, and mixed acids; ease of use; resistance to thermal shock; high early strength, unlimited shelf life; and economy.

### *Sodium Silicate Mortars*

Sodium silicate mortars are available as either a two-component system, which consists of the liquid sodium solution and the filler powder containing settling agents and selected aggregates, or a one-part system in powder form to be mixed with water when used. There are some differences in chemical resistance between the two types as shown in the table.

| Corrodent at room temp. | Type of mortar | |
|---|---|---|
| | Normal | Water-resistant |
| Acetic acid, glacial | P | P |
| Chlorine dioxide, water sol. | N | N |
| Hydrogen peroxide | N | R |
| Nitric acid 5% | C | R |
| Nitric acid 20% | C | R |
| Nitric acid, over 20% | R | R |
| Sodium bicarbonate | N | N |
| Sodium sulfite | R | R |
| Sulfates, aluminum | R | R |
| Sulfates, copper | P | P |
| Sulfates, iron | P | P |

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| Corrodent at room temp. | Type of mortar | |
|---|---|---|
| | Normal | Water-resistant |
| Sulfates, magnesium | P | P |
| Sulfates, nickel | P | P |
| Sulfates, zinc | P | P |
| Sulfuric acid, 93% | P | P |
| Sulfuric acid, over 93% | P | P |

R = recommended, N = not recommended, P = potential failure, C = conditional.

Sodium silicate mortars are useful in the pH range of 0–6, except where sulfuric acid exposures exist in vapor phase, wet-dry exposures, or in concentrations above 93%.

### *Potassium Silicate Mortars*

Potassium silicate mortars are preferable to sodium silicate mortars. They have better workability because of their smoothness and lack of tackiness. They do not run or flow from the brickwork and they do not stick to the trowel. The potassium silicate mortars have a greater resistance to strong acid solutions as well as to sulfation. These mortars are available with halogen-free hardening systems, which eliminate the remote possibility of catalyst poisoning in certain chemical operations. The general corrosion resistance of the two types of mortars is shown in the table.

| Corrodent at room temp. | Type of mortar | |
|---|---|---|
| | Normal | Halogen-free |
| Acetic acid, glacial | R | R |
| Chlorine dioxide, water sol. | R | R |
| Hydrogen peroxide | N | N |
| Nitric acid 5% | R | R |
| Nitric acid 20% | R | R |
| Nitric acid, over 20% | R | R |
| Sodium bicarbonate | N | N |
| Sodium sulfite | N | N |
| Sulfates, aluminum | R | R |
| Sulfates, copper | R | R |
| Sulfates, iron | R | R |
| Sulfates, magnesium | R | R |
| Sulfates, nickel | R | R |
| Sulfates, zinc | R | R |
| Sulfuric acid, to 93% | R | R |
| Sulfuric acid, over 93% | R | R |

R = recommended, N = not recommended.

### *Silica Mortars*

The silica-type mortars consist of a colloidal silica binder with quartz fillers. The main difference compared with the other mortars is total freedom from metal ions that could contribute to sulfation hydration within the mortar joints in high concentrations of sulfuric acid. This is a unique system. It can be used up to 2000°F (1093°C). The silica-type mortars used in the pH range of 0–7 are resistant to all materials except hydrofluoric acid and acid fluorides.

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## Organic Mortars

### *Epoxy*

The three main epoxy resins used in the formulation of corrosion-resistant mortars are based on bisphenol A, bisphenol F, and epoxy phenol. The corrosion resistance as well as the physical and mechanical properties are determined by the type of hardener used.

The three main types of hardeners used with the bisphenol A resin are aliphatic amines, modified aliphatic amines, and aromatic amines. Silica is the filler most often used with epoxy mortars. This prohibits the use of epoxy resins with hydrofluoric acid, other fluorine chemicals, and strong, hot alkalies. Carbon fillers can be substituted but with some sacrifice to the working properties.

The bisphenol F series of mortars are similar to the bisphenol A series. They both use alkaline hardeners and the same fillers. The main advantage of the bisphenol F resins is their improved resistance to aliphatic and aromatic solvents, and higher concentrations of oxidizing and nonoxidizing acids.

The general corrosion resistance is shown in the table.

| | Hardeners | | | |
|---|---|---|---|---|
| | | | Aromatic amines | |
| | | | Bisphenol | |
| Corrodent at room temp. | Aliphatic amines | Modified aliphatic amines | A | F |
| Acetic acid 5–10% | C | U | R | |
| Acetone | U | U | U | U |
| Benzene | U | U | R | R |
| Butyl acetate | U | U | U | R |
| Butyl alcohol | R | R | R | R |
| Chromic acid 5% | U | U | R | R |
| Chromic acid 10% | U | U | U | R |
| Formaldehyde 35% | R | R | R | R |
| Gasoline | R | R | R | R |
| Hydrochloric acid to 36% | U | U | R | R |
| Nitric acid 30% | U | U | U | U |
| Phosphoric acid 50% | U | U | R | R |
| Sulfuric acid 25% | R | U | R | R |
| Sulfuric acid 50% | U | U | R | R |
| Sulfuric acid 75% | U | U | U | U |
| Trichloroethylene | U | U | U | R |

R = recommended, U = unsatisfactory, C = conditional.

More extensive compatibility data can be found in Ref. 11.

### *Phenolic Mortars*

The phenolic mortars provide resistance to high concentrations of acids and to sulfuric acid at elevated temperatures. Fillers for the phenolic resins are 100% carbon, 100% silica, or part carbon and part silica. For high concentrations of sulfuric acid, silica is the filler of choice. Carbon fillers are used where resistance to high concentrations of hydrofluoric acid is required. Listed below are some typical compatibilities of phenolic mortars. A more comprehensive listing is found in Ref. 11.

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| Corrodent | Filler | |
|---|---|---|
| | Carbon | Silica |
| Amyl alcohol | R | R |
| Chromic acid 10% | U | U |
| Gasoline | R | R |
| Hydrofluoric acid to 50% | R | U |
| Hydrofluoric acid 93% | R | U |
| Methyl ethyl ketone | R | R |
| Nitric acid 10% | U | U |
| Sodium hydroxide to 5% | U | U |
| Sodium hydroxide 30% | U | U |
| Sodium hypochlorite 5% | U | U |
| Sulfuric acid to 50% | R | R |
| Sulfuric acid 93% | R | R |
| Xylene | R | R |

R = recommended, U = unsatisfactory.

### *Furan Mortars*

The furan mortars are resistant to most nonoxidizing organic and inorganic acids, alkalies, salts, oils, greases, and solvents to temperatures of 360°F (182°C). Fillers are either 100% carbon, 100% silica, or part carbon and part silica. The 100% carbon-filled resins provide the widest range of corrosion resistance. Typical corrosion resistance compatibilities are given in the table.

| Corrodent at room temp. | 100% carbon filler | Part carbon, part silica filler |
|---|---|---|
| Acetic acid, glacial | R | R |
| Benzene | R | R |
| Cadmium salts | R | R |
| Chlorine dioxide | U | U |
| Chromic acid | U | U |
| Copper salts | R | R |
| Ethyl acetate | R | R |
| Ethyl alcohol | R | R |
| Formaldehyde | R | R |
| Fatty acids | R | R |
| Gasoline | R | R |
| Hydrochloric acid | R | R |
| Hydrofluoric acid | R | U |
| Iron salts | R | R |
| Lactic acid | R | R |
| Methyl ethyl ketone | R | R |
| Nitric acid | U | U |
| Phosphoric acid | R | R |
| Sodium chloride | R | R |
| Sodium hydroxide to 20% | R | U |
| Sodium hydroxide 40% | R | U |
| Sulfuric acid 50% | R | R |
| Sulfuric acid 80% | U | U |
| Trichloroethylene | R | R |

R = recommended, U = unsatisfactory.

A more complete listing is found in Ref. 11.

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### Polyester Mortars

The polyester mortars were originally developed to resist chlorine dioxide. There are a number of types of polyester resins available. The ones most commonly used are the isophthalic, chlorendic, and bisphenol A fumarate. Depending on the application, the polyester mortars can be formulated to incorporate carbon and silica fillers. 100% carbon fillers are used to resist hydrofluoric acid, fluorine chemicals, and strong alkalies such as sodium and potassium hydroxide. The chlorendic and bisphenol A fumarate resins have improved chemical resistance and higher thermal capabilities than the isophthalic resins. The bisphenol A fumarate resins exhibit greatly improved resistance to strong alkalies. A comparison of the corrosion resistance between the chlorendic and bisphenol A fumarate resins is shown below. A more comprehensive compatibility chart can be found in Ref. 11.

| | Polyester | |
|---|---|---|
| Corrodent at room temp. | Chlorendic | Bisphenol A fumarate |
| Acetic acid, glacial | U | U |
| Benzene | U | U |
| Chlorine dioxide | R | R |
| Ethyl alcohol | R | R |
| Hydrochloric acid 36% | R | R |
| Hydrogen peroxide | R | U |
| Methanol | R | R |
| Methyl ethyl ketone | U | U |
| Motor oil and gasoline | R | R |
| Nitric acid 40% | R | U |
| Phenol 5% | R | R |
| Sodium hydroxide 50% | U | R |
| Sulfuric acid 75% | R | U |
| Toluene | U | U |
| Triethanolamine | U | R |
| Vinyl toluene | U | U |

R = recommended, U = unsatisfactory.

### Vinyl Ester and Vinyl Ester Novolac Mortars

These resins have many of the same properties as the epoxy, acrylic, and bisphenol A fumarate resins. The vinyl ester resins have replaced the polyester resins in mortars for bleach towers in the pulp and paper industry. The major advantages of these resin systems are their resistance to most oxidizing media and high concentrations of sulfuric acid, sodium hydroxide, and many solvents. The comparative resistance of the two types of vinyl ester resin systems is shown in the table.

| Corrodent | Vinyl ester | Novolac |
|---|---|---|
| Acetic acid, glacial | U | R |
| Benzene | R | R |
| Chlorine dioxide | R | R |
| Ethyl alcohol | R | R |
| Hydrochloric acid 36% | R | R |
| Hydrogen peroxide | R | R |
| Methanol | U | R |
| Methyl ethyl ketone | U | U |

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| Corrodent | Vinyl ester | Novolac |
|---|---|---|
| Motor oil and gasoline | R | R |
| Nitric acid 40% | U | R |
| Phenol 5% | R | R |
| Sodium hydroxide 50% | R | R |
| Sulfuric acid, 75% | R | R |
| Toluene | U | R |
| Triethanolamine | R | R |
| Vinyl toluene | U | R |
| Max. temp. °F(°C) | 220(104) | 230(110) |

R = recommended, U = unsatisfactory.

Table M.30 provides the compatibility of various mortars with selected corrodents. See Refs. 11, 16, and 17.

**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a]

| Mortar | Acetic acid 10% |
|---|---|
| Silicate | U |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | R |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 | | |

| Mortar | Acetic acid 50% |
|---|---|
| Silicate | U |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | U |
| Furan resin | R |
| Polyester | U |
| Epoxy | U |

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 | | |

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**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Acetic acid 80% |
|---|---|
| Silicate | U |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | U |
| Furan resin | R |
| Polyester | U |
| Epoxy | U |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Acetic and glacial |
|---|---|
| Silicate | U |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | U |
| Furan resin | R |
| Polyester | U |
| Epoxy | U |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Acetic anhydride |
|---|---|
| Silicate | |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | U |
| Furan resin | U |
| Polyester | U |
| Epoxy | U |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

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**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Aluminum chloride, aqueous |
|---|---|
| Silicate | R |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | R |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Aluminum fluoride |
|---|---|
| Silicate | U |
| Sodium silicate | U |
| Potassium silicate | U |
| Silica | U |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | R |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Ammonium chloride 10% |
|---|---|
| Silicate | R |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | R |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

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**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Ammonium chloride 50% |
|---|---|
| Silicate | R |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | R |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Ammonium chloride saturated |
|---|---|
| Silicate | R |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | R |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Ammonium fluoride 10% |
|---|---|
| Silicate | U |
| Sodium silicate | U |
| Potassium silicate | U |
| Silica | U |
| Sulfur | U |
| Furan resin | R |
| Polyester | R |
| Epoxy | R |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

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**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Ammonium fluoride 25% |
|---|---|
| Silicate | U |
| Sodium silicate | U |
| Potassium silicate | U |
| Silica | U |
| Sulfur | U |
| Furan resin | R——— |
| Polyester | R——— |
| Epoxy | R——— |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Ammonium hydroxide 25% |
|---|---|
| Silicate | U |
| Sodium silicate | U |
| Potassium silicate | U |
| Silica | U |
| Sulfur | U |
| Furan resin | R——— |
| Polyester | R——— |
| Epoxy | R——— |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Ammonium hydroxide saturated |
|---|---|
| Silicate | U |
| Sodium silicate | |
| Potassium silicate | U |
| Silica | U |
| Sulfur | U |
| Furan resin | R——— |
| Polyester | R——— |
| Epoxy | R——— |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

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**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Aqua regia 3:1 |
|---|---|
| Silicate | R |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | U |
| Furan resin | U |
| Polyester | U |
| Epoxy | U |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Bromine gas, dry |
|---|---|
| Silicate | |
| Sodium silicate | R |
| Potassium silicate | |
| Silica | |
| Sulfur | U |
| Furan resin | U |
| Polyester | U |
| Epoxy | U |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Bromine gas, moist |
|---|---|
| Silicate | |
| Sodium silicate | R |
| Potassium silicate | |
| Silica | |
| Sulfur | U |
| Furan resin | U |
| Polyester | U |
| Epoxy | U |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

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**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Bromine liquid |
|---|---|
| Silicate | R |
| Sodium silicate | |
| Potassium silicate | R |
| Silica | R |
| Sulfur | R |
| Furan resin | U |
| Polyester | U |
| Epoxy | U |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Calcium hypochlorite |
|---|---|
| Silicate | |
| Sodium silicate | U |
| Potassium silicate | R |
| Silica | R |
| Sulfur | U |
| Furan resin | U |
| Polyester | |
| Epoxy | U |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Carbon tetrachloride |
|---|---|
| Silicate | R |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | U |
| Furan resin | R |
| Polyester | R |
| Epoxy | R |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

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**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Chlorine gas, dry |
|---|---|
| Silicate | R |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | U |
| Furan resin | U |
| Polyester | U |
| Epoxy | U |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Chlorine gas, wet |
|---|---|
| Silicate | R |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | U |
| Furan resin | U |
| Polyester | U |
| Epoxy | U |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Chlorine liquid |
|---|---|
| Silicate | R |
| Sodium silicate | |
| Potassium silicate | R |
| Silica | R |
| Sulfur | U |
| Furan resin | U |
| Polyester | U |
| Epoxy | U |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

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**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Chromic acid 10% |
|---|---|
| Silicate | U |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | U |
| Furan resin | U |
| Polyester | R |
| Epoxy | U |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Chromic acid 50% |
|---|---|
| Silicate | R |
| Sodium silicate | |
| Potassium silicate | |
| Silica | R |
| Sulfur | U |
| Furan resin | U |
| Polyester 30% | R |
| Epoxy | U |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Ferric chloride |
|---|---|
| Silicate | R |
| Sodium silicate | U |
| Potassium silicate | R |
| Silica | R |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | R |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

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**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Ferric chloride, 50% in water |
|---|---|
| Silicate | R |
| Sodium silicate | U |
| Potassium silicate | R |
| Silica | R |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | R |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Hydrobromic acid, 20% |
|---|---|
| Silicate | R |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | U |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Hydrobromic acid, 50% |
|---|---|
| Silicate | R |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | U |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

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**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Hydrochloric acid, 20% |
|---|---|
| Silicate | R |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | U |

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 | | | | |

| Mortar | Hydrochloric acid, 38% |
|---|---|
| Silicate | R |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | U |

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 | | | | |

| Mortar | Hydrofluoric acid, 30% |
|---|---|
| Silicate | U |
| Sodium silicate | U |
| Potassium silicate | U |
| Silica | U |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | U |

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 | | | | |

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**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Hydrofluoric acid, 70% |
|---|---|
| Silicate | U |
| Sodium silicate | U |
| Potassium silicate | U |
| Silica | U |
| Sulfur | U |
| Furan resin | U |
| Polyester | |
| Epoxy | U |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Hydrofluoric acid, 100% |
|---|---|
| Silicate | U |
| Sodium silicate | U |
| Potassium silicate | U |
| Silica | U |
| Sulfur | U |
| Furan resin | U |
| Polyester | |
| Epoxy | U |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Magnesium chloride |
|---|---|
| Silicate | R— |
| Sodium silicate | |
| Potassium silicate | R— |
| Silica | R— |
| Sulfur | R— |
| Furan resin | R— |
| Polyester | R— |
| Epoxy | R— |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

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**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Nitric acid 5% |
|---|---|
| Silicate | R |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | R |
| Furan resin | U |
| Polyester | R |
| Epoxy | U |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Nitric acid 20% |
|---|---|
| Silicate | R |
| Sodium silicate | R |
| Potassium silicate | |
| Silica | |
| Sulfur | R |
| Furan resin | U |
| Polyester | R |
| Epoxy | U |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Nitric acid 70% |
|---|---|
| Silicate | R |
| Sodium silicate | R |
| Potassium silicate | |
| Silica | |
| Sulfur | U |
| Furan resin | U |
| Polyester | U |
| Epoxy | U |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

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**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Nitric acid, anhydrous |
|---|---|
| Silicate | R |
| Sodium silicate | R |
| Potassium silicate | |
| Silica | |
| Sulfur | U |
| Furan resin | U |
| Polyester | U |
| Epoxy | U |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Oleum |
|---|---|
| Silicate | |
| Sodium silicate | R |
| Potassium silicate | |
| Silica | |
| Sulfur | U |
| Furan resin | U |
| Polyester | U |
| Epoxy | U |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Phosphoric acid, 50–80% |
|---|---|
| Silicate | R |
| Sodium silicate | U |
| Potassium silicate | R |
| Silica | R |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | U |

| | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | | | | | | | | | | | | | | | | | | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

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M

**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Sodium chloride |
|---|---|
| Silicate | U |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | R |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Sodium hydroxide, 10% |
|---|---|
| Silicate | U |
| Sodium silicate | U |
| Potassium silicate | U |
| Silica | U |
| Sulfur | U |
| Furan resin | R |
| Polyester | R |
| Epoxy | R |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Sodium hydroxide, 50% |
|---|---|
| Silicate | U |
| Sodium silicate | U |
| Potassium silicate | U |
| Silica | U |
| Sulfur | U |
| Furan resin | R |
| Polyester | R |
| Epoxy | R |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

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**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Sodium hydroxide, concentrated |
|---|---|
| Silicate | U |
| Sodium silicate | U |
| Potassium silicate | U |
| Silica | U |
| Sulfur | U |
| Furan resin | |
| Polyester | |
| Epoxy | R— |

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 | | | | |

| Mortar | Sodium hypochlorite, 20% |
|---|---|
| Silicate | U |
| Sodium silicate | U |
| Potassium silicate | U |
| Silica | U |
| Sulfur | U |
| Furan resin | U |
| Polyester | U |
| Epoxy | U |

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 | | | | |

| Mortar | Sodium hypochlorite, concentrated |
|---|---|
| Silicate | U |
| Sodium silicate | U |
| Potassium silicate | U |
| Silica | U |
| Sulfur | U |
| Furan resin | U |
| Polyester | U |
| Epoxy | U |

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 | | | | |

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M

**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Sulfuric acid, 10% |
|---|---|
| Silicate | U |
| Sodium silicate | R |
| Potassium silicate | |
| Silica | |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | R |

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 | | | | |

| Mortar | Sulfuric acid, 50% |
|---|---|
| Silicate | U |
| Sodium silicate | R |
| Potassium silicate | |
| Silica | |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | U |

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 | | | | |

| Mortar | Sulfuric acid, 70% |
|---|---|
| Silicate | U |
| Sodium silicate | R |
| Potassium silicate | R |
| Silica | R |
| Sulfur | R |
| Furan resin | R |
| Polyester | R |
| Epoxy | U |

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 | | | | |
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 | | | | |

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**Table M.30** Compatibility of Various Mortars with Selected Corrodents[a] (Continued)

| Mortar | Sulfuric acid, 90% |
|---|---|
| Silicate | U |
| Sodium silicate | R——— |
| Potassium silicate | |
| Silica | |
| Sulfur | U |
| Furan resin | U |
| Polyester | U |
| Epoxy | U |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

| Mortar | Sulfuric acid, 98% |
|---|---|
| Silicate | U |
| Sodium silicate | R——— |
| Potassium silicate | |
| Silica | |
| Sulfur | U |
| Furan resin | U |
| Polyester | U |
| Epoxy | U |

| °F | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 420 | 440 | 460 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | 15 | 26 | 38 | 49 | 60 | 71 | 82 | 93 | 104 | 116 | 127 | 138 | 149 | 160 | 171 | 182 | 193 | 204 | 216 | 227 | 238 |

[a]The table is arranged alphabetically according to corrodent. Unless otherwise noted, the corrodent is considered pure in the case of liquids, and a saturated aqueous solution in the case of solids. All percentages shown are weight percents.

Corrosion is a function of temperature. When using the tables, note that the vertical lines refer to temperatures midway between the temperatures cited. An entry of R indicates that the material is resistant to the maximum temperature shown. An entry of U indicates that the material is unsatisfactory. A blank indicates that no data are available.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

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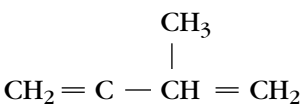
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# N

## NATURAL RUBBER (NR)

Natural rubber of the best quality is prepared by coagulating the latex of the *Heve brasiliensis* tree, which is cultivated primarily in the Far East.

Chemically, natural rubber is a polymer of methylbutadiene (isoprene):



When polymerized, the units link together, forming long chains that each contain over 1000 units. Simple butadiene does not yield a good grade of rubber, apparently because the chains are too smooth and do not form a strong enough interlock. Synthetic rubbers are produced by introducing side groups into the chain either by modifying butadiene or by making a copolymer of butadiene and some other compound.

Purified raw rubber becomes sticky in hot weather and brittle in cold weather. Its valuable properties become apparent after vulcanization.

Depending upon the degree of curing, natural rubber is classified as soft, semihard, or hard rubber. Only soft rubber meets the ASTM definition of an elastomer.

Most rubber is made to combine with sulfur or sulfur-bearing organic compounds or with other cross-linking chemical agents in a process known as vulcanization, which was invented by Charles Goodyear in 1839 and forms the basis of all later developments in the rubber industry.

When properly carried out, vulcanization improves mechanical properties, eliminates tackiness, renders the rubber less susceptible to temperature changes, and makes it insoluble in all known solvents. Other materials are added for various purposes as follows:

Carbon blacks, precipitated pigments, and organic vulcanization accelerators are added to increase tensile strength and resistance to abrasion.

Whiting, barite, talc, silica, silicates, clays, and fibrous materials are added to cheapen and stiffen.

Bituminous substances, coal tar and its products, vegetable and mineral oils, paraffin, petrolatum, petroleum, oils, and asphalt are added to soften (for purposes of processing or for final properties).

Condensation amines and waxes are added as protective agents against natural aging, sunlight, heat, and flexing.

Pigments are added to provide coloration.



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## Physical and Mechanical Properties

The physical and mechanical properties of natural rubber are shown in Table N.1. It is these properties that are responsible for the many varied applications of natural rubber. Many of these properties are modified somewhat through the process of vulcanization. Freshly cut or torn rubber has the power of self-adhesion. This property is for all intents and purposes absent in vulcanized rubber.

Dry heat up to 120°F (49°C) has little deteriorating effect on natural rubber. At temperatures of 300–400°F (148–205°C) rubber begins to melt and becomes sticky; at higher temperatures it becomes entirely carbonized. Natural rubber has good electrical insulation properties but poor flame resistance.

Vulcanization has the greatest effect on the mechanical properties of natural rubber. Vulcanized rubber can be stretched to approximately ten times its length and at this point will bear a load of 10 tons/in.$^2$. It can be compressed to one-third of its thickness thousands of times without injury. When most types of vulcanized rubbers are stretched, their resistance increases in greater proportion than their extension. Even when stretched just short of their rupture, they recover almost all of their original dimensions on being

**Table N.1** Physical and Mechanical Properties of Natural Rubber[a]

| | |
|---|---|
| Specific gravity | 0.92 |
| Refractive index | 1.52 |
| Specific heat, cal/g | 0.452 |
| Swelling, % by volume | |
| in kerosene at 77°F (25°C) | 200 |
| in benzene at 77°F (25°C) | 200 |
| in acetone at 77°F (25°C) | 25 |
| in mineral oil at 100°F (70°C) | 120 |
| Brittle point | –68°F (–56°C) |
| Relative permeability to hydrogen | 50 |
| Relative permeability to air | 11 |
| Insulation resistance, ohms/cm | 10 |
| Resilience, % | 90 |
| Tear resistance, psi | 1640 |
| Coefficient of linear expansion at 32–140°F, in./in.-°F | 0.000036 |
| Coefficient of heat conduction K, Btu/ft$^2$-in.-°F | 1.07 |
| Tensile strength, psi | 3000–4500 |
| Elongation, % at break | 775–780 |
| Hardness, Shore A | 40–100 |
| Abrasion resistance | Excellent |
| Maximum temperature, continuous use | 175°F (80°C) |
| Impact resistance | Excellent |
| Compression set | Good |
| Machining qualities | Can be ground |
| Effect of sunlight | Deteriorates |
| Effect of aging | Moderately resistant |
| Effect of heat | Softens |

[a]These are representative values since they may be altered by compounding.

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released and then gradually recover a portion of the residual distortion. The outstanding property of natural rubber in comparison with synthetic rubbers is its resilience. It has excellent rebound properties, either hot or cold.

## Resistance to Sun, Weather, and Ozone

Cold water preserves natural rubber, but if it is exposed to the air, particularly in sunlight, rubber tends to become hard and brittle. It has only fair resistance to ozone. Unlike the synthetic elastomers, natural rubber softens and reverts with aging to sunlight. In general, it has relatively poor weathering and aging properties.

## Chemical Resistance

Natural rubber offers excellent resistance to most inorganic salt solutions, alkalies, and nonoxidizing acids. Hydrochloric acid will react with soft rubber to form rubber hydrochloride, and therefore it is not recommended that natural rubber be used for items that will come into contact with that acid. Strong oxidizing media such as nitric acid, concentrated sulfuric acid, permanganates, dichromates, chlorine dioxide, and sodium hypochlorite will severely attack rubber. Mineral and vegetable oils, gasoline, benzene, toluene, and chlorinated hydrocarbons also affect rubber. Cold water tends to preserve natural rubber. Natural rubber offers good resistance to radiation and alcohols.

Unvulcanized rubber is soluble in gasoline, naphtha, carbon bisulfide, benzene, petroleum ether, turpentine, and other liquids.

Refer to Tables N.2, N.3, and N.4 for the compatibility of natural rubber with selected corrodents.

**Table N.2** Compatibility of Soft Natural Rubber with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | x | x | Aluminum chloride, dry | 160 | 71 |
| Acetamide | x | x | Aluminum fluoride | x | x |
| Acetic acid 10% | 150 | 66 | Aluminum hydroxide | | |
| Acetic acid 50% | x | x | Aluminum nitrate | x | x |
| Acetic acid 80% | x | x | Aluminum oxychloride | | |
| Acetic acid, glacial | x | x | Aluminum sulfate | 140 | 60 |
| Acetic anhydride | x | x | Ammonia gas | | |
| Acetone | 140 | 60 | Ammonium bifluoride | | |
| Acetyl chloride | x | x | Ammonium carbonate | 140 | 60 |
| Acrylic acid | | | Ammonium chloride 10% | 140 | 60 |
| Acrylonitrile | | | Ammonium chloride 50% | 140 | 60 |
| Adipic acid | | | Ammonium chloride, sat. | 140 | 60 |
| Allyl alcohol | | | Ammonium fluoride 10% | x | x |
| Allyl chloride | | | Ammonium fluoride 25% | x | x |
| Alum | 140 | 60 | Ammonium hydroxide 25% | 140 | 60 |
| Aluminum acetate | | | Ammonium hydroxide, sat. | 140 | 60 |
| Aluminum chloride, aqueous | 140 | 60 | Ammonium nitrate | 140 | 60 |

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**Table N.2** Compatibility of Soft Natural Rubber with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Ammonium persulfate | | | Carbon disulfide | x | x |
| Ammonium phosphate | 140 | 60 | Carbon monoxide | x | x |
| Ammonium sulfate 10–40% | 140 | 60 | Carbon tetrachloride | x | x |
| Ammonium sulfide | 140 | 60 | Carbonic acid | 140 | 60 |
| Ammonium sulfite | | | Cellosolve | x | x |
| Amyl acetate | x | x | Chloracetic acid | x | x |
| Amyl alcohol | 140 | 60 | Chloracetic acid, 50% water | x | x |
| Amyl chloride | x | x | Chlorine gas, dry | x | x |
| Aniline | x | x | Chlorine gas, wet | x | x |
| Antimony trichloride | | | Chlorine liquid | x | x |
| Aqua regia 3:1 | x | x | Chlorobenzene | x | x |
| Barium carbonate | 140 | 60 | Chloroform | x | x |
| Barium chloride | 140 | 60 | Chlorosulfonic acid | x | x |
| Barium hydroxide | 140 | 60 | Chromic acid 10% | x | x |
| Barium sulfate | 140 | 60 | Chromic acid 50% | x | x |
| Barium sulfide | 140 | 60 | Chromyl chloride | | |
| Benzaldehyde | x | x | Citric acid 15% | 140 | 60 |
| Benzene | x | x | Citric acid, concentrated | x | x |
| Benzene sulfonic acid 10% | x | x | Copper acetate | | |
| Benzoic acid | 140 | 60 | Copper carbonate | x | x |
| Benzyl alcohol | x | x | Copper chloride | x | x |
| Benzyl chloride | x | x | Copper cyanide | 140 | 60 |
| Borax | 140 | 60 | Copper sulfate | 140 | 60 |
| Boric acid | 140 | 60 | Cresol | x | x |
| Bromine gas, dry | | | Cupric chloride 5% | x | x |
| Bromine gas, moist | | | Cupric chloride 50% | x | x |
| Bromine liquid | | | Cyclohexane | x | x |
| Butadiene | | | Cyclohexanol | | |
| Butyl acetate | x | x | Dichloroacetic acid | | |
| Butyl alcohol | 140 | 60 | Dichloroethane (ethylene dichloride) | x | x |
| *n*-Butylamine | | | Ethylene glycol | 140 | 60 |
| Butyl phthalate | | | Ferric chloride | 140 | 60 |
| Butyric acid | x | x | Ferric chloride 50% in water | 140 | 60 |
| Calcium bisulfide | | | Ferric nitrate 10–50% | x | x |
| Calcium bisulfite | 140 | 60 | Ferrous chloride | 140 | 60 |
| Calcium carbonate | 140 | 60 | Ferrous nitrate | x | x |
| Calcium chlorate | 140 | 60 | Fluorine gas, dry | x | x |
| Calcium chloride | 140 | 60 | Fluorine gas, moist | | |
| Calcium hydroxide 10% | 140 | 60 | Hydrobromic acid, dilute | 140 | 60 |
| Calcium hydroxide, sat. | 140 | 60 | Hydrobromic acid 20% | 140 | 60 |
| Calcium hypochlorite | x | x | Hydrobromic acid 50% | 140 | 60 |
| Calcium nitrate | x | x | Hydrochloric acid 20% | x | x |
| Calcium oxide | 140 | 60 | Hydrochloric acid 38% | 140 | 60 |
| Calcium sulfate | 140 | 60 | Hydrocyanic acid 10% | | |
| Caprylic acid | | | Hydrofluoric acid 30% | x | x |
| Carbon bisulfide | x | x | Hydrofluoric acid 70% | x | x |
| Carbon dioxide, dry | | | Hydrofluoric acid 100% | x | x |
| Carbon dioxide, wet | | | Hypochlorous acid | | |

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**Table N.2** Compatibility of Soft Natural Rubber with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Iodine solution 10% | | | Silver bromide 10% | | |
| Ketones, general | | | Sodium carbonate | 140 | 60 |
| Lactic acid 25% | x | x | Sodium chloride | 140 | 60 |
| Lactic acid, concentrated | x | x | Sodium hydroxide 10% | 140 | 60 |
| Magnesium chloride | 140 | 60 | Sodium hydroxide 50% | x | x |
| Malic acid | x | x | Sodium hydroxide, concentrated | x | x |
| Manganese chloride | | | Sodium hypochlorite 20% | x | x |
| Methyl chloride | x | x | Sodium hypochlorite, concentrated | x | x |
| Methyl ethyl ketone | x | x | Sodium sulfide to 50% | 140 | 60 |
| Methyl isobutyl ketone | x | x | Stannic chloride | 140 | 60 |
| Muriatic acid | 140 | 60 | Stannous chloride | 140 | 60 |
| Nitric acid 5% | x | x | Sulfuric acid 10% | 140 | 60 |
| Nitric acid 20% | x | x | Sulfuric acid 50% | x | x |
| Nitric acid 70% | x | x | Sulfuric acid 70% | x | x |
| Nitric acid, anhydrous | x | x | Sulfuric acid 90% | x | x |
| Nitrous acid, concentrated | x | x | Sulfuric acid 98% | x | x |
| Oleum | | | Sulfuric acid 100% | x | x |
| Perchloric acid 10% | | | Sulfuric acid, fuming | x | x |
| Perchloric acid 70% | | | Sulfurous acid | x | x |
| Phenol | x | x | Thionyl chloride | | |
| Phosphoric acid 50–80% | 140 | 60 | Toluene | | |
| Picric acid | | | Trichloroacetic acid | | |
| Potassium bromide 30% | 140 | 60 | White liquor | | |
| Salicylic acid | | | Zinc chloride | 140 | 60 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

**Table N.3** Compatibility of Semi-Hard Natural Rubber with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | | | Allyl alcohol | | |
| Acetamide | x | x | Allyl chloride | | |
| Acetic acid 10% | | | Alum | 180 | 82 |
| Acetic acid 50% | | | Aluminum acetate | | |
| Acetic acid 80% | | | Aluminum chloride, aqueous | 180 | 82 |
| Acetic acid, glacial | x | x | Aluminum chloride, dry | | |
| Acetic anhydride | x | x | Aluminum fluoride | x | x |
| Acetone | x | x | Aluminum hydroxide | | |
| Acetyl chloride | | | Aluminum nitrate | 100 | 38 |
| Acrylic acid | | | Aluminum oxychloride | | |
| Acrylonitrile | | | Aluminum sulfate | 180 | 82 |
| Adipic acid | | | Ammonia gas | | |

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**Table N.3** Compatibility of Semi-Hard Natural Rubber with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Ammonium bifluoride | | | Calcium hydroxide 10% | 180 | 82 |
| Ammonium carbonate | 180 | 82 | Calcium hydroxide, sat. | 180 | 82 |
| Ammonium chloride 10% | 180 | 82 | Calcium hypochlorite | x | x |
| Ammonium chloride 50% | 180 | 82 | Calcium nitrate | | |
| Ammonium chloride, sat. | 180 | 82 | Calcium oxide | | |
| Ammonium fluoride 10% | x | x | Calcium sulfate | | |
| Ammonium fluoride 25% | x | x | Caprylic acid | | |
| Ammonium hydroxide 25% | | | Carbon bisulfide | | |
| Ammonium hydroxide, sat. | | | Carbon dioxide, dry | | |
| Ammonium nitrate | 180 | 82 | Carbon dioxide, wet | | |
| Ammonium persulfate | | | Carbon disulfide | | |
| Ammonium phosphate | 180 | 82 | Carbon monoxide | | |
| Ammonium sulfate 10–40% | 180 | 82 | Carbon tetrachloride | | |
| Ammonium sulfide | 180 | 82 | Carbonic acid | | |
| Ammonium sulfite | | | Cellosolve | | |
| Amyl acetate | | | Chloracetic acid | 100 | 38 |
| Amyl alcohol | 180 | 82 | Chloracetic acid, 50% water | 100 | 38 |
| Amyl chloride | | | Chlorine gas, dry | | |
| Aniline | x | x | Chlorine gas, wet | | |
| Antimony trichloride | | | Chlorine liquid | | |
| Aqua regia 3:1 | | | Chlorobenzene | | |
| Barium carbonate | 180 | 82 | Chloroform | | |
| Barium chloride | 180 | 82 | Chlorosulfonic acid | | |
| Barium hydroxide | 180 | 82 | Chromic acid 10% | x | x |
| Barium sulfate | 180 | 82 | Chromic acid 50% | x | x |
| Barium sulfide | | | Chromyl chloride | | |
| Benzaldehyde | | | Citric acid 15% | 100 | 38 |
| Benzene | x | x | Citric acid, concentrated | 100 | 38 |
| Benzene sulfonic acid 10% | | | Copper acetate | | |
| Benzoic acid | 180 | 82 | Copper carbonate | 180 | 82 |
| Benzyl alcohol | | | Copper chloride | x | x |
| Benzyl chloride | | | Copper cyanide | 180 | 82 |
| Borax | 180 | 82 | Copper sulfate | 180 | 82 |
| Boric acid | 180 | 82 | Cresol | | |
| Bromine gas, dry | | | Cupric chloride 5% | x | x |
| Bromine gas, moist | | | Cupric chloride 50% | x | x |
| Bromine liquid | | | Cyclohexane | | |
| Butadiene | | | Cyclohexanol | | |
| Butyl acetate | 100 | 38 | Dichloroacetic acid | | |
| Butyl alcohol | 180 | 82 | Dichloroethane (ethylene dichloride) | | |
| *n*-Butylamine | | | Ethylene glycol | 180 | 82 |
| Butyl phthalate | | | Ferric chloride | 180 | 82 |
| Butyric acid | 100 | 38 | Ferric chloride 50% in water | 180 | 82 |
| Calcium bisulfide | | | Ferric nitrate 10–50% | 100 | 38 |
| Calcium bisulfite | 180 | 82 | Ferrous chloride | 180 | 82 |
| Calcium carbonate | 180 | 82 | Ferrous nitrate | 100 | 38 |
| Calcium chlorate | | | Fluorine gas, dry | | |
| Calcium chloride | 180 | 82 | Fluorine gas, moist | | |

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**Table N.3** Compatibility of Semi-Hard Natural Rubber with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Hydrobromic acid, dilute | 180 | 82 | Phenol | x | x |
| Hydrobromic acid 20% | 180 | 82 | Phosphoric acid 50–80% | 180 | 82 |
| Hydrobromic acid 50% | 180 | 82 | Picric acid | | |
| Hydrochloric acid 20% | 180 | 82 | Potassium bromide 30% | 180 | 82 |
| Hydrochloric acid 38% | 180 | 82 | Salicylic acid | | |
| Hydrocyanic acid 10% | | | Silver bromide 10% | | |
| Hydrofluoric acid 30% | | | Sodium carbonate | 180 | 82 |
| Hydrofluoric acid 70% | x | x | Sodium chloride | 180 | 82 |
| Hydrofluoric acid 100% | x | x | Sodium hydroxide 10% | 180 | 82 |
| Hypochlorous acid | | | Sodium hydroxide 50% | 100 | 38 |
| Iodine solution 10% | | | Sodium hydroxide, concentrated | 100 | 38 |
| Ketones, general | | | Sodium hypochlorite 20% | x | x |
| Lactic acid 25% | 100 | 38 | Sodium hypochlorite, concentrated | x | x |
| Lactic acid, concentrated | 100 | 38 | Sodium sulfide to 50% | 180 | 82 |
| Magnesium chloride | 180 | 82 | Stannic chloride | 180 | 82 |
| Malic acid | 100 | 38 | Stannous chloride | 180 | 82 |
| Manganese chloride | | | Sulfuric acid 10% | 180 | 82 |
| Methyl chloride | 100 | 38 | Sulfuric acid 50% | 100 | 38 |
| Methyl ethyl ketone | | | Sulfuric acid 70% | x | x |
| Methyl isobutyl ketone | | | Sulfuric acid 90% | x | x |
| Muriatic acid | | | Sulfuric acid 98% | x | x |
| Nitric acid 5% | 100 | 38 | Sulfuric acid 100% | x | x |
| Nitric acid 20% | x | x | Sulfuric acid, fuming | x | x |
| Nitric acid 70% | x | x | Sulfurous acid | 150 | 66 |
| Nitric acid, anhydrous | x | x | Thionyl chloride | | |
| Nitrous acid, concentrated | 100 | 38 | Toluene | | |
| Oleum | | | Trichloroacetic acid | | |
| Perchloric acid 10% | | | White liquor | | |
| Perchloric acid 70% | | | Zinc chloride | 180 | 82 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable.

*Source:* PA Schweitzer. *Corrosion Resistance Tables,* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

**Table N.4** Compatibility of Hard Natural Rubber with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | | | Acetone | x | x |
| Acetamide | x | x | Acetyl chloride | | |
| Acetic acid 10% | 200 | 93 | Acrylic acid | | |
| Acetic acid 50% | 200 | 93 | Acrylonitrile | 90 | 32 |
| Acetic acid 80% | 150 | 66 | Adipic acid | 80 | 27 |
| Acetic acid, glacial | 100 | 38 | Allyl alcohol | x | x |
| Acetic anhydride | 100 | 38 | Allyl chloride | | |

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**Table N.4** Compatibility of Hard Natural Rubber with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Alum | 200 | 93 | Butyl acetate | x | x |
| Aluminum acetate | | | Butyl alcohol | 160 | 71 |
| Aluminum chloride, aqueous | 200 | 93 | *n*-Butylamine | | |
| Aluminum chloride, dry | | | Butyl phthalate | | |
| Aluminum fluoride | x | x | Butyric acid | 150 | 66 |
| Aluminum hydroxide | 200 | 93 | Calcium bisulfide | | |
| Aluminum nitrate | 190 | 88 | Calcium bisulfite | 200 | 93 |
| Aluminum oxychloride | | | Calcium carbonate | 200 | 93 |
| Aluminum sulfate | 200 | 93 | Calcium chlorate | | |
| Ammonia gas | | | Calcium chloride | 200 | 93 |
| Ammonium bifluoride | 200 | 93 | Calcium hydroxide 10% | 200 | 93 |
| Ammonium carbonate | 200 | 93 | Calcium hydroxide, sat. | 200 | 93 |
| Ammonium chloride 10% | 200 | 93 | Calcium hypochlorite | x | x |
| Ammonium chloride 50% | 200 | 93 | Calcium nitrate | 200 | 93 |
| Ammonium chloride, sat. | 200 | 93 | Calcium oxide | 200 | 93 |
| Ammonium fluoride 10% | x | x | Calcium sulfate | 200 | 93 |
| Ammonium fluoride 25% | x | x | Caprylic acid | | |
| Ammonium hydroxide 25% | x | x | Carbon bisulfide | x | x |
| Ammonium hydroxide, sat. | x | x | Carbon dioxide, dry | | |
| Ammonium nitrate | 150 | 66 | Carbon dioxide, wet | | |
| Ammonium persulfate | 200 | 93 | Carbon disulfide | x | x |
| Ammonium phosphate | 200 | 93 | Carbon monoxide | x | x |
| Ammonium sulfate 10–40% | 200 | 93 | Carbon tetrachloride | x | x |
| Ammonium sulfide | 200 | 93 | Carbonic acid | 200 | 93 |
| Ammonium sulfite | | | Cellosolve | | |
| Amyl acetate | | | Chloracetic acid | 120 | 49 |
| Amyl alcohol | 200 | 93 | Chloracetic acid, 50% water | 120 | 49 |
| Amyl chloride | | | Chlorine gas, dry | x | x |
| Aniline | x | x | Chlorine gas, wet | 190 | 88 |
| Antimony trichloride | | | Chlorine liquid | x | x |
| Aqua regia 3:1 | x | x | Chlorobenzene | x | x |
| Barium carbonate | 200 | 93 | Chloroform | x | x |
| Barium chloride | 200 | 93 | Chlorosulfonic acid | x | x |
| Barium hydroxide | x | x | Chromic acid 10% | x | x |
| Barium sulfate | 200 | 93 | Chromic acid 50% | x | x |
| Barium sulfide | 200 | 93 | Chromyl chloride | | |
| Benzaldehyde | x | x | Citric acid 15% | 150 | 66 |
| Benzene | x | x | Citric acid, concentrated | 150 | 66 |
| Benzene sulfonic acid 10% | | | Copper acetate | | |
| Benzoic acid | 200 | 93 | Copper carbonate | 200 | 93 |
| Benzyl alcohol | | | Copper chloride | 100 | 38 |
| Benzyl chloride | | | Copper cyanide | 200 | 93 |
| Borax | 200 | 93 | Copper sulfate | 200 | 93 |
| Boric acid | 200 | 93 | Cresol | | |
| Bromine gas, dry | | | Cupric chloride 5% | | |
| Bromine gas, moist | | | Cupric chloride 50% | | |
| Bromine liquid | | | Cyclohexane | | |
| Butadiene | | | Cyclohexanol | | |

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**Table N.4** Compatibility of Hard Natural Rubber with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Dichloroacetic acid | | | Nitric acid, anhydrous | x | x |
| Dichloroethane (ethylene dichloride) | | | Nitrous acid, concentrated | 150 | 66 |
| Ethylene glycol | 200 | 93 | Oleum | | |
| Ferric chloride | 200 | 93 | Perchloric acid 10% | | |
| Ferric chloride 50% in water | 200 | 93 | Perchloric acid 70% | | |
| Ferric nitrate 10–50% | 150 | 66 | Phenol | x | x |
| Ferrous chloride | 200 | 93 | Phosphoric acid 50–80% | 200 | 93 |
| Ferrous nitrate | 150 | 66 | Picric acid | | |
| Fluorine gas, dry | | | Potassium bromide 30% | 200 | 93 |
| Fluorine gas, moist | | | Salicylic acid | | |
| Hydrobromic acid, dilute | 200 | 93 | Silver bromide 10% | | |
| Hydrobromic acid 20% | 200 | 93 | Sodium carbonate | 200 | 93 |
| Hydrobromic acid 50% | 200 | 93 | Sodium chloride | 200 | 93 |
| Hydrochloric acid 20% | 200 | 93 | Sodium hydroxide 10% | 200 | 93 |
| Hydrochloric acid 38% | 200 | 93 | Sodium hydroxide 50% | 150 | 66 |
| Hydrocyanic acid 10% | 200 | 93 | Sodium hydroxide, concentrated | 150 | 66 |
| Hydrofluoric acid 30% | x | x | Sodium hypochlorite 20% | x | x |
| Hydrofluoric acid 70% | x | x | Sodium hypochlorite, concentrated | x | x |
| Hydrofluoric acid 100% | x | x | Sodium sulfide to 50% | 200 | 93 |
| Hypochlorous acid | 150 | 66 | Stannic chloride | 200 | 93 |
| Iodine solution 10% | | | Stannous chloride | 200 | 93 |
| Ketones, general | | | Sulfuric acid 10% | 200 | 93 |
| Lactic acid 25% | 150 | 66 | Sulfuric acid 50% | | |
| Lactic acid, concentrated | 150 | 66 | Sulfuric acid 70% | x | x |
| Magnesium chloride | 200 | 93 | Sulfuric acid 90% | | |
| Malic acid | 150 | 66 | Sulfuric acid 98% | | |
| Manganese chloride | | | Sulfuric acid 100% | | |
| Methyl chloride | | | Sulfuric acid, fuming | | |
| Methyl ethyl ketone | x | x | Sulfurous acid | 200 | 93 |
| Methyl isobutyl ketone | | | Thionyl chloride | | |
| Muriatic acid | 200 | 93 | Toluene | | |
| Nitric acid 5% | 150 | 66 | Trichloroacetic acid | | |
| Nitric acid 20% | x | x | White liquor | | |
| Nitric acid 70% | x | x | Zinc chloride | 200 | 93 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable.

*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

## Applications

Natural rubber finds its major use in the manufacture of pneumatic tires and tubes, power transmission belts, conveyor belts, gaskets, mountings, hose, chemical tank linings, printing press platens, sound and/or shock absorbers, and seals against air, moisture, sound, and dirt.

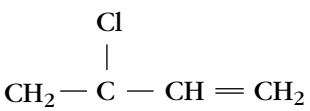
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Rubber has been used for many years as a lining material for steel tanks, particularly for protection against corrosion of inorganic salt solutions, especially brine, alkalies, and nonoxidizing acids. These linings have the advantage of being readily repaired in place. Natural rubber is also used for lining pipelines used to convey these types of materials. Some of these applications have been replaced by synthetic rubbers that have been developed over the years.

See Refs. 1 and 2.

## NEOPRENE (CR)

Neoprene is one of the oldest and most versatile of the synthetic rubbers. Chemically it is polychloroprene. Its basic unit is a chlorinated butadiene whose formula is



The raw material is acetylene, which makes this product more expensive than some of the other elastomeric materials.

Neoprene was introduced commercially by DuPont in 1932 as an oil-resistant substitute for natural rubber. Its dynamic properties are very similar to those of natural rubber, but its range of chemical resistance overcomes many of the shortcomings of natural rubber.

As with other elastomeric materials, neoprene is available in a variety of formulations. Depending on the compounding procedure, material can be produced to impart specific properties to meet specific application needs.

Neoprene is also available in a variety of forms. In addition to a neoprene latex that is similar to natural rubber latex, neoprene is produced in a "fluid" form as either a compounded latex dispersion or a solvent solution. Once these materials have solidified or cured, they have the same physical and chemical properties as the solid or cellular forms.

### Physical and Mechanical Properties

The properties discussed here are attainable with neoprene but may not necessarily be incorporated into every neoprene product. Nor will every neoprene product perform the same in all environments. The reason for this variation is compounding. By selective addition and/or deletion of specific ingredients during compounding, specific properties can be enhanced or reduced to provide the neoprene formulation best suited for the application. A neoprene compound can be produced that will provide whichever of the properties discussed are desired. When the hardness of neoprene is above 55 Shore A, its resilience exceeds that of natural rubber by approximately 5%. At hardnesses below 50 Shore A, its resilience is not as good as that of natural rubber even though its resilience is measured at 75%, which is a high value. Because of its high resilience, neoprene products have low hysteresis and a minimum heat buildup during dynamic operations.

Solid neoprene products can be ignited by an open flame but will stop burning when the flame is removed. Because of its chlorine content, neoprene is more resistant to

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burning than exclusively hydrocarbon elastomers. Natural rubber and many of the other synthetic elastomers will continue to burn once ignited even if the flame is removed. In an actual fire situation, neoprene will burn. Although compounding can improve the flame resistance of neoprene, it cannot make it immune to burning.

Compared with natural rubber, neoprene is relatively impermeable to gases. Table N.5 lists typical permeability constants. Because of this impermeability, neoprene can be used to seal against freon blowing agents, propane, butane, and other gases.

Neoprene is used in many electrical applications, although its dielectric characteristics limit its use as an insulation to low voltage (600 V) and low frequency (60 Hz). Because of its high degree of resistance to indoor and outdoor aging and its resistance to weathering, neoprene is often used as a protective outer jacket to insulation at all voltages. It is also immune to high-voltage corona discharge effects that cause severe surface cutting in many types of elastomers.

**Table N.5** Physical and Mechanical Properties of Neoprene (CR)[a]

| | |
|---|---|
| Specific gravity | 1.4 |
| Refractive index | 1.56 |
| Specific heat, cal/g | 0.40 |
| Volumetric coefficient of thermal expansions | |
| at 77°F | $403 \times 10^{-6}$/°F |
| at 25°C | $725 \times 10^{-6}$/°C |
| Thermal conductivity | |
| Btu/h-ft$^2$-in. °F | 1.45 |
| g-cal/h-cm$^2$cm °C | 1.80 |
| Brittle point | –40°F (–40°C) |
| DC resistivity, ohm-cm | $2 \times 10^{13}$ |
| Dielectric strength, V/mil | 600 |
| Permeability (cm$^3$/cm$^2$-cm-sec-atm) at 77°F (25°C) | |
| to nitrogen | $1 \times 10^{-8}$ |
| to methane | $2 \times 10^{-8}$ |
| to oxygen | $3 \times 10^{-8}$ |
| to helium | $10 \times 10^{-8}$ |
| to carbon dioxide | $19 \times 10^{-8}$ |
| Tensile strength, psi | 1000–2500 |
| Elongation, % at break | 200–600 |
| Hardness, Shore A | 40–95 |
| Abrasion resistance | Excellent |
| Maximum temperature, continuous use | 180–200°F (82–93°C) |
| Impact resistance | Excellent |
| Compression set, % | 15–35 |
| Machining qualities | Can be ground |
| Resistance to sunlight | Excellent |
| Effect of aging | Little effect |
| Resistance to heat | Good |

[a]These are representative values since they may be altered by compounding.

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At the maximum operating temperature of 200°F (93°C), neoprene continues to maintain good physical properties and has excellent resistance to long-term heat degradation. Unlike other elastomers, neoprene does not soften or melt when heated, regardless of the degree of heat. Heat failure results from the hardening of the product and lack of resilience. Neoprene products display little change in performance characteristics down to approximately 0°F (−18°C). As temperatures decrease further, the material stiffens until the brittle point is reached. Although the brittle point for standard neoprene products is −40°F (−40°C), special compounding can produce materials that can be used at temperatures as low as −67°F (−55°C).

Neoprene will form an extremely strong mechanical bond with cotton fabric. If suitable treatments or additives are provided, it can also be made to adhere to such man-made fibers as glass, nylon, rayon, acrylic, and polyester. It can also be molded in contact with metals, particularly carbon and alloy steels, stainless steels, aluminum and aluminum alloys, brass, and copper, using any one of the commercially available bonding agents.

Neoprene provides no nourishment for microorganisms, but it will not deter them from consuming other ingredients in the compound. Consequently, products containing metabolizable compounding ingredients require the inclusion of a fungicide, bactericide, or pesticide in the formulation to provide protection.

Pigmentation of neoprene products is a simple matter since the elastomer readily accepts color additives. However, the lighter shades, such as tones of yellow, red, blue, and other bright colors, will eventually discolor with prolonged exposure to sunlight and ultraviolet light. Because of this, products intended for prolonged outdoor service are usually produced in shades of gray, maroon, brown, or black. The lighter shades are used for products having limited exposure to sunlight, such as rainwear and appliance parts.

## Resistance to Sun, Weather, and Ozone

Neoprene displays excellent resistance to sun, weather, and ozone. Because of its low rate of oxidation, products made of neoprene have a high resistance to both outdoor and indoor aging. Over prolonged periods of time in an outdoor environment, the physical properties of neoprene display insignificant change. If neoprene is properly compounded, ozone in atmospheric concentrations has little effect on the product. When severe ozone exposure is expected, as for example around electrical equipment, compositions of neoprene can be provided to resist thousands of parts per million of ozone for hours without surface cracking. Natural rubber will crack within minutes when subjected to ozone concentrations of only 50 ppm.

## Chemical Resistance

Neoprene's resistance to attack from solvents, waxes, fats, oils, greases, and many other petroleum-based products is one of its outstanding properties. Excellent service is also experienced when it is in contact with aliphatic compounds (methyl and ethyl alcohols, ethylene glycols, etc.), aliphatic hydrocarbons, and most freon refrigerants. A minimum amount of swelling and relatively little loss of strength occur when neoprene is in contact with these fluids.

When exposed to dilute mineral acids, inorganic salt solutions, or alkalies, neoprene products show little if any change in appearance or change in properties.

Chlorinated and aromatic hydrocarbons, organic esters, aromatic hydroxy compounds, and certain ketones have an adverse effect on neoprene, and consequently only

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limited serviceability can be expected with them. Highly oxidizing acid and salt solutions also cause surface deterioration and loss of strength. Included in this category are nitric acid and concentrated sulfuric acid.

Neoprene formulations can be produced that provide products with outstanding resistance to water absorption. These products can be used in continuous or periodic immersion in either fresh water or salt water without loss of properties.

Properly compounded neoprene can he buried underground successfully, since moisture, bacteria, and soil chemicals usually found in the earth have little effect on its properties. It is unaffected by soils saturated with water, sea water, chemicals, oils, gasolines, wastes, and other industrial by-products. Refer to Table N.6 for the compatibility of neoprene with selected corrodents.

**Table N.6** Compatibility of Neoprene with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | 200 | 93 | Ammonium hydroxide, sat. | 200 | 93 |
| Acetamide | 200 | 93 | Ammonium nitrate | 200 | 93 |
| Acetic acid 10% | 160 | 71 | Ammonium persulfate | 200 | 93 |
| Acetic acid 50% | 160 | 71 | Ammonium phosphate | 150 | 66 |
| Acetic acid 80% | 160 | 71 | Ammonium sulfate 10–40% | 150 | 66 |
| Acetic acid, glacial | x | x | Ammonium sulfide | 160 | 71 |
| Acetic anhydride | x | x | Ammonium sulfite | | |
| Acetone | x | x | Amyl acetate | x | x |
| Acetyl chloride | x | x | Amyl alcohol | 200 | 93 |
| Acrylic acid | x | x | Amyl chloride | x | x |
| Acrylonitrile | 140 | 60 | Aniline | x | x |
| Adipic acid | 160 | 71 | Antimony trichloride | 140 | 60 |
| Allyl alcohol | 120 | 49 | Aqua regia 3:1 | x | x |
| Allyl chloride | x | x | Barium carbonate | 150 | 66 |
| Alum | 200 | 93 | Barium chloride | 150 | 66 |
| Aluminum acetate | | | Barium hydroxide | 230 | 110 |
| Aluminum chloride, aqueous | 150 | 66 | Barium sulfate | 200 | 93 |
| Aluminum chloride, dry | | | Barium sulfide | 200 | 93 |
| Aluminum fluoride | 200 | 93 | Benzaldehyde | x | x |
| Aluminum hydroxide | 180 | 82 | Benzene | x | x |
| Aluminum nitrate | 200 | 93 | Benzene sulfonic acid 10% | 100 | 38 |
| Aluminum oxychloride | | | Benzoic acid | 150 | 66 |
| Aluminum sulfate | 200 | 93 | Benzyl alcohol | x | x |
| Ammonia gas | 140 | 60 | Benzyl chloride | x | x |
| Ammonium bifluoride | x | x | Borax | 200 | 93 |
| Ammonium carbonate | 200 | 93 | Boric acid | 150 | 66 |
| Ammonium chloride 10% | 150 | 66 | Bromine gas, dry | x | x |
| Ammonium chloride 50% | 150 | 66 | Bromine gas, moist | x | x |
| Ammonium chloride, sat. | 150 | 66 | Bromine liquid | x | x |
| Ammonium fluoride 10% | 200 | 93 | Butadiene | 140 | 60 |
| Ammonium fluoride 25% | 200 | 93 | Butyl acetate | 60 | 16 |
| Ammonium hydroxide 25% | 200 | 93 | Butyl alcohol | 200 | 93 |

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**Table N.6** Compatibility of Neoprene with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| *n*-Butylamine | | | Ethylene glycol | 100 | 38 |
| Butyl phthalate | | | Ferric chloride | 160 | 71 |
| Butyric acid | x | x | Ferric chloride 50% in water | 160 | 71 |
| Calcium bisulfide | | | Ferric nitrate 10–50% | 200 | 93 |
| Calcium bisulfite | x | x | Ferrous chloride | 90 | 32 |
| Calcium carbonate | 200 | 93 | Ferrous nitrate | 200 | 93 |
| Calcium chlorate | 200 | 93 | Fluorine gas, dry | x | x |
| Calcium chloride | 150 | 66 | Fluorine gas, moist | x | x |
| Calcium hydroxide 10% | 230 | 110 | Hydrobromic acid, dilute | x | x |
| Calcium hydroxide, sat. | 230 | 110 | Hydrobromic acid 20% | x | x |
| Calcium hypochlorite | x | x | Hydrobromic acid 50% | x | x |
| Calcium nitrate | 150 | 66 | Hydrochloric acid 20% | x | x |
| Calcium oxide | 200 | 93 | Hydrochloric acid 38% | x | x |
| Calcium sulfate | 150 | 66 | Hydrocyanic acid 10% | x | x |
| Caprylic acid | | | Hydrofluoric acid 30% | x | x |
| Carbon bisulfide | x | x | Hydrofluoric acid 70% | x | x |
| Carbon dioxide, dry | 200 | 93 | Hydrofluoric acid 100% | x | x |
| Carbon dioxide, wet | 200 | 93 | Hypochlorous acid | x | x |
| Carbon disulfide | x | x | Iodine solution 10% | 80 | 27 |
| Carbon monoxide | x | x | Ketones, general | x | x |
| Carbon tetrachloride | x | x | Lactic acid 25% | 140 | 60 |
| Carbonic acid | 150 | 66 | Lactic acid, concentrated | 90 | 32 |
| Cellosolve | x | x | Magnesium chloride | 200 | 93 |
| Chloracetic acid | x | x | Malic acid | | |
| Chloracetic acid, 50% water | x | x | Manganese chloride | 200 | 93 |
| Chlorine gas, dry | x | x | Methyl chloride | x | x |
| Chlorine gas, wet | x | x | Methyl ethyl ketone | x | x |
| Chlorine liquid | x | x | Methyl isobutyl ketone | x | x |
| Chlorobenzene | x | x | Muriatic acid | x | x |
| Chloroform | x | x | Nitric acid 5% | x | x |
| Chlorosulfonic acid | x | x | Nitric acid 20% | x | x |
| Chromic acid 10% | 140 | 60 | Nitric acid 70% | x | x |
| Chromic acid 50% | 100 | 38 | Nitric acid, anhydrous | x | x |
| Chromyl chloride | | | Nitrous acid, concentrated | x | x |
| Citric acid 15% | 150 | 66 | Oleum | x | x |
| Citric acid, concentrated | 150 | 66 | Perchloric acid 10% | | |
| Copper acetate | 160 | 71 | Perchloric acid 70% | x | x |
| Copper carbonate | | | Phenol | x | x |
| Copper chloride | 200 | 93 | Phosphoric acid 50–80% | 150 | 66 |
| Copper cyanide | 160 | 71 | Picric acid | 200 | 93 |
| Copper sulfate | 200 | 93 | Potassium bromide 30% | 160 | 71 |
| Cresol | x | x | Salicylic acid | | |
| Cupric chloride 5% | 200 | 93 | Silver bromide 10% | | |
| Cupric chloride 50% | 160 | 71 | Sodium carbonate | 200 | 93 |
| Cyclohexane | x | x | Sodium chloride | 200 | 93 |
| Cyclohexanol | x | x | Sodium hydroxide 10% | 230 | 110 |
| Dichloroacetic acid | x | x | Sodium hydroxide 50% | 230 | 110 |
| Dichloroethane (ethylene dichloride) | x | x | Sodium hydroxide, concentrated | 230 | 110 |

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**Table N.6** Compatibility of Neoprene with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Sodium hypochlorite 20% | x | x | Sulfuric acid 98% | x | x |
| Sodium hypochlorite, concentrated | x | x | Sulfuric acid 100% | x | x |
| Sodium sulfide to 50% | 200 | 93 | Sulfuric acid, fuming | x | x |
| Stannic chloride | 200 | 93 | Sulfurous acid | 100 | 38 |
| Stannous chloride | x | x | Thionyl chloride | x | x |
| Sulfuric acid 10% | 150 | 66 | Toluene | x | x |
| Sulfuric acid 50% | 100 | 38 | Trichloroacetic acid | x | x |
| Sulfuric acid 70% | x | x | White liquor | 140 | 60 |
| Sulfuric acid 90% | x | x | Zinc chloride | 160 | 71 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable.

*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

## Applications

Neoprene products are available in three basic forms:

1. Conventional solid rubber parts
2. Highly compressed cellular materials
3. Free-flowing fluids

Each form has certain specific properties that can be of advantage to final products.

Solid products can be produced by molding, extruding, or calendering. Molding can be accomplished by compression, transfer, injection, blow, vacuum, or wrapped-mandrel methods. Typical products produced by these methods are instrument seals, shoe soles and heels, auto sparkplug boots, radiator hose, boating accessories, appliance parts, O-rings, and other miscellaneous components.

Extrusion processes provide means of economically and uniformly mass producing products quickly. Neoprene products manufactured by these processes include tubing, sealing strips, wire jacketing, filaments, rods, and many types of hose.

Calendered products include sheet stock, belting, and friction and coated fabrics. A large proportion of sheet stock is later die-cut into finished products such as pads, gaskets, and diaphragms.

Cellular forms of neoprene are used primarily for gasketing, insulation, cushioning, and sound and vibration damping. This material provides compressibility not found in solid rubber but still retains the advantageous properties of neoprene. It is available as an open-cell sponge, a closed-cell neoprene, and a foam neoprene.

Open-cell neoprene is a compressible, absorbent material whose cells are uniform and connected. This is particularly useful for gasketing and dust-proofing applications where exposure to fluids is not expected.

Closed-cell neoprene is a resilient complex of individual nonconnecting cells that impart an added advantage of nonabsorbency. This property makes closed-cell neoprene especially suitable for sealing applications where fluid contact is expected, for products

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such as wet suits for divers, shoe soles, automotive deck lid seals, and for other applications where a compressible nonabsorbent weather-resistant material is required.

Foam neoprene is similar to open-cell neoprene in that it is a compressible material with connecting cells. Its main area of application is for cushioning, for example, in mattresses and seating and carpet underlay. Because of the good heat and oil resistance of neoprene, it has also found application as a railroad car lubricator. This absorbent open-cell structure provides a wicking action to deliver oil to the journal bearings.

Fluid forms of neoprene are important in the manufacture of many products because of their versatility. "Fluid" neoprene is the primary component in such products as adhesives, coatings and paints, sealants, caulks, and fiber binders. It is available in two forms, as a neoprene latex or as a solvent solution. Neoprene latex is an elastomer–water dispersion. It is used primarily in the manufacture of dipped products, such as household and industrial gloves, meteorological balloons, sealed fractional horsepower motors, and a variety of rubber-covered metal parts. Other applications include use as a binder for curled animal hair in resilient furniture cushioning, transportation seating, acoustical filtering, and packaging. It is also used extensively in latex-based gloves, foams, protective coatings, and knife-coated fabrics, as a binder for cellulose and asbestos, and as an elasticizing additive for concrete, mortar, and asphalt. These products produced from neoprene latex possess the same properties as those associated with solid neoprene, including resistance to oil, chemicals, ozone, weather, and flame.

Neoprene solvent solutions are prepared by dissolving neoprene in standard rubber solvents. These solutions can be formulated in a range of viscosities suitable for application by brush, spray, or roller. Major areas of application include coating for storage tanks, industrial equipment, and chemical processing equipment. These coatings protect the vessels from corrosion by acids, oils, alkalies, and most hydrocarbons. Neoprene roofing applied in liquid form is used to protect concrete, plywood, and metal decks. The solvent solution can be readily applied and will cure into a roofing membrane that is tough, elastic, and weather resistant.

Solvent-based adhesives develop quick initial bonds and remain strong and flexible almost indefinitely. They can be used to join a wide variety of rigid and flexible materials.

Collapsible nylon containers coated with neoprene are used for transporting and/or storing liquids, pastes, and flowable dry solids. Containers have been designed to hold oils, fuels, molasses, and various bulk-shipped products.

Neoprene in its many forms has proven to be reliable and indeed indispensable as a substitute for natural rubber, possessing many of the advantageous properties of natural rubber while also overcoming many of its shortcomings.

See Refs. 1 and 2.

## NEUTRAL SOLUTION

A neutral solution is one that contains an equal number of hydrogen and hydroxyl ions, making it neither acidic nor basic. It will have a pH of 7.

## NEXUS

Nexus is the trademark of Burlington Industries for their polyester surfacing veil material. See "Thermoset Reinforcing Materials."

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## NICKEL

This family is represented by nickel alloys 200 (N02200) and 201 (N02201). The chemical composition is shown in Table N.7. Commercially pure nickel is a white magnetic metal very similar to copper in its physical and mechanical properties. Refer to Table N.8 for the physical and mechanical properties of nickel 200 and nickel 201.

**Table N.7** Chemical Composition of Nickel 200 and Nickel 201

| | Weight percent, max. | |
|---|---|---|
| Chemical | Nickel 200 | Nickel 201 |
| Carbon | 0.1 | 0.02 |
| Copper | 0.25 | 0.25 |
| Iron | 0.4 | 0.4 |
| Nickel | 99.2 | 99.0 |
| Silicon | 0.15 | 0.15 |
| Titanium | 0.1 | 0.1 |

**Table N.8** Mechanical and Physical Properties of Nickel 200 and Nickel 201

| Property | Nickel 200 | Nickel 201 |
|---|---|---|
| Modulus of elasticity $\times 10^6$, psi | 28 | 30 |
| Tensile strength $\times 10^3$ psi | 27000 | 58500 |
| Yield strength 0.2% offset $\times 10^3$, psi | 21500 | 15000 |
| Elongation in 2 in., % | 47 | 50 |
| Hardness, Brinell | 105 | 87 |
| Density, lb/in.$^3$ | 0.321 | 0.321 |
| Specific gravity | 8.89 | 8.89 |
| Specific heat, Btu/lb °F | 0.109 | 0.109 |
| Thermal conductivity, Btu/h/ft$^2$/°F/in. | | |
| at 0–70° | 500 | 569 |
| at 70–200°F | 465 | 512 |
| at 70–400°F | 425 | 460 |
| at 70–600°F | 390 | 408 |
| at 70–800°F | 390 | 392 |
| at 70–1000°F | 405 | 410 |
| at 70–1200°F | 420 | 428 |
| Thermal expansion coefficient, in./in./°F $\times 10^{-6}$ | | |
| at 0–70°F | 6.3 | |
| at 70–200°F | 7.4 | 7.3 |
| at 70–400°F | 7.7 | |
| at 70–600°F | 8.0 | |
| at 70–800°F | 8.3 | |
| at 70–1000°F | 8.5 | |
| at 70–1200°F | 8.7 | |

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The Curie point—the temperature at which it loses its magnetism—varies with the type and quantity of alloy additions, rising with increased iron and cobalt additions and falling as copper, silicon, and most other elements are added. Nickel is also an important alloying element in other families of corrosion-resistant materials.

Alloy 201 is the low-carbon version of alloy 200. Alloy 200 is subject to the formation of a grain boundary graphitic phase, which reduces ductility tremendously. Consequently, nickel alloy 200 is limited to a maximum operating temperature of 600°F (315°C). For applications above this temperature, alloy 201 should be used.

The corrosion resistance of alloy 200 and alloy 201 are the same. They exhibit outstanding resistance to hot alkalies, particularly caustic soda. Excellent resistance is shown at all concentrations at temperatures up to and including the molten state. Below 50% the corrosion rates are negligible, usually being less than 0.2 mpy even in boiling solutions. As concentrations and temperatures increase, corrosion rates increase very slowly. Impurities in the caustic, such as chlorates and hypochlorites, will determine the corrosion rate.

Nickel is not subject to stress corrosion cracking in any of the chloride salts, and it exhibits excellent general resistance to nonoxidizing halides. Oxidizing acid chlorides, such as ferric, cupric, and mercuric, are very corrosive and should be avoided.

Nickel 201 finds application in the handling of hot, dry chlorine and hydrogen chloride gas on a continuous basis up to 1000°F (540°C). The resistance is attributed to the formation of a nickel chloride film. Dry fluorine and bromine can be handled in the same manner. The resistance will decrease when moisture is present.

Nickel exhibits excellent resistance to most organic acids, particularly fatty acids such as stearic and oleic, if aeration is not high.

Nickel is not attacked by anhydrous ammonia or ammonium hydroxide in concentrations of 1% or less. Stronger concentrations cause rapid attack.

Nickel also finds application in the handling of food and synthetic fibers because of its ability to maintain product purity. The presence of nickel ions is not detrimental to the flavor of food products, and it is not toxic. Unlike iron and copper, nickel will not discolor organic chemicals such as phenol and viscous rayon.

Refer to Table N.9 for the compatibility of nickel 200 and nickel 201 with selected corrodents.

**Table N.9** Compatibility of Nickel 200 and Nickel 201 with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | 200 | 93 | Acrylic acid | | |
| Acetamide | | | Acrylonitrile | 210 | 99 |
| Acetic acid 10% | 90 | 32 | Adipic acid | 210 | 99 |
| Acetic acid 50% | 90 | 32 | Allyl alcohol | 220 | 104 |
| Acetic acid 80% | 120 | 49 | Allyl chloride | 190 | 88 |
| Acetic acid, glacial | x | x | Alum | 170 | 77 |
| Acetic anhydride | 170 | 77 | Aluminum acetate | | |
| Acetone | 190 | 88 | Aluminum chloride, aqueous | 300 | 149 |
| Acetyl chloride | 100 | 38 | Aluminum chloride, dry | 60 | 16 |

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**Table N.9** Compatibility of Nickel 200 and Nickel 201 with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Aluminum fluoride | 90 | 32 | Butyl phthalate | 210 | 99 |
| Aluminum hydroxide | 80 | 27 | Butyric acid | x | x |
| Aluminum nitrate | | | Calcium bisulfide | | |
| Aluminum oxychloride | | | Calcium bisulfite | x | x |
| Aluminum sulfate | 210 | 99 | Calcium carbonate | | |
| Ammonia gas | 90 | 32 | Calcium chlorate | 140 | 60 |
| Ammonium bifluoride | | | Calcium chloride | 80 | 27 |
| Ammonium carbonate | 190 | 88 | Calcium hydroxide 10% | 210 | 99 |
| Ammonium chloride 10% | 230 | 110 | Calcium hydroxide, sat. | 200 | 93 |
| Ammonium chloride 50% | 170 | 77 | Calcium hypochlorite | x | x |
| Ammonium chloride, sat. | 570 | 299 | Calcium nitrate | | |
| Ammonium fluoride 10% | 210 | 99 | Calcium oxide | 90 | 32 |
| Ammonium fluoride 25% | 200 | 93 | Calcium sulfate | 210 | 99 |
| Ammonium hydroxide 25% | x | x | Caprylic acid[b] | 210 | 99 |
| Ammonium hydroxide, sat. | 320 | 160 | Carbon bisulfide | x | x |
| Ammonium nitrate | 90 | 32 | Carbon dioxide, dry | 210 | 99 |
| Ammonium persulfate | x | x | Carbon dioxide, wet | 200 | 93 |
| Ammonium phosphate 30% | 210 | 99 | Carbon disulfide | x | x |
| Ammonium sulfate 10–40% | 210 | 99 | Carbon monoxide | 570 | 290 |
| Ammonium sulfide | | | Carbon tetrachloride | 210 | 99 |
| Ammonium sulfite | x | x | Carbonic acid | 80 | 27 |
| Amyl acetate | 300 | 149 | Cellosolve | 210 | 99 |
| Amyl alcohol | | | Chloracetic acid | 210 | 99 |
| Amyl chloride | 90 | 32 | Chloracetic acid, 50% water | | |
| Aniline | 210 | 99 | Chlorine gas, dry | 200 | 93 |
| Antimony trichloride | 210 | 99 | Chlorine gas, wet | x | x |
| Aqua regia 3:1 | x | x | Chlorine liquid | | |
| Barium carbonate | 210 | 99 | Chlorobenzene | 120 | 49 |
| Barium chloride | 80 | 27 | Chloroform | 210 | 99 |
| Barium hydroxide | 90 | 32 | Chlorosulfonic acid | 80 | 27 |
| Barium sulfate | 210 | 99 | Chromic acid 10% | 100 | 38 |
| Barium sulfide | 110 | 43 | Chromic acid 50% | x | x |
| Benzaldehyde | 210 | 99 | Chromyl chloride | 210 | 99 |
| Benzene | 210 | 99 | Citric acid 15% | 210 | 99 |
| Benzene sulfonic acid 10% | 190 | 88 | Citric acid, concentrated | 80 | 27 |
| Benzoic acid | 400 | 204 | Copper acetate | 100 | 38 |
| Benzyl alcohol | 210 | 99 | Copper carbonate | x | x |
| Benzyl chloride | 210 | 99 | Copper chloride | x | x |
| Borax | 200 | 93 | Copper cyanide | x | x |
| Boric acid | 210 | 99 | Copper sulfate | x | x |
| Bromine gas, dry | 60 | 16 | Cresol | 100 | 38 |
| Bromine gas, moist | x | x | Cupric chloride 5% | x | x |
| Bromine liquid | | | Cupric chloride 50% | x | x |
| Butadiene | 80 | 27 | Cyclohexane | 80 | 27 |
| Butyl acetate | 80 | 27 | Cyclohexanol | 80 | 27 |
| Butyl alcohol | 200 | 93 | Dichloroacetic acid | | |
| *n*-Butylamide | | | Dichloroethane (ethylene dichloride) | x | x |

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**Table N.9** Compatibility of Nickel 200 and Nickel 201 with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Ethylene glycol | 210 | 99 | Nitrous acid, concentrated | x | x |
| Ferric chloride | x | x | Oleum | | |
| Ferric chloride 50% in water | x | x | Perchloric acid 10% | x | x |
| Ferric nitrate 10–50% | x | x | Perchloric acid 70% | | |
| Ferrous chloride | x | x | Phenol, sulfur free | 570 | 299 |
| Ferrous nitrate | | | Phosphoric acid 50–80% | x | x |
| Fluorine gas, dry | 570 | 290 | Picric acid | 80 | 27 |
| Fluorine gas, moist | 60 | 16 | Potassium bromide 30% | | |
| Hydrobromic acid, dilute | x | x | Salicylic acid | 80 | 27 |
| Hydrobromic acid 20% | x | x | Silver bromide 10% | | |
| Hydrobromic acid 50% | x | x | Sodium carbonate to 30% | 210 | 99 |
| Hydrochloric acid 20% | 80 | 27 | Sodium chloride to 30% | 210 | 99 |
| Hydrochloric acid 38% | x | x | Sodium hydroxide 10%c | 210 | 99 |
| Hydrocyanic acid 10% | | | Sodium hydroxide 50%[c] | 300 | 149 |
| Hydrofluoric acid 30%[c] | 170 | 77 | Sodium hydroxide, concentrated | 200 | 93 |
| Hydrofluoric acid 70%[c] | 100 | 38 | Sodium hypochlorite 20% | x | x |
| Hydrofluoric acid 100%[c] | 120 | 49 | Sodium hypochlorite, concentrated | x | x |
| Hypochlorous acid | x | x | Sodium sulfide to 50% | x | x |
| Iodine solution 10% | | | Stannic chloride | x | x |
| Ketones, general | 100 | 38 | Stannous chloride, dry | 570 | 299 |
| Lactic acid 25% | x | x | Sulfuric acid 10% | x | x |
| Lactic acid, concentrated | x | x | Sulfuric acid 50% | x | x |
| Magnesium chloride | 300 | 149 | Sulfuric acid 70% | x | x |
| Malic acid | 210 | 99 | Sulfuric acid 90% | x | x |
| Manganese chloride 37% | 90 | 32 | Sulfuric acid 98% | x | x |
| Methyl chloride | 210 | 99 | Sulfuric acid 100% | x | x |
| Methyl ethyl ketone | | | Sulfuric acid, fuming | x | x |
| Methyl isobutyl ketone | 200 | 93 | Sulfurous acid | x | x |
| Muriatic acid | x | x | Thionyl chloride | 210 | 99 |
| Nitric acid 5% | x | x | Toluene | 210 | 99 |
| Nitric acid 20% | x | x | Trichloroacetic acid | 80 | 27 |
| Nitric acid 70% | x | x | White liquor | | |
| Nitric acid, anhydrous | x | x | Zinc chloride to 80% | 200 | 93 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable. When compatible, corrosion rate is <20 mpy.
[b]Material subject to pitting.
[c]Material subject to stress cracking.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

In addition to alloy 200, there are a number of alloy modifications developed for increased strength, hardness, resistance to galling, and improved corrosion resistance. Other alloys in this family are not specifically used for their corrosion resistance. Alloy 270 is a high-purity, low-inclusion version of alloy 200. Alloy 301 (also referred to by the trade name Duranickel) is a precipitation-hardenable alloy containing aluminum and titanium. Alloy 300 (also referred to by the trade name Permanickel) is a moderately pre-

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cipitation-hardenable alloy containing titanium and magnesium that also possesses higher thermal and electrical conductivity.

See Refs. 3–8.

## NICKEL COATINGS

There are three types of nickel coatings: bright, semibright, and dull bright. The difference between the coatings is in the quantity of sulfur contained in them, as shown below:

| | |
|---|---|
| Bright nickel deposits | > 0.05% sulfur |
| Semibright nickel deposits | <0.005% sulfur |
| Dull bright nickel deposits | <0.001% sulfur |

The corrosion potentials of the nickel deposits are dependent on the sulfur content. Figure N.1 shows the effect of sulfur content on the corrosion potential of a nickel deposit. A single-layer nickel coating must be greater than 30 $\mu$m to ensure absence of defects (25 $\mu$m = 1mil).

As the sulfur content increases, the corrosion potential of a nickel deposit becomes more negative. A bright nickel coating is less protective than a semibright or dull nickel coating. The difference in the corrosion potential of bright nickel and semibright nickel deposits is more than 50 mV.

Use is made of the differences in the potential in the application of multilayer coatings. The more negative bright nickel deposits are used as sacrificial intermediate layers. When bright nickel is used as an intermediate layer, the corrosion behavior is characterized by a sideways diversion. Pitting corrosion is diverted laterally when it reaches the more noble semibright nickel deposit. Thus, the corrosion behavior of bright nickel prolongs the time for pitting penetration to reach the base metal.

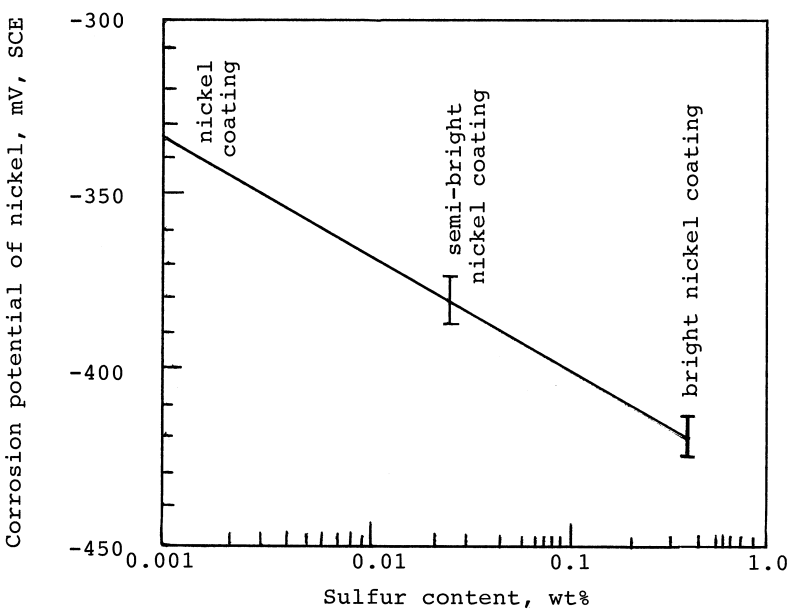



**Figure N.1** Effect of sulfur content on corrosion potential of nickel (*Source:* Ref. 10).

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The most negative of all nickel deposits is trinickel. In the triplex layer coating system, a coating of trinickel approximately 1 $\mu$m thick, containing 0.1–0.25% sulfur, is applied between bright nickel and semibright nickel deposits. The high-sulfur nickel layer dissolves preferentially, even when pitting corrosion reaches the surface of the semibright nickel deposit. Since the high-sulfur layer reacts with the bright nickel layer, pitting corrosion does not penetrate the high-sulfur nickel layer in the tunneling form. The application of a high sulfur nickel strike definitely improves the protective ability of a multilayer nickel coating.

In the duplex nickel coating system, the thickness ratio of semibright nickel deposit to bright nickel deposit is nominally 3:1, and a thickness of 20–25 $\mu$m is required to provide high corrosion resistance. The properties required for a semibright nickel deposit are as follows:

1. The deposit contains little sulfur.
2. Internal stress must be slight.
3. Surface appearance is semibright and extremely level.

For a trinickel (high sulfur) strike, the following properties are required:

1. The deposit contains a stable 0.1–0.25% sulfur.
2. The deposit provides good adhesion for semibright nickel deposits.

Nickel coatings can be applied by electrodeposition or electrolessly from an aqueous solution without the use of an externally applied current.

Depending on the production facilities and the electrolyte composition, electrodeposited nickel can be relatively hard (120–400 HV). Despite competition from hard chromium and electroless nickel, electrodeposited nickel is still being used as an engineering coating because of its relatively low price. Some of its properties are

1. Good general corrosion resistance.
2. Good protection from fretting corrosion.
3. Good machinability.
4. The ability of layers of 50–75 $\mu$m to prevent scaling at high temperatures.
5. Mechanical properties, including internal stress and hardness, that are variable and can be fixed by selecting the manufacturing parameters.
6. Excellent combination with chromium layers.
7. A certain porosity.
8. A tendency for layer thicknesses below 10–20 $\mu$m on steel to give corrosion spots due to porosity.

The electrodeposition can be either directly on steel or over an intermediate coating of copper. Copper is used as an underlayment to facilitate buffing, because it is softer than steel, and to increase the required coating thickness with a material less expensive than nickel.

The most popular electroless nickel plating process is the one in which hypophosphite is used as the reducer. Autocatalytic nickel ion reduction by hypophosphite takes place in both acid and alkaline solutions. In a stable solution with a high coating quality, the deposition rate may be as high as 20–25 $\mu$m/h. However, a relatively high temperature of 194°F/90°C is required.

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Since hydrogen ions are formed in the reduction reaction,

$$Ni^{2+} + 2H_2PO_2^- + 2H_2O \rightarrow Ni + 2H_2\ 2H^-$$

a high buffering capacity of the solution is necessary to ensure a steady-state process. For this reason, acetate, citrate, propionate, glycolate, lactate, or aminoacetate is added to the solutions. These substances along with buffering may form complexes with nickel ions. Binding $Ni^{2+}$ ions into a complex is required in alkaline solutions (here, ammonia and pyrophosphate may be added in addition to citrate and aminoacetate). In addition, such binding is desirable in acid solutions because free nickel ions form a compound with the reaction product (phosphate), which precipitates and prevents further use of the solution.

When hypophosphate is used as the reducing agent, phosphorus will be present in the coating. Its amount, in the range of 2–15 mass percent, depends on pH buffering capacity, ligands, and other parameters of electroless solutions.

Depending upon exposure conditions, certain minimum coating thicknesses to control porosity are recommended for the coating to maintain its appearance and have a satisfactory life:

| | |
|---|---|
| Indoor exposures | 0.3–0.5 mil (0.008–0.013 mm) |
| Outdoor exposures | 0.5–1.5 mil (0.013–0.04 mm) |
| Chemical industry | 1–10 mil (0.025–0.25 mm) |

For application near the seacoast, thicknesses of approximately 1.5 mil (0.04 mm) should be considered. This also applies to automobile bumpers and applications in general industrial atmospheres.

Nickel is sensitive to attack by industrial atmospheres and forms a film of basic nickel sulfate that causes the surface to "fog" or lose its brightness. To overcome this fogging, a thin coating of chromium (0.01–0.03 mil/0.003–0.007 mm) is electrodeposited over the nickel. This finish is applied to all materials for which continued brightness is desired.

Single-layer coatings of nickel exhibit less corrosion resistance than multilayer coatings because of their discontinuities. The electroless plating process produces a coating with fewer discontinuous deposits. Therefore, the single layer deposited by electroless plating provides more corrosion resistance than does an electroplated single layer.

Most electroless plated nickel deposits contain phosphorus, which enhances corrosion resistance. In the same manner, an electroplated nickel deposit containing phosphorus will also be more protective.

## Satin-Finish Nickel Coating

A satin-finish nickel coating consists of nonconductive materials such as aluminum oxide, kaolin, and quartz, which are codeposited with chromium on the nickel deposit. Some particles are exposed on the surface of the chromium deposit, so the deposit has a rough surface. Since the reflectance of the deposit is decreased to less than half of that of a level surface, the surface appearance is like satin.

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A satin nickel coating provides good corrosion resistance because of the discontinuity of the top coat of chromium.

### Nickel–Iron Alloy Coating

In order to reduce production costs of bright nickel, the nickel–iron alloy coating was developed. The nickel–iron alloy deposits full brightness, high leveling, and excellent ductility and good reception for chromium.

This coating has the disadvantage of forming red rust when immersed in water; consequently, nickel–iron alloy coating is suitable for use in mild atmospheres only. Typical applications include kitchenware and tubular furniture.

See Ref. 9.

## NIOBIUM

Niobium is a soft, ductile metal that can be cold worked over 90% before annealing becomes necessary. The metal is somewhat similar to stainless steel in appearance. It has a moderate density of 8.57 g/cc compared to the majority of the high-melting-point metals, being less than that of molybdenum at 10.2 g/cc and only half that of tantalum at 16.6 g/cc. The physical properties are shown in Table N.10.

Niobium finds many applications as an alloy in a wide variety of end uses, such as beams and girders in buildings and offshore drilling towers, special industrial machinery, oil and gas pipelines, railroad equipment, and automobiles. It is also used as an additive in superalloys for jet and turbine engines.

**Table N.10** Physical Properties of Niobium

| | |
|---|---|
| Melting point | 4474°F/2468°C |
| Boiling point | 8900°F/4927°C |
| Density, g/cm$^3$ | 8.57 |
| Thermal neutron absorption cross-section, barns | 1.1 |
| Electronegativity, Pauling's | 1.6 |
| Thermal conductivity at | |
| 0°C J (s cm °C) | 0.523 |
| 1600°C J (s cm °C) | 0.691 |
| Coefficient of thermal expansion at | |
| 20°C $\times$ 10$^{-6}$/°C | 7.1 |
| Electric resistivity, microhm | 15 |
| Volume electrical conductivity, % IACS | 13.3 |
| Specific heat at | |
| 15°C J/g | 0.268 |
| 1227°C J/g | 0.320 |
| Heat capacity J/mol °C at | |
| 0°C | 24.9 |
| 1200°C | 29.7 |
| 2700°C | 33.5 |

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**Table N.11** Mechanical Properties of Niobium

| | |
|---|---|
| Modulus of elasticity $\times 10^6$ kg/cm$^2$ | 1.05 |
| Poisson's ratio | 0.38 |
| Hardness, VHN | 60–100 |
| Resistance to thermal shock | Good |
| Workability, ductile to brittle transition | –238°F/–150°C |
| Stress-relieving temperature | 1472°F/800°C |

Niobium is used extensively in aerospace equipment and missiles because of its relative light weight and because it can maintain its strength at elevated temperatures. The mechanical properties of niobium are shown in Table N.11.

Niobium is available in the form of sheet, foils, rod, wire, and tubing.

## Corrosion Resistance

A readily formed adherent passive oxide film is responsible for niobium's corrosion resistance. Its corrosion-resistant properties resemble those of tantalum, but it is slightly less resistant in aggressive media such as hot concentrated mineral acids.

Niobium is susceptible to hydrogen embrittlement if cathodically polarized by either galvanic coupling or by impressed potential.

Except for hydrofluoric acid, niobium is resistant to most mineral and organic acids at all concentrations below 212°F (100°C). This includes hydrochloric, hydriodic, hydrobromic, nitric, sulfuric, and phosphoric acids. It is especially resistant under oxidizing conditions such as concentrated sulfuric acid and ferric chloride or cupric chloride solutions.

Niobium experiences corrosion rates of less than 1 mpy in ambient aqueous alkaline solutions. Even though the corrosion rate may not seem excessive at higher temperatures, niobium is embrittled even at low concentrations. Niobium is also embrittled in salts such as sodium and potassium carbonates and phosphates that hydrolyze to form alkaline solutions.

As long as a salt solution does not hydrolyze to form an alkali, niobium has excellent corrosion resistance. It is resistant to chloride solutions even with oxidizing agents present. It does not corrode in 10% ferric chloride at room temperature, and it is resistant to attacks in seawater.

Niobium is inert in most common gases (bromine, chlorine, nitrogen, hydrogen, oxygen, carbon dioxide, carbon monoxide, and sulfur dioxide, wet or dry) at 212°F/100°C. However, at higher temperatures niobium will be attacked, in some cases catastrophically.

Niobium is resistant to attack in many liquid metals to relatively high temperatures, as illustrated in the following:

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| Liquid metal | Maximum temperature °F/°C |
|---|---|
| Bismuth | 950/110 |
| Gallium | 752/400 |
| Lead | 1562/850 |
| Lithium | 1832/1000 |
| Mercury | 1112/600 |
| Sodium | 1832/1000 |
| Potassium | 1832/1000 |
| Uranium | 2552/1400 |
| Zinc | 842/450 |

Niobium's resistance may be reduced by the presence of excessive amounts of gas impurities.

In general, niobium is less expensive than tantalum but possesses similar corrosion-resistant properties and is often considered as an alternative for tantalum. Refer to Table N.12 for the compatibility of niobium with selected corrodents.

**Table N.12** Compatibility of Niobium with Selected Corrodents

| Corrodent | Conc. weight % | Temp., °F/°C | Corrosion rate, mpy |
|---|---|---|---|
| Acetic acid | 5–99.7 | Boiling | Nil |
| Aluminum chloride | 25 | Boiling | 0.2 |
| Aluminum potassium sulfate | 10 | Boiling | Nil |
| Aluminum sulfate | 25 | Boiling | Nil |
| Ammonium chloride | 40 | Boiling | 10 |
| Ammonium hydroxide | | Room temp. | Nil |
| Bromine, liquid | | 68/20 | Nil |
| Bromine, vapor | | 68/20 | 1.0 |
| Calcium chloride | 70 | Boiling | Nil |
| Citric acid | 10 | Boiling | 1.0 |
| Copper nitrate | 40 | Boiling | Nil |
| Copper sulfate | 40 | 219/104 | 1.0 |
| Ferric chloride | 10 | Room temp.–boiling | Nil |
| Formaldehyde | 37 | Boiling | 0.1 |
| Formic acid | 10 | Boiling | Nil |
| Formic acid | 50 | Boiling | 1.0 |
| Hydrochloric acid | 1 | Boiling | Nil |
| Hydrochloric acid, aerated | 15 | 140/60 | Nil |
| Hydrochloric acid, aerated | 15 | 212/100 | 1.0 |
| Hydrochloric acid, aerated | 30 | 95/35 | 1.0 |
| Hydrochloric acid, aerated | 30 | 140/60 | 2.0 |
| Hydrochloric acid, aerated | 30 | 212/100 | 5.0 |
| Hydrochloric acid | 37 | Room temp. | 1.0 |
| Hydrochloric acid | 37 | 140/60 | 1.0 |

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**Table N.12** Compatibility of Niobium with Selected Corrodents (Continued)

| Corrodent | Conc. weight % | Temp., °F/°C | Corrosion rate, mpy |
|---|---|---|---|
| Lactic acid | 10–48 | Boiling | 1.0 |
| Magnesium chloride | 47 | Boiling | 1.0 |
| Mercuric chloride | Sat. | Boiling | 0.1 |
| Nickel chloride | 30 | Boiling | Nil |
| Nickel nitrate | 40 | 219/104 | 1.0 |
| Nitric acid | 50 | 170/80 | 5.0 |
| Nitric acid | 65 | Room temp. | Nil |
| Nitric acid | 65 | Boiling | 1.0 |
| Nitric acid | 70 | 482/250 | 1.0 |
| Oxalic acid | 10 | Boiling | 5.0 |
| Peroxide | 30 | Room temp. | 1.0 |
| Peroxide | 30 | Boiling | 2.0 |
| Phosphoric acid | 50 | 86/30 | Nil |
| Phosphoric acid | 50 | 194/90 | 5.0 |
| Phosphoric acid | 60 | Boiling | 20 |
| Phosphoric acid | 85 | 86/30 | Nil |
| Phosphoric acid | 85 | 190/88 | 2.0 |
| Phosphoric acid | 85 | 212/100 | 5.0 |
| Phosphoric acid | 85 | 311/155 | 150 |
| Potassium carbonate | 1–10 | Room temp. | 1.0 |
| Potassium carbonate | 10–20 | 208/98 | Embrittle |
| Potassium hydroxide | 5–40 | Room temp. | Embrittle |
| Potassium hydroxide | 1–5 | 208/98 | Embrittle |
| Potassium phosphate | 10 | Room temp. | 1.0 |
| Seawater, natural | | Boiling | Nil |
| Sodium bisulfate | 40 | Boiling | 5.0 |
| Sodium carbonate | 10 | Room temp. | 1.0 |
| Sodium carbonate | 10 | Boiling | 20 |
| Sodium hydroxide | 1–40 | Room temp. | 5.0 |
| Sodium hydroxide | 1–10 | 208/98 | Embrittle |
| Sulfuric acid | 5-40 | Room temp. | Nil |
| Sulfuric acid | 25 | 212/100 | 5.0 |
| Sulfuric acid | 98 | Room temp. | Embrittle |
| Sulfuric acid | 10 | Boiling | 50 |
| Sulfuric acid | 40 | Boiling | 20 |
| Sulfuric acid | 60 | Boiling | 50 |
| Sulfuric acid | 60 | 194/90 | 2.0 |
| Sulfuric acid | 65 | 307/153 | 100 |
| Sulfuric acid | 70 | 332/167 | 200 |
| Tartaric acid | 20 | Room temp.–boiling | Nil |
| Trichloroacetic acid | 50 | Boiling | Nil |
| Trichloroethylene | 90 | Boiling | Nil |
| Zinc chloride | 40–70 | Boiling | Nil |
| Zirconium chloride | 70 | Boiling | Nil |
| Zirconium chloride | 88 | Boiling | Nil |

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## Niobium–Titanium Alloys

These alloys are fabricated in all forms, although they aregenerally used in multifilamentary cables. The alloys are manufactured in both grade 1 and grade 2 types. Grade 2 type has a higher allowable tantalum content, which has no effect on the superconducting properties. A wet-grade niobium–55% titanium alloy is also available, which finds application in the aircraft industry.

## WC-103 Alloy

This is a niobium–10% hafnium–1% titanium alloy. Application is primarily in aerospace programs because of its weight savings over other materials and its ability to withstand high stress levels and high temperatures up to 2700°F/1482°C. Refer to Table N.13 for the mechanical and physical properties.

## WC-1Zr Alloy

The creep strength of niobium is greatly improved by the addition of 1% zirconium. This is a medium-strength alloy that is less expensive than the higher-strength alloys such as WC-103. It is used in applications where a high-temperature material is required with low loads, such as a load-free thermal shield. See Table N.14 for the mechanical and physical properties.

**Table N.13** Mechanical and Physical Properties of Alloy WC-103

| | |
|---|---|
| Density, lb/in.$^3$ | 0.320 |
| Melting point, °F/°C | 4280 ± 90/2350 ± 50 |
| Thermal expansion × $10^{-6}$ cm/cm °C$^{-1}$ | 8.73 ± 0.09 |
| Specific heat, Btu/°F/lb | 0.832 |
| Modulus of elasticity × $10^6$ psi at | |
| room temperature | 13.1 |
| 2200°F/1204°C | 9 .3 |

**Table N.14** Physical and Mechanical Properties of Alloy WC-1Zr

| | |
|---|---|
| Density, lb/in.$^3$ | 0.31 |
| Melting point, °F/°C | 4365 ± 15/2410 ± 10 |
| Thermal conductivity at 77°F/25°C | |
| Btu/h-ft$^2$/°F/ft | 24.2 |
| Specific heat, Btu/°F/lb at 70°F/23°C | 0.065 |
| Modulus of elasticity at room temperature psi | 10 × $10^6$ |
| Charpy impact, ft-lb at 32°F/0°C | 100 |

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### General Alloy Information

In addition to the two niobium alloys discussed, there are other high-strength and medium-strength alloys available. Table N.15 gives the chemical composition of niobium alloys, and Table N.16 provides the tensile properties. Also see "Columbium."

## NITRIDING

Stainless steels and many higher alloys such as alloy 800, as well as elements such as chromium, aluminum, and titanium, readily form nitrides. When exposed to a nitriding atmosphere at temperatures exceeding about 750°F (400°C), a brittle nitride layer is formed, which destroys the normally protective oxide film. The most common nitriding atmosphere is ammonia or a mixture of gases rich in ammonia. Gaseous nitrogen is not considered a nitriding atmosphere.

Special alloys and/or aluminum or aluminum vapor–deposited coatings are used to resist nitriding.

## NITRILE RUBBER (NBR, BUNA-N)

The nitrile rubbers are an outgrowth of German Buna-N or Perbunan. They are copolymers of butadiene and acrylonitrile ($CH_2 = CH - C = N$) and are one of the four most widely used elastomers. XNBR is a carboxylic acrylonitrile butadiene nitrile rubber with somewhat improved abrasion resistance over that of the standard NBR nitrile rubbers. The main advantages of the nitrile rubbers are their low cost, good oil and abrasion resistance, and good low-temperature and swell characteristics. Their greater resistance to oils, fuel, and solvents compared with that of neoprene is their primary advantage. As with other elastomers, appropriate compounding will improve certain properties.

**Table N.15** Chemical Composition of Niobium Alloys

| | Composition, wt% | | | | | |
|---|---|---|---|---|---|---|
| Alloy | Hf | Ti | W | Y | Zr | Nb |
| WC-103 | 10 | 1 | | | | Balance |
| WC-129Y | 10 | | 10 | 0.1 | | Balance |
| WC-lZr | | | | | 1 | Balance |
| WC-752 | | | 10 | | 2.5 | Balance |

**Table N.16** Tensile Properties of Niobium Alloys

| Alloy | UTS $\times 10^3$ psi | YS, 0.2% offset $\times 10^3$ psi | Elongation, % in 1 in. |
|---|---|---|---|
| Nb | 25 | 11 | 35 |
| WC-103 | 54 | 38 | 20 |
| WC-129Y | 80 | 60 | 20 |
| WC-1Zr | 35 | 15 | 20 |
| WC-752 | 75 | 55 | 20 |

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## Physical and Mechanical Properties

The physical and mechanical properties of the nitrile rubbers are very similar to those of natural rubber (see Table N.17). These rubbers have the exceptional ability to retain both their strength and elasticity at extreme low temperatures. It is this property that makes them valuable for use as hose used in operating the hydraulic controls of airplanes.

Buna-N does not have exceptional heat resistance. It has a maximum operating temperature of 250°F (120°C), but it has a tendency to harden at high temperatures. The nitrile rubbers will support combustion and burn. Their electrical properties are relatively poor, and consequently they do not find wide use in electrical applications, since there are so many other elastomeric materials with far superior electrical properties.

NBR has good compression set recovery from deformation and good abrasion resistance and tensile strength.

## Resistance to Sun, Weather, and Ozone

The nitrile rubbers offer poor resistance to sunlight and ozone, and their weathering qualities are not good.

## Chemical Resistance

The nitrile rubbers exhibit good resistance to solvents, oil, water, and hydraulic fluids. A very slight swelling occurs in the presence of aliphatic hydrocarbons, fatty acids, alcohols,

**Table N.17** Physical and Mechanical Properties of Nitrile Rubber (NBR, Buna-N)[a]

| | |
|---|---|
| Specific gravity | 0.99 |
| Refractive index | 1.54 |
| Brittle point | –32°F to –40°F (–1°C to –40°C) |
| Swelling, % by volume | |
| in kerosene at 77°F (25°C) | 9–10 |
| in benzene at 77°F (25°C) | 120 |
| in acetone at 77°F (25°C) | 60–50 |
| in mineral oil at 100°F (70°C) | 2–10 |
| in air at 77°F (25°C) | 30–50 |
| Tensile strength, psi | 500–4000 |
| Elongation, % at break | 400 |
| Hardness, Shore A | 40–95 |
| Abrasion resistance | Excellent |
| Maximum temperature, continuous use | 250°F (120°C) |
| Compression set | Good |
| Tear resistance | Excellent |
| Resilience, % | 63–74 |
| Machining qualities | Can be ground |
| Resistance to sunlight | Fair |
| Effect of aging | Highly resistant |
| Resistance to heat | Softens |

[a]These are representative values since they may be altered by compounding.

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and glycols. The deterioration of physical properties as a result of this swelling is small, making NBR suitable for gasoline- and oil-resistant applications. NBR has excellent resistance to water. The use of highly polar solvents such as acetone and methyl ethyl ketone, chlorinated hydrocarbons, ozone, nitro hydrocarbons, ether, or esters should be avoided, since these materials will attack the nitrile rubbers.

The XNBR rubbers are used primarily in nonalkaline service. Refer to Table N.18 for the compatibility of nitrile rubber with selected corrodents.

**Table N.18** Compatibility of Nitrile Rubber with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | x | x | Ammonium sulfite | | |
| Acetamide | 180 | 82 | Amyl acetate | | |
| Acetic acid 10% | x | x | Amyl alcohol | 150 | 66 |
| Acetic acid 50% | x | x | Amyl chloride | | |
| Acetic acid 80% | x | x | Aniline | x | x |
| Acetic acid, glacial | x | x | Antimony trichloride | | |
| Acetic anhydride | x | x | Aqua regia 3:1 | | |
| Acetone | x | x | Barium carbonate | | |
| Acetyl chloride | x | x | Barium chloride | 125 | 52 |
| Acrylic acid | x | x | Barium hydroxide | | |
| Acrylonitrile | x | x | Barium sulfate | | |
| Adipic acid | 180 | 82 | Barium sulfide | | |
| Allyl alcohol | 180 | 82 | Benzaldehyde | | |
| Allyl chloride | x | x | Benzene | 150 | 66 |
| Alum | 150 | 66 | Benzene sulfonic acid 10% | | |
| Aluminum acetate | | | Benzoic acid | 150 | 66 |
| Aluminum chloride, aqueous | 150 | 66 | Benzyl alcohol | | |
| Aluminum chloride, dry | | | Benzyl chloride | | |
| Aluminum fluoride | | | Borax | | |
| Aluminum hydroxide | 180 | 82 | Boric acid | 150 | 66 |
| Aluminum nitrate | 190 | 88 | Bromine gas, dry | | |
| Aluminum oxychloride | | | Bromine gas, moist | | |
| Aluminum sulfate | 200 | 93 | Bromine liquid | | |
| Ammonia gas | 190 | 88 | Butadiene | | |
| Ammonium bifluoride | | | Butyl acetate | | |
| Ammonium carbonate | x | x | Butyl alcohol | | |
| Ammonium chloride 10% | | | *n*-Butylamine | | |
| Ammonium chloride 50% | | | Butyl phthalate | | |
| Ammonium chloride, sat. | | | Butyric acid | | |
| Ammonium fluoride 10% | | | Calcium bisulfide | | |
| Ammonium fluoride 25% | | | Calcium bisulfite | | |
| Ammonium hydroxide 25% | | | Calcium carbonate | | |
| Ammonium hydroxide, sat. | | | Calcium chlorate | | |
| Ammonium nitrate | 150 | 66 | Calcium chloride | | |
| Ammonium persulfate | | | Calcium hydroxide 10% | | |
| Ammonium phosphate | 150 | 66 | Calcium hydroxide, sat. | | |
| Ammonium sulfate 10–40% | | | Calcium hypochlorite | x | x |
| Ammonium sulfide | | | Calcium nitrate | | |

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**Table N.18** Compatibility of Nitrile Rubber with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Calcium oxide | | | Hydrochloric acid 38% | | |
| Calcium sulfate | | | Hydrocyanic acid 10% | | |
| Caprylic acid | | | Hydrofluoric acid 30% | | |
| Carbon bisulfide | | | Hydrofluoric acid 70% | x | x |
| Carbon dioxide, dry | | | Hydrofluoric acid 100% | x | x |
| Carbon dioxide, wet | | | Hypochlorous acid | | |
| Carbon disulfide | | | Iodine solution 10% | | |
| Carbon monoxide | | | Ketones, general | | |
| Carbon tetrachloride | | | Lactic acid 25% | | |
| Carbonic acid | 100 | 38 | Lactic acid, concentrated | | |
| Cellosolve | | | Magnesium chloride | | |
| Chloracetic acid | | | Malic acid | | |
| Chloracetic acid, 50% water | | | Manganese chloride | | |
| Chlorine gas, dry | | | Methyl chloride | | |
| Chlorine gas, wet | | | Methyl ethyl ketone | | |
| Chlorine liquid | | | Methyl isobutyl ketone | | |
| Chlorobenzene | | | Muriatic acid | | |
| Chloroform | | | Nitric acid 5% | | |
| Chlorosulfonic acid | | | Nitric acid 20% | x | x |
| Chromic acid 10% | | | Nitric acid 70% | x | x |
| Chromic acid 50% | | | Nitric acid, anhydrous | x | x |
| Chromyl chloride | | | Nitrous acid, concentrated | | |
| Citric acid 15% | | | Oleum | | |
| Citric acid, concentrated | | | Perchloric acid 10% | | |
| Copper acetate | | | Perchloric acid 70% | | |
| Copper carbonate | | | Phenol | x | x |
| Copper chloride | | | Phosphoric acid 50–80% | 150 | 66 |
| Copper cyanide | | | Picric acid | | |
| Copper sulfate | | | Potassium bromide 30% | | |
| Cresol | | | Salicylic acid | | |
| Cupric chloride 5% | | | Silver bromide 10% | | |
| Cupric chloride 50% | | | Sodium carbonate | 125 | 52 |
| Cyclohexane | | | Sodium chloride | 200 | 93 |
| Cyclohexanol | | | Sodium hydroxide 10% | 150 | 66 |
| Dichloroacetic acid | | | Sodium hydroxide 50% | | |
| Dichloroethane (ethylene dichloride) | | | Sodium hydroxide, concentrated | | |
| Ethylene glycol | 100 | 38 | Sodium hypochlorite 20% | x | x |
| Ferric chloride | 150 | 66 | Sodium hypochlorite, concentrated | x | x |
| Ferric chloride 50% in water | | | Sodium sulfide to 50% | | |
| Ferric nitrate 10–50% | 150 | 66 | Stannic chloride | 150 | 66 |
| Ferrous chloride | | | Stannous chloride | | |
| Ferrous nitrate | | | Sulfuric acid 10% | 150 | 66 |
| Fluorine gas, dry | | | Sulfuric acid 50% | 150 | 66 |
| Fluorine gas, moist | | | Sulfuric acid 70% | x | x |
| Hydrobromic acid, dilute | | | Sulfuric acid 90% | x | x |
| Hydrobromic acid 20% | | | Sulfuric acid 98% | x | x |
| Hydrobromic acid 50% | | | Sulfuric acid 100% | x | x |
| Hydrochloric acid 20% | | | Sulfuric acid, fuming | x | x |

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**Table N.18** Compatibility of Nitrile Rubber with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Sulfurous acid | | | Trichloroacetic acid | | |
| Thionyl chloride | | | White liquor | | |
| Toluene | | | Zinc chloride | 150 | 66 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1.–3. New York: Marcel Dekker, 1995.

### Applications

Because of its exceptional resistance to fuels and hydraulic fluids, Buna-N's major area of application is in the manufacture of aircraft hose, gasoline and oil hose, and self-sealing fuel tanks. Other applications include carburetor diaphragms, gaskets, cables, printing rolls, and machinery mountings.

See Refs. 1, 2, and 10.

## NOBLE METAL

A noble metal is any metal that has a standard electrode potential more noble (positive) than that of hydrogen. The noble metals are gold, silver, platinum, iridium, osmium, palladium, rhodium, and ruthenium. The term is often used synonymously for precious metals when referring to metals such as platinum and gold.

## NORMALIZING

Normalizing is a heat treatment process in which carbon or low -alloy steel is heated to approximately 1650°F (900°C) and is then air cooled. This process partially relieves residual stresses produced by prior processing, reduces the grain size, and makes the grain structure more homogeneous. This produces a tougher and more ductile material.

Also see "Annealing."

## $NO_x$

$NO_x$ is a term used to describe nitrogen oxides that are emitted to the atmosphere as pollutants. These emissions contribute to atmospheric corrosion. $NO_x$ emissions are the result of energy production and road traffic. During the combustion process, the nitrogen oxides are emitted as NO, which is oxidized to $NO_2$, which can be further oxidized to $HNO_3$ (nitric acid). This latter reaction has a very slow rate, so that in the immediate vicinity of the emissions the predominant corrodent is $NO_2$. At further distances, the concentration of nitric acid increases.

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## NYLON

See "Polyamides."

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# O

## OIL ASH CORROSION

Oil ash corrosion takes place on secondary superheater and reheater tube sections of boilers using bunker "C" oil high in vanadium content or using residual oil as the fuel. Molten ash deposits from this fuel dissolve protective iron oxide layers on the tube surfaces, act as an oxidation catalyst, and allow oxygen and other combustion gases to diffuse rapidly to the metal surface. If sodium, chlorine, or sulfur are present in the ash, the corrosion will be accelerated.

## OIL/GAS WELL CORROSION INHIBITORS

These inhibitors are used in oil/gas wells to reduce the corrosion resulting from the presence of water, salt, carbon dioxide, and hydrogen sulfide contained in the hydrocarbon mix. The inhibitors can be classified as to their solubility and dispersibility in the two phases (water and oil/gas) of the well. They are described as (a) oil and water insoluble, (b) oil soluble and water soluble, (c) oil soluble and water dispersible, (d) oil and water soluble, (e) volatile inhibitors. Organic nitrogen molecules with molecular weights exceeding 200 are the most commonly used inhibitors.

See "Corrosion Inhibitors."

## OXIDATION

Oxidation is the increase in positive valence or decrease in negative valence of any element in a substance. On the basis of the electron theory, oxidation is a process in which an element loses electrons. In a narrow sense, oxidation means the chemical addition of oxygen to a substance.

An oxidizing agent (or oxidant) is a chemical agent that causes oxidation of other substances and is itself reduced.

It also refers to the corrosion of a metal exposed to an oxidizing gas at elevated temperatures.

Common oxidizing agents include nitric acid, chromic acid, concentrated sulfuric acid, oleum, ferric chloride, cupric chloride, dissolved oxygen, ferric sulfate, ammonia, wet chlorine, and sulfur dioxide.

## OXIDIZING ACIDS

The cathodic reaction in an oxidizing acid is the reduction of the acidic anion rather than hydrogen evolution. The reaction of dilute to moderate concentrations of nitric acid on



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steel is to liberate the brown oxides of nitrogen. It should be noted that the nature of the metal also influences the metal/acid reaction. For example, boiling 55% sulfuric acid is a reducing acid to steel or type 300 stainless steel liberating hydrogen, while it is oxidizing to cast silicon–nickel alloy, the sulfate ion being reduced to sulfur dioxide and hydrogen sulfide (and elemental sulfur formed as a consequence of their interaction). This is in accord with the generality that any "oxidizing agent" can be a reducing agent in the presence of a stronger oxidant.

Solutions of oxidizing acid salts (e.g., ammonium nitrate) act like dilute solutions of the parent acid.

In general, oxidizing acids tend to corrode metals that do not form a passive oxide film (e.g., copper, lead) rather than those that do form passive films such as chromium-bearing alloys, titanium, and aluminum.

Reducing acids at times are more aggressive to the normally passive metals than to the more active metals, because of the reaction of nascent hydrogen with the oxide film or the direct hydriding of the metal itself as with zirconium, titanium, and tantalum.

Some of the most important oxidizing acids are nitric acid, chromic acid, concentrated sulfuric acid, and oleum.

## Nitric Acid

Nitric acid is a strong mineral acid and a powerful oxidizing agent, even in dilute solutions. Sixty percent concentration acid is produced by a process involving the oxidation of ammonia. To produce 70% concentration reagent-grade acid (chemically pure), the 60% acid is purified and concentrated. Strong acid in the 90–100% range is produced by dehydrating weaker concentrations with concentrated sulfuric acid. Nitric acid above a concentration of 85% is known as fuming nitric acid because red or white fumes of oxides of nitrogen are evolved. Very strong concentrations of nitric acid have different corrosion properties from those of dilute concentrations.

## Chromic Acid

Chromic acid is a very strong oxidizing acid, but because of its nature more discrimination must be used when selecting materials of construction. Materials such as copper or nickel, which are attacked by oxidizing acids, are unsuitable.

Aluminum can handle a 10% concentration to approximately 150°F (66°C). Molybdenum-free type 300 stainless steels may be used to a 30% concentration, but corrosion rates increase rapidly above 5% and 175°F (80°C).

Fluorinated plastics can handle chromic acid to their normal temperature limits, but conventional plastics (CPVC, PE, PP) are limited to not more than 50% acid at or below 160°F (70°C).

## Concentrated Sulfuric Acid

Sulfuric acid in the 70–100% range is considered concentrated and, as such, is an oxidizing acid. Below 70% concentration it tends to act as a reducing acid. The oxidizing or reducing effect of sulfuric acid is also dependent upon the material to which it is exposed. For example, it starts to have an oxidizing effect at 25% when exposed to nickel or alloy 400 at the boiling point. At 60% and 175°F (80°C) it will carbonize PVDC over a prolonged period of time. At 95% and 77°F (25°C) it will carbonize FRP instantly.

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## Oleum

Oleum is 100% sulfuric acid with dissolved sulfur trioxide and is generally designated as, for example, 20% oleum, which is equivalent to 104.5% sulfuric acid if all of the sulfur trioxide is converted.

## Compatibility of Various Materials of Construction with the Oxidizing Acids

### *Aluminum*

Aluminum and its alloys are resistant to concentrations of nitric acid in excess of 80% at room temperature and to fuming acids in the 93–96% concentration range to a maximum temperature of 110°F (43°C). Higher temperatures can be employed above 96% concentration. Since weaker concentrations than 80% will rapidly attack aluminum, it is important that no moisture (moist air) be allowed to come into contact with the aluminum.

A 10% concentration of chromic acid to a temperature of approximately 150°F (66°C) can be handled satisfactorily by aluminum.

Sulfuric acid at concentrations greater than 96% can be handled in aluminum, even at elevated temperature. However, great care must be taken against dilution.

### *Iron and Steel*

Dilute nitric acid attacks cast iron and steel rapidly. Even passivated iron and steel experience corrosion rates in excess of what would be considered acceptable for practical applications.

Conventional steel and cast irons are attacked by chromic acid solutions and should not be used.

Concentrations of sulfuric acid above 90% can be handled in carbon steel and cast iron. Care must be taken to prevent dilution.

Carbon steel is compatible with 20–30% concentration of oleum.

### *Silicon Cast Irons*

Silicon cast irons form an adherent siliceous film when exposed to nitric acid above 45% concentration even up to the atmospheric boiling point. As the acid concentration increases, the corrosion resistance increases. In high concentrations at high temperatures, the corrosion rate is essentially nil.

Chromic acid up to concentrations of 50% can be handled at a temperature up to 200°F (93°C).

Silicon cast irons are resistant to concentrated sulfuric acid up to the boiling point. These materials would replace ordinary iron or steel above 122°F (50°C).

High-silicon iron should not be exposed to oleum.

### *Stainless Steels*

Because of the problem of intergranular attack, the low-carbon type 304L or carbon-stabilized grades Type 347 of the molybdenum-free austenitic stainless steels should be used for handling all grades of nitric acid. If hexavalent chromium ions accumulate in the nitric acid to some concentration level, intergranular attack can take place regardless of the composition of the stainless steel.

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Wrought type 316L stainless steel should not be used in nitric acid service because of the corrosion of the sigma phase.

Type 304 stainless steel is resistant to chromic acid in concentrations up to 50%. Concentrations up to 10% can be handled at temperatures up to 200°F (93°C). Concentrations exceeding 10% are limited to a maximum temperature of 175°F (80°C). However, type 304 stainless steel is subject to pitting.

Type 316 stainless steel has a greater corrosion rate than type 304 at the comparable concentration and temperature and is subject to crevice corrosion.

Cold concentrated sulfuric acid can be handled by the 300 series austenitic stainless steels. The molybdenum-free grades (type 304 and 304L) should be used in concentrations above 93% and in oleum. Higher alloys, such as type 309, are successfully used at elevated temperatures.

### *Titanium*

Titanium is resistant to nitric acid below a concentration of 25% and in the 65–90% concentration range at the atmospheric boiling point. Boiling acid within the concentration range of 25–50% will corrode titanium at the rate of 10 mpy. Although titanium is resistant to fuming nitric acid, if the water content drops below 1.3% or the nitrogen dioxide concentration exceeds 6%, there is the danger of a violent pyrophoric reaction.

Chromic acid can be handled up to 50% concentration to a temperature of 212°F (100°C).

Concentrated sulfuric acid will attack titanium.

### *Other Metals*

With the exception of the chromium-bearing nickel alloys such as alloy 600, 625, or C-276, other nickel and copper alloys are rapidly attacked by even dilute nitric acid. Lead will also be attacked by nitric acid.

In the concentration range of 60–90% nitric acid, zirconium has a better resistance than titanium, but at concentrations greater than 70% it is subject to stress corrosion cracking and fails rapidly in boiling 94% nitric acid.

Of the noble metals, gold and platinum are resistant, but silver will corrode.

Zirconium and tantalum are resistant to chromic acid up to 50% concentration at 212°F (100°C).

In the absence of chloride ion contamination, magnesium is highly resistant to chromic acid. A boiling 20% solution will not attack magnesium.

Tin will resist chromic acid to approximately 80% at 212°F (100°C).

Lead has a corrosion rate of <20 mpy in chromic acid at temperatures up to 200°F (93°C).

Tantalum will resist 95% sulfuric acid to 350°F (175°C) and lower concentrations to the atmospheric boiling point. Since tantalum is attacked by sulfur trioxide, it cannot be used in the presence of oleum.

Zirconium will be attacked by concentrated sulfuric acid.

### *Nonmetallic Materials*

PTFE, plain or glass-filled, and viton are employed in nitric acid service. Carbon, if it is free of oxidizable binders, can also be used. Materials such as FEP, PVC, polypropylene, polyethylene, butyl rubber, and other elastomeric materials are also satisfactory with limitations. Refer to Ref. 1 for more complete details.

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Most thermoplastic materials are compatible with chromic acid up to 50% concentration at a temperature of 160°F (70°C). Halogenated polyesters can also be used. Reference 1 provides more complete information on elastomers, thermoplastics, thermoset resins, and other nonmetallic materials.

Sulfuric acid concentrations up to 75% to 120°F (50°C) are compatible with thermoplastic materials such as polyethylene, polypropylene, and polyvinyl chloride and with 90% acid at 85°F (30°C). Carbonization occurs above these limits. Thermoset plastics with the proper resin will withstand 75% acid up to 77°F (25°C).

Fluorinated plastics such as PTFE, PFA, FEP, and PVDF are compatible with all concentrations of concentrated acid up to the maximum service temperature of the plastic. Oleum service is questionable because of permeability problems.

Pure carbon resists boiling 100% sulfuric acid and resists 115% acid to 160°F (70°C).

Elastomers other than the fluorinated variety are limited to a maximum of 75% sulfuric acid up to a temperature of 175°F (80°C).

Kalrez and viton can be used for oleum service.

See Ref. 1.

## OXIDIZING AGENT

See "Oxidation."

## OXYGEN CONCENTRATION CELL

Concentration cells occur when the concentration of identical ions differs from one region to another in the system. One of the common cells of this type is the oxygen concentration cell, which is a galvanic cell caused by a difference in oxygen concentration at two points on a metal surface. The effect is the same as galvanic action between two dissimilar metals, which can cause and accelerate pitting. Oxygen concentration cells are also known as differential aeration cells. Refer to "Concentration Cells" and "Pitting."

See Refs. 2 and 3.

## OZHENNITE ALLOYS

Ozhennite alloys are zirconium alloys containing tin, iron, nickel, and niobium with a total alloy content of 0.5–1.5%. They were originally developed in the Soviet Union for use in pressurized water and steam in nuclear operations. Researchers at Atomic Energy of Canada Ltd. took a lead from the Russian zirconium–niobium alloys and developed the zirconium–2.5%-niobium alloy. This alloy is strong and heat treatable.

## OZONE

The ozone molecule consists of three atoms of oxygen ($O_3$) and is a powerful oxidizing allotropic form of oxygen.

## REFERENCES

1. PA Schweitzer. Corrosion Resistance Tables. 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.
2. DM Berger. Fundamentals and prevention of metallic corrosion. In: PA Schweitzer, ed. Corrosion and Corrosion Protection Handbook. 2nd ed. New York: Marcel Dekker, 1989, pp 1–22.
3. GT Murray. Introduction to Engineering Materials. New York: Marcel Dekker, 1993.

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# P

## PAINT

See "Coatings."

## PARTING

This is similar to dezincification in that one or more active components of the alloy corrode preferentially as in dezincification with the same results. Copper-base alloys containing aluminum are subject to this reaction, with the aluminum corroding preferentially. Refer to "Dezincification."

See Ref. 1.

## PASSIVATION

Metals, upon exposure to the atmosphere, form a protective oxide film on the exposed surface. This film, as long as it remains intact, will protect the metal from further corrosion. Some fabrication processes can prevent or retard the reformation of this protective film. To ensure the reformation of the protective film, the metal is subjected to "passivation" treatments.

For stainless steels the most common passivation treatment is to expose the metal to an oxidizing acid such as nitric and nitric–hydrofluoric acids.

See Refs. 2 and 3.

## PASSIVE FILMS

All metals develop a diffusion barrier layer of reaction products on the surface, which is referred to as a passive film. These reaction products are either metal oxides or other compounds. The resistance of these films to dissolution is related to their physical and chemical nature, which determines the corrosion resistance of the metal. Other factors that influence the rate of metallic corrosion are pH, temperature, and anion content of the solution.

There are two theories regarding the formation of these films. The first theory states that the film formed is a metal oxide or other reaction compound. This is known as the "oxide-film theory." The second theory states that oxygen is adsorbed on the surface forming a chemisorbed film. However, all chemisorbed films react over a period of time with the underlying metal to form metal oxides. Oxide films are formed at room temperature.



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Metal oxides can be classified as network formers, intermediates, or modifiers. This division can be related to thin oxide films on metals. The metals that fall into the network-forming or intermediate classes tend to grow protective oxides that support anion or mixed anion–cation movement. The network formers are noncrystalline, while the intermediates tend to be microcrystalline at low temperatures.

### Passive Film on Iron

Iron in iron oxides can assume a valence of 2 or 3. The former acts as a modifier and the latter as a network former. The iron is protected from the corrosive environment by a thin oxide film 1–4 mm in thickness with a composition of $\sqrt{Fe_2O_3}/Fe_3O_4$. This is the same type of film formed by the reaction of clean iron with oxygen or dry air. The $\sqrt{Fe_2O_3}$ layer is responsible for the passivity, while the $Fe_3O_4$ provides the basis for the formation of a higher oxidizing state. Iron is more difficult to passivate than nickel, because with iron it is not possible to go directly to the passivation species $\sqrt{Fe_2O_3}$. Instead, a lower oxidation state film of $Fe_3O_4$ is required, and this film is highly susceptible to chemical dissolution. The $\sqrt{Fe_2O_3}$ layer will not form until the $Fe_3O_4$ phase has existed on the surface for a reasonable period of time. During this time, the $Fe_3O_4$ layer continues to form.

### Passive Film on Nickel

The passive film on nickel can be achieved quite readily, in contrast to the formation of the passive film on iron. Differences in the nature of the oxide film on iron and nickel are responsible for this phenomenon. The film thickness on nickel is between 0.9 and 1.2 mm, while iron oxide film is between 1.5 and 4.5 mm. There are two theories as to exactly what the passive film on nickel is. Either it is entirely NiO with a small amount of nonstoichiometry giving rise to $Ni^{+3}$ and cation vacancies or it consists of an inner layer of NiO and an outer hydrous layer of $Ni(OH)_2$. Once formed, the passive oxide film on nickel cannot be easily removed by either cathodic treatment or chemical dissolution.

### Passive Film on Austenitic Stainless Steel

The passive film formed on austenitic stainless steel is duplex in nature, consisting of an inner barrier oxide film and an outer deposit hydroxide or salt film. Passivation takes place by the rapid formation of surface-absorbed hydrated complexes of metals, which are sufficiently stable on the alloy surface that further reaction with water enables the formation of a hydroxide phase that rapidly deprotonates to form an insoluble surface oxide film. The three most commonly used austenite stabilizers—nickel, manganese, and nitrogen—all contribute to the passivity. Chromium, a major alloying ingredient, is in itself very corrosion resistant and is found in greater abundance in the passive film than iron, which is the majority element in the alloy.

See Refs. 1, 4–6.

## PASSIVE METAL

A passive metal is one that substantially resists corrosion in a given environment resulting from marked anodic polarization.

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## PATENTING

See "Annealing."

## PATINA

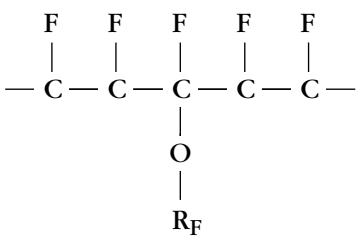
When exposed to the atmosphere over long periods of time, copper will form a coloration on the surface known as patina which in reality is a corrosion product that acts as a protective film against further corrosion. When first formed, the patina has a dark color that gradually turns green. The length of time required to form the patina depends upon the atmosphere, because the coloration is given by copper hydroxide compounds. In a marine atmosphere, the compound is a mixture of copper hydroxide and chloride, and in urban or industrial atmospheres, it is copper hydroxide and sulfate. These compounds will form in approximately seven years. When exposed in a clean rural atmosphere, tens or hundreds of years may be required to form the patina. For further information, see "Copper and Copper Alloys."

## PEARLITE

Although most carbon steels contain enough carbon to allow hardening by heat treatment, they are not intended to be hardened by heat treatment. They are normally produced with a more ductile, lower strength microstructure that forms during cooling from austenitic temperatures. This microstructure is a mixture of ferrite and pearlite. As the carbon steel is cooled from the austenitic temperature, ferrite starts to form. Since the ferrite contains essentially no carbon, it leaves behind an increasing concentration of carbon in the remaining austenite, which is eventually ejected. Under normal circumstances, the excess carbon combines with iron to form iron carbide ($Fe_3C$), called cementite. If the austenite is cooled slowly in air, a binary mixture of ferrite and cementite is formed, which is called pearlite. The structure of pearlite is lamellar, consisting of very fine alternating layers of ferrite and cementite. Consequently, the gross microstructure of normal carbon steel consists of a mixture of ferrite and pearlite.

## PERFLUOROALKOXY (PFA)

PFA is a fully fluorinated thermoplast having the formula



in which $R_F = C_nF_{2n} + 1$. Perfluoroalkoxy lacks the physical strength of PTFE at elevated temperatures but has somewhat better physical and mechanical properties than FEP above 300°F (149°C) and can be used up to 500°F (260°C). For example, PFA

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**Table P.1** Physical and Mechanical Properties of PFA

| | |
|---|---|
| Specific gravity | 2.12–2.17 |
| Water absorption, 24 h at 73°F/23°C, % | <0.03 |
| Tensile strength, psi | |
| at 73°F/23°C | 4000 |
| at 482°F/250°C | 2000 |
| Modulus of elasticity in tension, psi | |
| at 73°F/23°C | 40,000 |
| at 482°F/250°C | 6000 |
| Compressive strength, psi | |
| at 73°F/23°C | 3500 |
| at 320°F/196°C | 60,000 |
| Flexural modulus, psi | |
| at 73°F/23°C | 90,000 |
| at 482°F/250°C | 10,000 |
| Izod impact, notched at 73°F/23°C, ft-lb/in. | No break |
| Coefficient of linear thermal expansion, in./in.°F | |
| at 70–212°F/20–100°C | $7.8 \times l0^{-5}$ |
| at 212–300°F/100–150°C | $9.8 \times 10^{-5}$ |
| at 300–480°F/150–210°C | $12.1 \times 10^{-5}$ |
| Heat distortion temperature, °F/°C | |
| at 66 psi | 164/73 |
| at 264 psi | 118/48 |
| Limiting oxygen index, % | <95 |
| Flame spread | 10 |
| Underwriters Lab rating, Sub 94 | 94-VO |

has reasonable tensile strength at 68°F (20°C), but its heat deflection temperature is the lowest of all the fluoroplastics. While PFA matches the hardness and impact strength of PTFE, it sustains only one quarter of the life of PTFE in flexibility tests. Refer to Table P.1 for the physical and mechanical properties of PFA.

Like PTFE, PFA is subject to permeation by certain gases and will absorb selected chemicals. Perfluoroalkoxy also performs well at cryogenic temperatures. Table P.2 compares the mechanical properties of PFA at room temperature and cryogenic temperatures.

**Table P.2** Comparison of Mechanical Properties of PFA at Room Temperature and Cryogenic Temperature

| | Temperature | |
|---|---|---|
| Property | 73°F/23°C | –320°F/–190°C |
| Yield strength, psi | 2100 | No yield |
| Ultimate tensile strength, psi | 2600 | 18,700 |
| Elongation, % | 260 | 8 |
| Flexural modulus, psi | 81,000 | 840,000 |
| Izod impact strength, notched, ft-lb/in. | No break | 12 |
| Compressive strength, psi | 3500 | 60,000 |
| Compressive strain, % | 20 | 35 |
| Modulus of elasticity, psi | 10,000 | 680,000 |

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PFA is inert to strong mineral acids, organic bases, inorganic oxidizers, aromatics, some aliphatic hydrocarbons, alcohols, aldehydes, ketones, ethers, esters, chlorocarbons, fluorocarbons, and mixtures of these.

PFA will be attacked by certain halogenated complexes containing fluorine. This includes chlorine trifluoride, bromine trifluoride, iodine pentafluoride, and fluorine. It can also be attacked by such metals as sodium or potassium, particularly in their molten state. Refer to Table P.3 for the compatibility of PFA with selected corrodents.

Refer to Ref. 7 and 8 for the compatibility of PFA with a wide variety of selected corrodents.

**Table P.3** Compatibility of PFA with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | 450 | 232 | Amyl acetate | 450 | 232 |
| Acetamide | 450 | 232 | Amyl alcohol | 450 | 232 |
| Acetic acid 10% | 450 | 232 | Amyl chloride | 450 | 232 |
| Acetic acid 50% | 450 | 232 | Aniline[c] | 450 | 232 |
| Acetic acid 80% | 450 | 232 | Antimony trichloride | 450 | 232 |
| Acetic acid, glacial | 450 | 232 | Aqua regia 3:1 | 450 | 232 |
| Acetic anhydride | 450 | 232 | Barium carbonate | 450 | 232 |
| Acetone | 450 | 232 | Barium chloride | 450 | 232 |
| Acetyl chloride | 450 | 232 | Barium hydroxide | 450 | 232 |
| Acrylonitrile | 450 | 232 | Barium sulfate | 450 | 232 |
| Adipic acid | 450 | 232 | Barium sulfide | 450 | 232 |
| Allyl alcohol | 450 | 232 | Benzaldehyde[c] | 450 | 232 |
| Allyl chloride | 450 | 232 | Benzene sulfonic acid 10% | 450 | 232 |
| Alum | 450 | 232 | Benzene[b] | 450 | 232 |
| Aluminum chloride, aqueous | 450 | 232 | Benzoic acid | 450 | 232 |
| Aluminum fluoride | 450 | 232 | Benzyl alcohol[c] | 450 | 232 |
| Aluminum hydroxide | 450 | 232 | Benzyl chloride[b] | 450 | 232 |
| Aluminum nitrate | 450 | 232 | Borax | 450 | 232 |
| Aluminum oxychloride | 450 | 232 | Boric acid | 450 | 232 |
| Aluminum sulfate | 450 | 232 | Bromine gas, dry[b] | 450 | 232 |
| Ammonia gas[b] | 450 | 232 | Bromine liquid[b,c] | 450 | 232 |
| Ammonium bifluoride[b] | 450 | 232 | Butadiene[b] | 450 | 232 |
| Ammonium carbonate | 450 | 232 | Butyl acetate | 450 | 232 |
| Ammonium chloride 10% | 450 | 232 | Butyl alcohol | 450 | 232 |
| Ammonium chloride 50% | 450 | 232 | *n*-Butlamine[c] | 450 | 232 |
| Ammonium chloride, sat. | 450 | 232 | Butyl phthalate | 450 | 232 |
| Ammonium fluoride 10%[b] | 450 | 232 | Butyric acid | 450 | 232 |
| Ammonium fluoride 25%[b] | 450 | 232 | Calcium bisulfide | 450 | 232 |
| Ammonium hydroxide 25% | 450 | 232 | Calcium bisulfite | 450 | 232 |
| Ammonium hydroxide, sat. | 450 | 232 | Calcium carbonate | 450 | 232 |
| Ammonium nitrate | 450 | 232 | Calcium chlorate | 450 | 232 |
| Ammonium persulfate | 450 | 232 | Calcium chloride | 450 | 232 |
| Ammonium phosphate | 450 | 232 | Calcium hydroxide 10% | 450 | 232 |
| Ammonium sulfate 10–40% | 450 | 232 | Calcium hydroxide, sat. | 450 | 232 |
| Ammonium sulfide | 450 | 232 | Calcium hypochlorite | 450 | 232 |

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**Table P.3** Compatibility of PFA with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Calcium nitrate | 450 | 232 | Fluorine gas, moist | x | x |
| Calcium oxide | 450 | 232 | Hydrobromic acid, dilute[b,d] | 450 | 232 |
| Calcium sulfate | 450 | 232 | Hydrobromic acid 20%[b,d] | 450 | 232 |
| Caprylic acid | 450 | 232 | Hydrobromic acid 50%[bd] | 450 | 232 |
| Carbon bisulfide[b] | 450 | 232 | Hydrochloric acid 20%[b,d] | 450 | 232 |
| Carbon dioxide, dry | 450 | 232 | Hydrochloric acid 38%[b,d] | 450 | 232 |
| Carbon dioxide, wet | 450 | 232 | Hydrocyanic acid 10% | 450 | 232 |
| Carbon disulfide[b] | 450 | 232 | Hydrofluoric acid 30%[b] | 450 | 232 |
| Carbon monoxide | 450 | 232 | Hydrofluoric acid 70%[b] | 450 | 232 |
| Carbon tetrachloride[b,c,d] | 450 | 232 | Hydrofluoric acid I00%[b] | 450 | 232 |
| Carbonic acid | 450 | 232 | Hypochlorous acid | 450 | 232 |
| Chloracetic acid | 450 | 232 | Iodine solution 10%[b] | 450 | 232 |
| Chloracetic acid, 50% water | 450 | 232 | Ketones, general | 450 | 232 |
| Chlorine gas, dry | x | x | Lactic acid 25% | 450 | 232 |
| Chlorine gas, wet[b] | 450 | 232 | Lactic acid, concentrated | 450 | 232 |
| Chlorine liquid[c] | x | x | Magnesium chloride | 450 | 232 |
| Chlorobenzene[b] | 450 | 232 | Malic acid | 450 | 232 |
| Chloroform[b] | 450 | 232 | Methyl chloride[b] | 450 | 232 |
| Chlorosulfonic acid[c] | 450 | 232 | Methyl ethyl ketone[b] | 450 | 232 |
| Chromic acid 10% | 450 | 232 | Methyl isobutyl ketone[b] | 450 | 232 |
| Chromic acid 50%[c] | 450 | 232 | Muriatic acid[b] | 450 | 232 |
| Chromyl chloride | 450 | 232 | Nitric acid 5%[b] | 450 | 232 |
| Citric acid 15% | 450 | 232 | Nitric acid 20%[b] | 450 | 232 |
| Citric acid, concentrated | 450 | 232 | Nitric acid 70%[b] | 450 | 232 |
| Copper carbonate | 450 | 232 | Nitric acid, anhydrous[b] | 450 | 232 |
| Copper chloride | 450 | 232 | Nitrous acid 10% | 450 | 232 |
| Copper cyanide | 450 | 232 | Oleum | 450 | 232 |
| Copper sulfate | 450 | 232 | Perchloric acid 10% | 450 | 232 |
| Cresol | 450 | 232 | Perchloric acid 70% | 450 | 232 |
| Cupric chloride 5% | 450 | 232 | Phenol[b] | 450 | 232 |
| Cupric chloride 50% | 450 | 232 | Phosphoric acid 50–80%[c] | 450 | 232 |
| Cyclohexane | 450 | 232 | Picric acid | 450 | 232 |
| Cyclohexanol | 450 | 232 | Potassium bromide 30% | 450 | 232 |
| Dichloroacetic acid | 450 | 232 | Salicylic acid | 450 | 232 |
| Dichloroethane (ethylene dichloride)[b] | 450 | 232 | Sodium carbonate | 450 | 232 |
| | | | Sodium chloride | 450 | 232 |
| Ethylene glycol | 450 | 232 | Sodium hydroxide 10% | 450 | 232 |
| Ferric chloride | 450 | 232 | Sodium hydroxide 50% | 450 | 232 |
| Ferric chloride 50% in water[c] | 450 | 232 | Sodium hydroxide, concentrated | 450 | 232 |
| Ferric nitrate 10–50% | 450 | 232 | Sodium hypochlorite 20% | 450 | 232 |
| Ferrous chloride | 450 | 232 | Sodium hypochlorite, concentrated | 450 | 232 |
| Ferrous nitrate | 450 | 232 | | | |
| Fluorine gas, dry | x | x | Sodium sulfide to 50% | 450 | 232 |

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**Table P.3** Compatibility of PFA with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Stannic chloride | 450 | 232 | Sulfuric acid, fuming[b] | 450 | 232 |
| Stannous chloride | 450 | 232 | Sulfurous acid | 450 | 232 |
| Sulfuric acid 10% | 450 | 232 | Thionyl chloride[b] | 450 | 232 |
| Sulfuric acid 50% | 450 | 232 | Toluene[b] | 450 | 232 |
| Sulfuric acid 70% | 450 | 232 | Trichloroacetic acid | 450 | 232 |
| Sulfuric acid 90% | 450 | 232 | White liquor | 450 | 232 |
| Sulfuric acid 98% | 450 | 232 | Zinc chloride[c] | 450 | 232 |
| Sulfuric acid 100% | 450 | 232 | | | |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that the data are unavailable.
[b]Material will permeate.
[c]Material will be absorbed.
[d]Material will cause stress cracking.
*Source:* Schweitzer, PA. *Corrosion Resistance Tables.* 4th ed. Vols 1–3. New York: Marcel Dekker, 1995.

## PERFLUOROELASTOMERS (FPM)

Perfluoroelastomers provide the elastomeric properties of fluoroelastomers and the chemical resistance of PTFE. These compounds are true rubbers. Compared with other elastomeric compounds, they are more resistant to swelling and embrittlement and retain their elastomeric properties over the long term. In difficult environments, there are no other elastomers that can outperform the perfluoroelastomers. These synthetic rubbers provide the sealing force of a true elastomer and the chemical inertness and thermal stability of polytetrafluoroethylene.

As with other elastomers, perfluoroelastomers are compounded to modify certain of their properties. Such materials as carbon black, perfluorinated oil, and various fillers are used for this purpose.

The ASTM designation for these elastomers is FPM.

### Physical and Mechanical Properties

One of the outstanding physical properties of the perfluoroelastomers is their thermal stability. They retain their elasticity and recovery properties up to 600°F (316°C) in long-term service and up to 650°F (343°C) in intermittent service. This is the highest temperature rating of any elastomer.

In general, the physical properties of the perfluoroelastomers are similar to those of the fluoroelastomers. As with most compounding, the enhancement of one property usually has the opposite effect on another property. For example, as the coefficient of friction increases, the hardness decreases. Because of these factors, the physical and mechanical properties given in Table P.4 are in ranges where they are compound dependent. Special compounds are available for applications requiring thermal cycling, increased resistance

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**Table P.4** Physical and Mechanical Properties of Perfluoroelastomers[a]

| | |
|---|---|
| Specific gravity | 1.9–2.0 |
| Specific heat at 122–302°F (50–150°C), cal/g | 0.226–0.250 |
| Brittle point | –9 to –58°F (–23 to –50°C) |
| Coefficient of friction (to steel) | 0.25–0.60 |
| Tear strength, psi | 1.75–27 |
| Coefficient of linear expansion | |
| in./°F | $1.3 \times 10^{-4}$ |
| in./°C | $2.3 \times 10^{-4}$ |
| Thermal conductivity, Btu-in./hr-°F-ft$^2$ | |
| at 122°F (50°C) | 1.3 |
| at 212°F (100°C) | 1.27 |
| at 392°F (200°C) | 1.19 |
| at 572°F (300°C) | 1.10 |
| Dielectric constant, kV/mm | 17.7 |
| Dielectric constant at 1000 Hz | 4.9 |
| Dissipation factor at 1000 Hz | $5 \times 10^{-3}$ |
| Permeability ($\times 10^{-9}$ cm$^3$-cm/S-cm$^2$-cmHg P) | |
| to nitrogen, at room temperature | 0.05 |
| to oxygen, at room temperature | 0.09 |
| to helium, at room temperature | 2.5 |
| to hydrogen, at 199°F (93°C) | 113 |
| Tensile strength, psi | 1850–3800 |
| Elongation, % at break | 20–190 |
| Hardness, Shore A | 65–95 |
| Maximum temperature, continuous use | 600°F (316°C) |
| Abrasion resistance, NBS | 121 |
| Compression set, % | |
| at room temperature | 15–40 |
| at 212°F (100°C) | 32–54 |
| at 400°F (204°C) | 63–82 |
| at 500°F (260°C) | 63–79 |
| Resistance to sunlight | Excellent |
| Effect of aging | Nil |
| Resistance to heat | Excellent |

[a]These are representative values since they may be altered by compounding.

to strong oxidizing environments, other pressures, different hardnesses, or other specific physical properties. Selection of specific compounds for special applications should be done in cooperation with the manufacturer.

These elastomers provide excellent performance in high-vacuum environments. They exhibit negligible outgassing over a wide temperature range. This is an important property in any application where freedom from contamination of process streams is critical. Typical applications include semiconductor manufacturing operations, aerospace applications, and use in analytical instruments.

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The perfluoroelastomers have good mechanical properties. See Table P.4. Because these elastomers are based on expensive monomers and require complex processing, they cost more than other elastomeric materials. As a result, these materials are limited to use in extremely hostile environments and/or applications where high heat will quickly attack other elastomers. Perfluoro rubbers retain their elastic properties in long-term service at elevated temperatures.

## Resistance to Sun, Weather, and Ozone

The perfluoroelastomers provide excellent resistance to sun, weather, and ozone. Long-term exposure under these conditions has no effect on them.

## Chemical Resistance

The perfluoroelastomers have outstanding chemical resistance. They are virtually immune to chemical attack at ambient and elevated temperatures. Typical corrodents to which the perfluoroelastomers are resistant include the following:

Polar solvents (ketones, esters, ethers)
Strong organic solvents (benzene, dimethyl formamide, perchloroethylene, tetrahydrofuran)
Inorganic and organic acids (hydrochloric, nitric, sulfuric, trichloroacetic) and bases (hot caustic soda)
Strong oxidizing agents (dinitrogen tetroxide, fuming nitric acid)
Metal halides (titanium tetrachloride, diethyl aluminum chloride)
Hot mercury
Chlorine, wet and dry
Inorganic salt solutions
Fuels (ASTM Reference Fuel C, JP-5 jet fuel, aviation gas, kerosene)
Hydraulic fluids
Heat transfer fluids
Oil well sour gas (methane, hydrogen sulfide, carbon dioxide, steam)
Steam

These perfluoroelastomers should not be exposed to molten or gaseous alkali metals such as sodium because a highly exothermic reaction may occur. Service life can be greatly reduced in fluids containing high concentrations of some diamines, nitric acid, and basic phenol when the temperature exceeds 212°F (100°C). Uranium hexafluoride and fully halogenated freons (F-11 and F-12) cause considerable swelling.

The corrosion resistance as given above is for the base polymer. Since the polymer is quite often compounded with fillers and curatives, these additives may interact with the environment even though the polymer is resistant. Therefore, a knowledge of the additives present is essential in determining the material's suitability for a particular application. A corrosion testing program is the best method whereby this evaluation can be undertaken. Refer to Table P.33 for the compatibility of PTFE with selected corrodents.

## Applications

Perfluoroelastomer parts are a practical solution wherever the sealing performance of rubber is desirable but not feasible because of severe chemical or thermal conditions. In the

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petrochemical industry, FPM is widely used for O-ring seals on equipment. O-rings of FPM are employed in mechanical seals, pump housings, compressor casings, valves, rotameters, and other instruments. Custom-molded parts are also used as valve seats, packings, diaphragms, gaskets, and miscellaneous sealing elements including U-cups and V-rings.

Other industries where FPM contributes importantly are aerospace (versus jet fuels, hydrazine, $N_2O_4$ and other oxidizers, Freon-21 fluorocarbon, etc.); nuclear power (versus radiation, high temperatures); oil, gas, and geothermal drilling (versus sour gas, acidic fluids, amine-containing hydraulic fluids, extreme temperatures and pressures); and analytical and process instruments (versus high vacuum, liquid and gas chromotography exposures, high-purity reagents, high-temperature conditions).

The semiconductor industry makes use of FPM O-rings to seal the aggressive chemical reagents and specialty gases required for producing silicon chips. Also, the combination of thermal stability and low outgassing characteristics are desirable in furnaces for growing crystals and in high-vacuum applications.

The chemical transportation industry is also a heavy user of FPM components in safety relief and unloading valves to prevent leakage from tank trucks and trailers, rail cars, ships, and barges carrying hazardous and corrosive chemicals.

Other industries that also use FPM extensively include pharmaceuticals, agricultural chemicals, oil and gas recovery, and analytical and process-control instrumentation.

Because of their cost, the perfluoroelastomers are used primarily as seals where their corrosion- and/or heat-resistance properties can be utilized and other elastomeric materials will not do the job or where high maintenance costs will result if other elastomeric materials are used.

See Refs. 7 and 8.

## PERMEATION

Also see "Sheet Linings."

All materials are somewhat permeable to chemical molecules, but plastic materials tend to be an order of magnitude greater in their permeability rates than metals. Gases, vapors, or liquids will permeate polymers.

Permeation is a molecular migration either through microvoids in the polymer (if the polymer is more or less porous) or between polymer molecules. In neither case is there any attack on the polymer. This action is strictly a physical phenomenon. In lined equipment, permeation can result in

1. Failure of the substrate from corrosive attack.
2. Bond failure and blistering, resulting from accumulation of fluids at the bond when the substrate is less permeable than the liner or from corrosion/reaction products if the substrate is attacked by the permeant.
3. Loss of contents through substrate and liner as a result of the eventual failure of the substrate. In unbonded linings it is important that the space between the liner and support member be vented to the atmosphere, not only to allow minute quantities of permeant vapors to escape but also to prevent expansion of entrapped air from collapsing the liner.

Permeation is a function of two variables, one relating to diffusion between molecular chains and the other to the solubility of the permeant in the polymer. The driving

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force of diffusion is the partial pressure gradient for gases and the concentration gradient for liquids. Solubility is a function of the affinity of the permeant for the polymer.

There is no relation between permeation and the passage of materials through cracks and voids, even though in both cases migrating chemicals travel through the polymer from one side to the other.

The user has some control over permeation, which is affected by

1. Temperature and pressure
2. Permeant concentration
3. Thickness of the polymer

Increasing the temperature will increase the permeation rate, since the solubility of the permeant in the polymer will increase, and as the temperature rises the polymer chain movement is stimulated, permitting more permeants to diffuse among the chains more easily. For many gases, the permeation rates increase linearly with the partial pressure gradient, and the same effect is experienced with the concentration gradients of liquids. If the permeant is highly soluble in the polymer, the permeability increase may be nonlinear. The thickness will generally decrease permeation by the square of the thickness. For general corrosion resistance, thicknesses of 0.010–0.020 in. are usually satisfactory.

The density of the polymer, as well as the thickness, will have an effect on the permeation rate. The greater the density of the polymer, the fewer voids through which permeation can take place. A comparison of the density of sheets produced from different polymers does not provide any indication of the relative permeation rates. However, a comparison of the density of sheets produced from the same polymer will provide an indication of the relative permeation rates. The denser the sheet, the lower the permeation rate.

Thickness of lining is a factor affecting permeation. For general corrosion resistance, thicknesses of 0.010–0.020 in. are usually satisfactory, depending upon the combination of elastomeric material and specific corrodent. When mechanical factors such as thinning due to cold flow, mechanical abuse, and permeation rates are a consideration, thicker linings may be required.

Increasing the lining thickness will normally decrease permeation by the square of the thickness. Although this would appear to be the approach to follow to control permeation, there are disadvantages. First, as the thickness increases, the thermal stresses on the boundary increase, which can result in bond failure. Temperature changes and large differences in coefficients of thermal expansion are the most common causes of bond failure. Thickness and modulus of elasticity of the elastomer are two of the factors that would influence these stresses. Second, as the thickness of the lining increases, installation becomes more difficult, with a resulting increase in labor costs.

The rate of permeation is also affected by temperature and temperature gradient in the lining. Lowering these will reduce the rate of permeation. Lined vessels that are used under ambient conditions, such as storage tanks, provide the best service.

Other factors affecting permeation consisting of chemical and physiochemical properties are the following:

1. Ease of condensation of the permeant: Chemicals that condense readily will permeate at higher rates.

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**Table P.5** Vapor Permeation of PTFE[a]

| Gases | Permeation (g/100 in.$^2$/24 h/mil) at 73°F (23°C) | 86°F (30°C) |
|---|---|---|
| Carbon dioxide | | 0.66 |
| Helium | | 0.22 |
| Hydrogen chloride, anh. | | <0.01 |
| Nitrogen | | 0.11 |
| Acetophenone | 0.56 | |
| Benzene | 0.36 | 0.80 |
| Carbon tetrachloride | 0.06 | |
| Ethyl alcohol | 0.13 | |
| Hydrochloric acid 20% | <0.01 | |
| Piperdine | 0.07 | |
| Sodium hydroxide 50% | $5 \times 10^{-5}$ | |
| Sulfuric acid 98% | $1.8 \times 10^{-5}$ | |

[a]Based on PTFE having a specific gravity > 2.2.

2. The higher the intermolecular chain forces (e.g., van der Waals hydrogen bonding) of the polymer, the lower the permeation rate.
3. The higher the level of crystallinity in the polymer, the lower the permeation rate.
4. The greater the degree of cross-linking within the polymer, the lower the permeation rate.
5. Chemical similarity between the polymer and permeant. When the polymer and permeant both have similar functional groups, the permeation rate will increase.
6. The smaller the molecule of the permeant, the greater the permeation rate.Vapor permeation of PTFE, FEP, and PFA are shown in Tables P.5, P.6, and P.7.

## pH

The exact significance of pH is still in dispute. It is commonly considered to be the negative logarithm (to the base 10) of the hydrogen ion concentration of a solution. Others interpret it as the negative logarithm of the "activity" of the hydrogen ions in a solution. Neither is precisely correct, but the experimental determination of pH continues to offer valuable information as to the immediate acidity, as contrasted to the total acidity (which may be titrated), of a solution. A value of 7 indicates neutrality. The lower the number, the greater is the acidity; the higher the number, the greater is the alkalinity.

The pH of a solution is defined operationally by the following equation:

$$\mathrm{pH} = \mathrm{pH}_s + \frac{(E - E_s)}{0.000198404T}$$

where $\mathrm{pH}_s$ is the pH assigned to the standard buffer solution with which the pH cell is standardized; $E$ and $E_s$ are the electromotive forces of a suitable pH cell with unknown and standard, respectively; $T$ is the temperature on the Kelvin (absolute) scale; and

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**Table P.6** Vapor Permeation of FEP

| | Permeation (g/l00 in.$^2$/24 h/mil) at | | |
|---|---|---|---|
| | 73°F (23°C) | 95°F (35°C) | 122°F (50°C) |
| Gases | | | |
| Nitrogen | 0.18 | | |
| Oxygen | 0.39 | | |
| Vapors | | | |
| Acetic acid | | 0.42 | |
| Acetone | 0.13 | 0.95 | 3.29 |
| Acetophenone | 0.47 | | |
| Benzene | 0.15 | 0.64 | |
| *n*-Butyl ether | 0.08 | | |
| Carbon tetrachloride | 0.11 | 0.31 | |
| Decane | 0.72 | | 1.03 |
| Ethyl acetate | 0.06 | 0.77 | 2.9 |
| Ethyl alcohol | 0.11 | 0.69 | |
| Hexane | | 0.57 | |
| Hydrochloric acid 20% | <0.01 | | |
| Methanol | | | 5.61 |
| Sodium hydroxide 50% | $4 \times 10^{-5}$ | | |
| Sulfuric acid 98% | $8 \times 10^{-6}$ | | |
| Toluene | 0.37 | | 2.93 |
| Water | 0.09 | 0.45 | 0.89 |

**Table P.7** Permeation of Various Gases in PFA at 77°F (25°C)

| Gas | Permeation (cc mil thickness/100 in.$^2$ 24 h atm) |
|---|---|
| Carbon dioxide | 2260 |
| Nitrogen | 291 |
| Oxygen | 881 |

0.000198404 is 2.230250 $R/F$, where $R$ is the gas constant and $F$ is the Faraday constant. The values of 0.000198404$T$ from 0 to 70°C are given in Table P.8.

## PHENOL-FORMALDEHYDE RESIN

This is one of the oldest synthetic materials available, having been in existence for more than 50 years. In general, it does not have the impact resistance of the polyesters or epoxies.

### Corrosion Resistance

It is generally recommended for service with mineral acids, salts, and chlorinated aromatic hydrocarbons. Refer to Table P.9 for the compatibility of phenol-formaldehyde with selected corrodents. Since these resins possess little alkaline and bleach resistance, application in such services should be avoided.

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**Table P.8** Values of 0.00198404*T* at Various Temperatures

| *T* °C | Value | *T* °C | Value |
|---|---|---|---|
| 0 | 0.054196 | 24 | 0.058958 |
| 5 | 0.055188 | 25 | 0.059156 |
| 10 | 0.056180 | 26 | 0.059355 |
| 14 | 0.056974 | 27 | 0.059553 |
| 15 | 0.057172 | 28 | 0.059751 |
| 16 | 0.057371 | 29 | 0.059950 |
| 17 | 0.057569 | 30 | 0.060148 |
| 18 | 0.057767 | 35 | 0.061140 |
| 19 | 0.057966 | 38 | 0.061735 |
| 20 | 0.058164 | 40 | 0.062132 |
| 21 | 0.058363 | 50 | 0.064116 |
| 22 | 0.058561 | 60 | 0.066100 |
| 23 | 0.058759 | 70 | 0.068084 |

**Table P.9** Compatibility of Phenol-Formaldehyde with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetaldehyde | x | x | Calcium chloride | 300 | 149 |
| Acetamide | | | Calcium hydroxide 10% | x | x |
| Acetic acid 10% | 212 | 100 | Calcium hydroxide, sat. | x | x |
| Acetic acid 50% | 160 | 71 | Calcium hypochlorite | x | x |
| Acetic acid 80% | 120 | 49 | Carbon bisulfide | 160 | 71 |
| Acetic acid, glacial | 120 | 49 | Carbon tetrachloride | 212 | 100 |
| Acetone | x | x | Chlorine gas, dry | 160 | 71 |
| Acetyl chloride | x | x | Chlorine gas, wet | 160 | 71 |
| Acrylic acid 90% | 80 | 27 | Chlorobenzene | | |
| Acrylonitrile | x | x | Chloroform | 160 | 71 |
| Aluminum acetate | | | Chlorosulfonic acid | 80 | 27 |
| Aluminum chloride, aqueous | 300 | 149 | Chromic acid 10% | x | x |
| Aluminum chloride, dry | 300 | 149 | Chromic acid 50% | x | x |
| Aluminum sulfate | 300 | 149 | Copper sulfate | 300 | 149 |
| Ammonium hydroxide 25% | x | x | Cresol | | |
| Ammonium hydroxide, sat. | x | x | Cupric chloride 5% | 300 | 149 |
| Amyl alcohol | 160 | 71 | Cupric chloride 50% | 300 | 149 |
| Aniline | x | x | Ethylene glycol | 80 | 27 |
| Aqua regia 3:1 | x | x | Ferric chloride 50% in water | 300 | 149 |
| Benzene | 160 | 71 | Ferric nitrate 10–50% | 300 | 149 |
| Benzene sulfonic acid 10% | 160 | 71 | Ferrous chloride 40% | 300 | 149 |
| Benzyl chloride | 160 | 71 | Hydrobromic acid dilute | 212 | 100 |
| Boric acid | 300 | 149 | Hydrobromic acid, 20% | 212 | 100 |
| Bromine liquid 3% max. | 300 | 149 | Hydrochloric acid 20% | 300 | 149 |
| Butyric acid | 260 | 127 | Hydrochloric acid 38% | 300 | 149 |

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**Table P.9** Compatibility of Phenol-Formaldehyde with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Hydrocyanic acid 10% | 160 | 71 | Phosphoric acid 50% | 212 | 100 |
| Hydrofluoric acid 30% | x | x | Sodium carbonate | x | x |
| Hydrofluoric acid 70% | x | x | Sodium hydroxide 10% | x | x |
| Hydrofluoric acid 100% | x | x | Sodium hydroxide 50% | x | x |
| Ferric nitrate 10–50% | 300 | 149 | Sodium hydroxide, | | |
| Hypochlorous acid | | | concentrated | x | x |
| Iodine solution 10% | x | x | Sodium hypochlorite 15% | x | x |
| Lactic acid 25% | 160 | 71 | Sodium hypochlorite, | | |
| Lactic acid, concentrated | 160 | 71 | concentrated | x | x |
| Methyl chloride | 300 | 149 | Sulfuric acid 10% | 300 | 149 |
| Methyl ethyl ketone | x | x | Sulfuric acid 50% | 300 | 149 |
| Methyl isobutyl ketone | x | x | Sulfuric acid 70% | 250 | 121 |
| Muriatic acid | 300 | 149 | Sulfuric acid 90% | 100 | 38 |
| Nitric acid 5% | x | x | Sulfurous acid | 160 | 71 |
| Nitric acid 20% | x | x | Thionyl chloride | 80 | 27 |
| Nitric acid 70% | x | x | Toluene | 212 | 100 |
| Nitric acid, anhydrous | x | x | Trichloroacetic acid 30% | 80 | 27 |
| Phenol | x | x | Zinc chloride | 300 | 149 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that the data are unavailable,
*Source:* Schweitzer, PA. *Corrosion Resistance Tables.* 4th ed. Vols 1–3. New York: Marcel Dekker, 1995.

Furan resins are produced from furfuryl alcohol and furfural. These resins are more expensive than other thermoset set resins but are the most economical choice when the presence of solvents exists in a combination with acids and bases or when process changes may occur that result in exposure to solvents in oxidizing atmospheres.

The furan laminates have the ability to retain their physical properties at elevated temperatures.

See Refs. 8–10.

## PHENOLIC RESINS

These are the oldest commercial classes of polymers in use today. Although first discovered in 1872, it was not until 1907 after the "heat and pressure" patent was applied for by Leo H. Bakeland that the development of and application of phenolic molding compounds became economical.

The phenolics display excellent resistance to most organic solvents, particularly chlorinated and aromatic solvents. These resins are not suitable for use with caustics or strong mineral acids (such as nitric, chromic, and hydrochloric). Refer to Table P.10 for the compatibility of phenolic resins with selected corrodents.

See Refs. 8 and 11.

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**Table P.10** Compatibility of Phenolics with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | | | Barium hydroxide | | |
| Acetamide | | | Barium sulfate | | |
| Acetic acid 10% | 212 | 100 | Barium sulfide | | |
| Acetic acid 50% | | | Benzaldehyde | 70 | 21 |
| Acetic acid 80% | | | Benzene | 160 | 71 |
| Acetic acid, glacial | 70 | 21 | Benzene sulfonic acid 10% | 70 | 21 |
| Acetic anhydride | 70 | 21 | Benzoic acid | | |
| Acetone | x | x | Benzyl alcohol | | |
| Acetyl chloride | | | Benzyl chloride | 70 | 21 |
| Acrylic acid | | | Borax | | |
| Acrylonitrile | | | Boric acid | | |
| Adipic acid | | | Bromine gas, dry | | |
| Allyl alcohol | | | Bromine gas, moist | | |
| Allyl chloride | | | Bromine liquid | | |
| Alum | | | Butadiene | | |
| Aluminum acetate | | | Butyl acetate | x | x |
| Aluminum chloride, aqueous | 90 | 32 | Butyl alcohol | | |
| Aluminum chloride, dry | | | *n*-Butylamine | | |
| Aluminum fluoride | | | Butyl phthalate | | |
| Aluminum hydroxide | | | Butyric acid | 160 | 71 |
| Aluminum nitrate | | | Calcium bisulfide | | |
| Aluminum oxychloride | | | Calcium bisulfite | | |
| Aluminum sulfate | 300 | 149 | Calcium carbonate | | |
| Ammonia bifluoride | | | Calcium chlorate | | |
| Ammonia gas | 90 | 32 | Calcium chloride | 300 | 149 |
| Ammonium carbonate | 90 | 32 | Calcium hydroxide 10% | | |
| Ammonium chloride 10% | 80 | 27 | Calcium hydroxide, sat. | | |
| Ammonium chloride 50% | 80 | 27 | Calcium hypochlorite | x | x |
| Ammonium chloride, sat. | 80 | 27 | Calcium nitrate | | |
| Ammonium fluoride 10% | | | Calcium oxide | | |
| Ammonium fluoride 25% | | | Calcium sulfate | | |
| Ammonium hydroxide 25% | x | x | Caprylic acid | | |
| Ammonium hydroxide, sat. | x | x | Carbon bisulfide | | |
| Ammonium nitrate | 160 | 71 | Carbon dioxide, dry | 300 | 149 |
| Ammonium persulfate | | | Carbon dioxide, wet | 300 | 149 |
| Ammonium phosphate | | | Carbon disulfide | | |
| Ammonium sulfate 10–40% | 300 | 149 | Carbon monoxide | | |
| Ammonium sulfide | | | Carbon tetrachloride | 200 | 93 |
| Ammonium sulfite | | | Carbonic acid | 200 | 93 |
| Amyl acetate | | | Cellosolve | | |
| Amyl alcohol | | | Chloracetic acid | | |
| Amyl chloride | | | Chloracetic acid, 50% water | | |
| Aniline | x | x | Chlorine gas, dry | | |
| Antimony trichloride | | | Chlorine gas, wet | x | x |
| Aqua regia 3:1 | | | Chlorine liquid | x | x |
| Barium carbonate | | | Chlorobenzene | 260 | 127 |
| Barium chloride | | | Chloroform | 160 | 71 |

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**Table P.10** Compatibility of Phenolics with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Chlorosulfonic acid | | | Manganese chloride | | |
| Chromic acid 10% | x | x | Methyl chloride | 160 | 71 |
| Chromic acid 50% | x | x | Methyl ethyl ketone | x | x |
| Chromyl chloride | | | Methyl isobutyl ketone | 160 | 71 |
| Citric acid 15% | 160 | 71 | Muriatic acid | 300 | 149 |
| Citric acid, concentrated | 160 | 71 | Nitric acid 5% | x | x |
| Copper acetate | | | Nitric acid 20% | x | x |
| Copper carbonate | | | Nitric acid 70% | x | x |
| Copper chloride | | | Nitric acid, anhydrous | x | x |
| Copper cyanide | | | Nitrous acid, concentrated | | |
| Copper sulfate | 300 | 149 | Oleum | | |
| Cresol | | | Perchloric acid 10% | | |
| Cupric chloride 5% | | | Perchloric acid 70% | | |
| Cupric chloride 50% | | | Phenol | x | x |
| Cyclohexane | | | Phosphoric acid 50–80% | 212 | 100 |
| Cyclohexanol | | | Picric acid | | |
| Dichloroacetic acid | | | Potassium bromide 30% | | |
| Dichloroethane (ethylene dichloride) | | | Salicylic acid | | |
| Ethylene glycol | 70 | 21 | Silver bromide 10% | | |
| Ferric chloride | 300 | 149 | Sodium carbonate | | |
| Ferric chloride 50% in water | 300 | 149 | Sodium chloride | 300 | 149 |
| Ferric nitrate 10–50% | | | Sodium hydroxide 10% | x | x |
| Ferrous chloride 40% | | | Sodium hydroxide 50% | x | x |
| Ferrous nitrate | | | Sodium hydroxide, concentrated | x | x |
| Fluorine gas, dry | | | Sodium hypochlorite 15% | x | x |
| Fluorine gas, moist | | | Sodium hypochlorite, concentrated | x | x |
| Hydrobromic acid, dilute | 200 | 93 | Sodium sulfide to 50% | | |
| Hydrobromic acid 20% | 200 | 93 | Stannic chloride | | |
| Hydrobromic acid 50% | 200 | 93 | Stannous chloride | | |
| Hydrochloric acid 20% | 300 | 149 | Sulfuric acid 10% | 250 | 121 |
| Hydrochloric acid 38% | 300 | 149 | Sulfuric acid 50% | 250 | 121 |
| Hydrocyanic acid 10% | | | Sulfuric acid 70% | 200 | 93 |
| Hydrofluoric acid 30% | x | x | Sulfuric acid 90% | 70 | 21 |
| Hydrofluoric acid 60% | x | x | Sulfuric acid 98% | x | x |
| Hydrofluoric acid 100% | x | x | Sulfuric acid 100% | x | x |
| Hypochlorous acid | | | Sulfuric acid, fuming | | |
| Iodine solution 10% | | | Sulfurous acid | 80 | 27 |
| Ketones, general | | | Thionyl chloride | 200 | 93 |
| Lactic acid 25% | 160 | 71 | Toluene | | |
| Lactic acid, concentrated | | | Trichloroacetic acid 30% | | |
| Magnesium chloride | | | White liquor | | |
| Malic acid 10% | | | Zinc chloride | 300 | 149 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that the data are unavailable.

*Source:* Schweitzer, PA. *Corrosion Resistance Tables.* 4th ed. Vols 1–3. New York: Marcel Dekker, 1995.

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## PHOSPHATING

See "Coatings."

## PITTING

Pitting is a form of localized corrosion that is primarily responsible for the failure of iron and steel hydraulic structures. Pitting may result in the perforation of water pipe, making it unusable even though a relatively small percentage of the total metal has been lost due to rusting. Pitting can also cause structural failure from localized weakening effects even though there is considerable sound material remaining.

The initiation of a pit is associated with the breakdown of the protective film on the surface. The main factor that causes and accelerates pitting is electrical contact between dissimilar metals or between what are termed concentration cells (areas of the same metal where oxygen or conductive salt concentrations in water differ). These couples cause a difference of potential that results in an electric current flowing through the water or across moist steel, from the metallic anode to a nearby cathode. The cathode may be brass or copper, mill scale, or any other portion of the metal surface that is cathodic to the more active metal areas. However, when the anodic area is relatively large compared with the cathodic area, the damage is spread out and is usually negligible. When the anodic area is relatively small, the metal loss is concentrated and may be serious. For example, it can be expected when large areas of the surface are generally covered by mill scale, applied coatings, or deposits of various kinds but breaks exist in the continuity of the protective material. Pitting may also develop on clean, bare metal surfaces because of irregularities in the physical or chemical structure of the metal. Localized dissimilar soil conditions at the surface of steel can also create conditions that promote pitting. Figure P.1 shows diagrammatically how a pit forms when a break in the mill scale occurs.

If an appreciable attack is confined to a small area of metal acting as an anode, the developed pits are called shallow. The ratio of deepest metal penetration to average metal penetration, as determined by weight loss of the specimen, is known as the pitting factor. A pitting factor of 1 represents uniform corrosion.

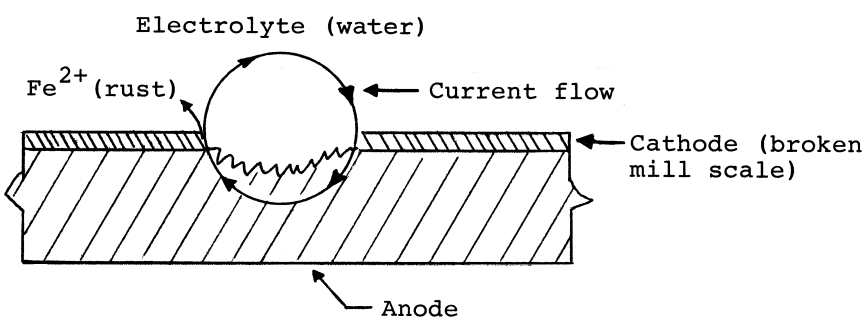



**Figure P.1** Formation of pit from break in mill scale.

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Performance in the area of pitting and crevice corrosion is often measured using critical pitting temperature (CPT), critical crevice temperature (CCT), and pitting resistance equivalent number (PREN). As a general rule, the higher the PREN, the better the resistance. Alloys with similar values may differ in actual service. The pitting resistance number is determined by the chromium, molybdenum, and nitrogen contents.

$$\text{PREN} = \%\text{Cr} + 3.3 \times \%\text{Mo} + 30 \times \%\text{N}$$

The PREN for various austenitic stainless steels are listed below:

| Alloy | PREN | Alloy | PREN |
|---|---|---|---|
| 654 | 63.09 | 317 | 33.2 |
| 31 | 54.45 | 316 | 27.90 |
| 686 | 51.1 | 316LN | 31.08 |
| 25-6Mo | 47.45 | 20Cb3 | 27.26 |
| A1-6XN | 46.96 | 348 | 25.60 |
| 20Mo-6 | 42.81 | 347 | 19.0 |
| 317N | 39.60 | 331 | 19.0 |
| 904L | 36.51 | 304N | 18.3 |
| 20Mo-4 | 36.20 | 304 | 18.0 |

Prevention can be accomplished first by proper material selection, followed by a design that prevents stagnation of material and alternate wetting and drying of the surface. Also, if coatings are to be applied, care should be taken that they are continuous without "holidays."

See Refs. 1, 12, and 13.

## PITTING POTENTIAL

The pitting potential of an alloy (specifically stainless steel alloys) indicates the relative susceptibility of that alloy to pitting. Potential is measured using an electrochemical apparatus in a standard chloride solution. The more positive the potential, the less likely the alloy is to suffer pitting.

## PITTING RESISTANCE EQUIVALENT NUMBER

See "Pitting."

## PLASTICS

See "Polymers."

## POLARIZATION

Polarization is the extent of potential charge caused by net current to or from an electrode, measured in volts, and results in the retardation of an electrochemical reaction

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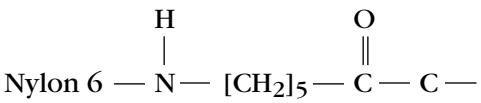
(corrosion) caused by various physical and chemical factors. There are three types of polarization, concentration polarization, activation polarization, and IR drop.

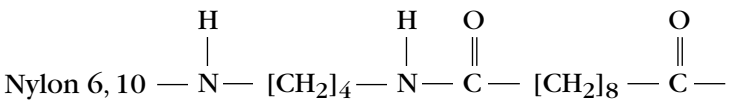
Concentration polarization refers to an electrochemical process controlled by the diffusion in the electrolyte. Activation polarization refers to an electrochemical process controlled by the reaction sequence at the metal–electrolyte interface. IR drop polarization is the change in voltage associated with effects of the environment and the circuit between the anode and cathode sites. It includes the resistivity of the media, surface films, corrosion products, etc.

See Refs. 1 and 14.

## POLYAMIDES (PA)

The polyamides are more commonly known as the nylons. They are linear molecules with a high degree of crystallinity and have the formula





They are a series of high-strength thermoplasts. Average physical and mechanical properties are shown in Table P.11.

**Table P.11** Physical and Mechanical Properties of PA

| | |
|---|---|
| Specific gravity | 1.01–1.17 |
| Water absorption, 24 h at 73°F/23°C, % | 0.4–1.8 |
| Tensile strength at 73°F/23°C, psi $\times 10^3$ | 8.3–12.5 |
| Modulus of elasticity in tension at 73°F/23°C $\times 10^3$ psi | 2–17 |
| Compressive strength, psi $\times 10^3$ | 9.7–12.5 |
| Flexural strength, psi $\times 10^3$ | 12.5–14 |
| Izod impact strength, notched at 73°F/23°C, ft-lb/in. | 0.5–3.3 |
| Coefficient of thermal expansion, in./in. °F $\times 10^{-5}$ | 4.5–5 |
| Thermal conductivity, Btu/h/ft$^2$/°F/in. | 1.2–1.7 |
| Heat distortion temperature, °F/°C | |
| at 66 psi | |
| Nylon 6 | 360/182 |
| Nylon 6/6 | 470/243 |
| Nylon 11 | 302/150 |
| at 264 psi | |
| Nylon 6 | 155–160/68–71 |
| Nylon 6/6 | 220/104 |
| Nylon 11 | 131/55 |

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The nylons are resistant to weak acids, strong and weak alkalies, most common solvents, hydrocarbons, esters, and ketones. They will be attacked by strong acids, Refer to Table P.12 for the compatibility of PA with selected corrodents.

See Ref. 8.

**Table P.12** Compatibility of Polyamides with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | x | x | Barium sulfate | 80 | 27 |
| Acetamide | 250 | 121 | Barium sulfide | 80 | 27 |
| Acetic acid 10% | 200 | 93 | Benzaldehyde | 150 | 66 |
| Acetic acid 50% | x | x | Benzene | 250 | 121 |
| Acetic acid 80% | x | x | Benzene sulfonic acid 10% | x | x |
| Acetic acid, glacial | x | x | Benzoic acid | 80 | 27 |
| Acetic anhydride | 200 | 93 | Benzyl alcohol | 200 | 93 |
| Acetone | 80 | 27 | Benzyl chloride | 250 | 121 |
| Acetyl chloride | x | x | Borax | 200 | 93 |
| Acrylonitrile | 80 | 27 | Boric acid | x | x |
| Allyl alcohol | 80 | 27 | Bromine gas, dry | x | x |
| Alum | x | x | Bromine gas, moist | x | x |
| Aluminum chloride, aqueous | x | x | Bromine liquid | x | x |
| Aluminum chloride, dry | x | x | Butadiene | 80 | 27 |
| Aluminum fluoride | 80 | 27 | Butyl acetate | 250 | 121 |
| Aluminum hydroxide | 250 | 121 | Butyl alcohol | 200 | 93 |
| Aluminum nitrate | 80 | 27 | *n*-Butylamine | 200 | 93 |
| Aluminum sulfate | 140 | 60 | Butyl phthalate | 240 | 116 |
| Ammonia gas | 200 | 93 | Butyric acid | x | x |
| Ammonium carbonate | 240 | 160 | Calcium bisulfite | 140 | 60 |
| Ammonium chloride 10% | 200 | 93 | Calcium carbonate | 200 | 93 |
| Ammonium chloride 50% | 200 | 93 | Calcium chloride | 250 | 121 |
| Ammonium fluoride 10% | 80 | 27 | Calcium hydroxide 10% | 150 | 66 |
| Ammonium fluoride 25% | 80 | 27 | Calcium hydroxide, sat. | 150 | 66 |
| Ammonium hydroxide 25% | 250 | 121 | Calcium hypochlorite | x | x |
| Ammonium hydroxide. sat. | 250 | 121 | Calcium nitrate | x | x |
| Ammonium nitrate | 190 | 88 | Calcium oxide | 80 | 27 |
| Ammonium persulfate | x | x | Calcium sulfate | 80 | 27 |
| Ammonium phosphate | 80 | 27 | Caprylic acid | 230 | 110 |
| Ammonium sulfite | 80 | 27 | Carbon bisulfide | 80 | 27 |
| Amyl acetate | 150 | 66 | Carbon dioxide, dry | 80 | 27 |
| Amyl alcohol | 200 | 93 | Carbon disulfide | 80 | 27 |
| Amyl chloride | x | x | Carbon monoxide | 80 | 27 |
| Aniline | x | x | Carbon tetrachloride | 250 | 121 |
| Antimony trichloride | x | x | Carbonic acid | 100 | 38 |
| Aqua regia 3:1 | x | x | Cellosolve | 250 | 121 |
| Barium carbonate | 80 | 27 | Chloracetic acid | x | x |
| Barium chloride | 250 | 121 | Chloracetic acid, 50% water | x | x |
| Barium hydroxide | 80 | 27 | Chlorine gas, dry | x | x |

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**Table P.12** Compatibility of Polyamides with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Chlorine gas, wet | x | x | Malic acid | x | x |
| Chlorine liquid | x | x | Methyl chloride | 80 | 27 |
| Chlorobenzene | 250 | 121 | Methyl ethyl ketone | 240 | 116 |
| Chloroform | 130 | 54 | Methyl isobutyl ketone | 110 | 42 |
| Chlorosulfonic acid | x | x | Nitric acid 5% | x | x |
| Chromic acid 10% | x | x | Nitric acid 20% | x | x |
| Chromic acid 50% | x | x | Nitric acid 70% | x | x |
| Citric acid 15% | 200 | 93 | Nitric acid, anhydrous | x | x |
| Citric acid, conc. | 200 | 93 | Nitrous acid, concentrated | x | x |
| Copper cyanide | 80 | 27 | Perchloric acid 10% | x | x |
| Copper sulfate | 140 | 60 | Perchloric acid 70% | x | x |
| Cresol | x | x | Phenol | x | x |
| Cupric chloride 5% | x | x | Phosphoric acid 50–80% | x | x |
| Cupric chloride 50% | x | x | Picric acid | x | x |
| Cyclohexane | 250 | 121 | Salicylic acid | 80 | 27 |
| Cyclohexanol | 250 | 121 | Sodium carbonate | 240 | 116 |
| Dichloroacetic acid | x | x | Sodium chloride | 230 | 110 |
| Dichloroethane | | | Sodium hydroxide 10% | 250 | 121 |
| (ethylene dichloride) | 80 | 27 | Sodium hydroxide 50% | 250 | 121 |
| Ethylene glycol | 200 | 93 | Sodium hypochlorite 20% | x | x |
| Ferric chloride | x | x | Sodium hypochlorite, | | |
| Ferric chloride 50% in water | x | x | concentrated | x | x |
| Ferric nitrate 10–50% | x | x | Sodium sulfide to 50% | 230 | 110 |
| Ferrous chloride | x | x | Stannic chloride | 80 | 27 |
| Fluorine gas, dry | x | x | Stannous chloride | x | x |
| Fluorine gas, moist | x | x | Sulfuric acid 10% | x | x |
| Hydrobromic acid, dilute | x | x | Sulfuric acid 50% | x | x |
| Hydrobromic acid 20% | x | x | Sulfuric acid 70% | x | x |
| Hydrobromic acid 50% | x | x | Sulfuric acid 90% | x | x |
| Hydrochloric acid 20% | x | x | Sulfuric acid 98% | x | x |
| Hydrochloric acid 38% | x | x | Sulfuric acid 100% | x | x |
| Hydrocyanic acid 10% | x | x | Sulfuric acid, fuming | x | x |
| Hydrofluoric acid 30% | x | x | Sulfurous acid | x | x |
| Hydrofluoric acid 70% | x | x | Thionyl chloride | x | x |
| Hydrofluoric acid 100% | x | x | Toluene | 200 | 93 |
| Ketones, general | 150 | 66 | Trichloroacetic acid | x | x |
| Lactic acid 25% | 200 | 93 | White liquor | 80 | 27 |
| Lactic acid, concentrated | 200 | 93 | Zinc chloride | x | x |
| Magnesium chloride | 240 | 116 | | | |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that the data are unavailable.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols 1–3. New York: Marcel Dekker, 1995.

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## POLYAMIDE/ACRYLONITRILE-BUTADIENE-STYRENE ALLOY

See "Triax."

## POLYAMIDE ELASTOMERS

Polyamides are produced under a variety of trade names, the most popular of which are the nylons (nylon 6, etc.) manufactured by DuPont. Although the polyamides find their greatest use as textile fibers, they can also be formulated into thermoplastic molding compounds with many attractive properties. Their relatively high price tends to restrict their use.

There are many varieties of polyamides in production, but the four major types are nylon 6, nylon 6/6, nylon 11, and nylon 12. Of these, nylon 11 and 12 find application as elastomeric materials.

### Physical and Mechanical Properties

The polyamide materials have an unusual combination of high tensile strength, ductility, and toughness. They can withstand extremely high impact, even at extremely low temperatures. According to ASTM test D-746, the cold brittleness temperature is –94°F (–74°C). Nylons 11 and 12 have an extremely high elastic memory that permits them to withstand repeated stretching and flexing over long periods of time. They also exhibit good abrasion resistance. Their absorption of moisture is very low, which means that parts produced from these materials will have good dimensional stability regardless of the humidity of the environment. Moisture also has little effect on the mechanical properties, particularly the modulus of elasticity.

The electrical insulation properties of polyamides grade 11 and grade 12 are good. They have a stable volume resistivity and offer excellent resistance to tracking. These materials are also self-extinguishing.

The physical and mechanical properties of the polyamides are given in Table P.13.

**Table P.13** Physical and Mechanical Properties of the Polyamide Elastomers[a]

| | Grade 11 | Grade 12 |
|---|---|---|
| Specific gravity | 1.03–1.05 | 1.01–1.02 |
| Specific heat, Btu/lb-°F | 0.3–0.5 | |
| Thermal conductivity | | |
| $10^{-4}$ cal/cm-s-°C | 5.2 | 5.2 |
| Btu/h-ft$^2$-°F-in. | 1.5 | 1.5 |
| Coefficient of linear thermal expansion | | |
| $10^{-5}$/°C | 10.0 | 10.0 |
| $10^{-5}$/°F | 5.1 | 5.3 |
| Continuous service temperature | | |
| °F | 180–300 | 180–250 |
| °C | 82–149 | 82–121 |
| Brittle point | | |
| °F | –94 | —[b] |
| °C | –70 | —[b] |
| Volume resistivity, ohm-cm | $10^{13}$ | $10^{13}$ |

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**Table P.13** Physical and Mechanical Properties of the Polyamide Elastomers[a] (Continued)

| | Grade 11 | Grade 12 |
|---|---|---|
| Dielectric strength (3 mm thick) | 17 | 18 |
| Dielectric constant at $10^3$–$10^6$ Hz | 3.2–3.7 | 3.8 |
| Dissipation factor | 0.05 | $5 \times 10^{12}$ |
| Water absorption, % | 0.3 | 0.25 |
| Tensile strength, psi | 8000 | 8000–9500 |
| Elongation, % at break | 300 | 300 |
| Hardness, Rockwell | R108 | R106–R109 |
| Abrasion resistance | Good | Good |
| Impact resistance, kg-cm/cm | 9.72 | 10.88–29.92 |
| Resistance to compression set | Good | Good |
| Tear resistance | Good | Good |
| Machining qualities | Can be machined | |
| Resistance to sunlight | Good | Good |
| Effect of aging | Nil | Nil |
| Resistance to heat | Good | Good |

[a]These are representative values since they may be altered by compounding.
[b]Data not available.

## Resistance to Sun, Weather, and Ozone

The polyamides are resistant to sun, weather, and ozone. Many metals are coated with polyamide to provide protection from harsh weather.

## Chemical Resistance

The polyamides exhibit excellent resistance to a broad range of chemicals and harsh environments. They have good resistance to most inorganic alkalies, particularly ammonium hydroxide and ammonia, even at elevated temperatures, and to sodium and potassium hydroxide at ambient temperatures. They also display good resistance to almost all inorganic salts and almost all hydrocarbons and petroleum-based fuels.

They are also resistant to organic acids, such as citric, lactic, oleic, oxalic, stearic, tartaric, and uric, and most aldehydes and ketones at normal temperatures. They display limited resistance to hydrochloric, sulfonic, and phosphoric acids at ambient temperatures. Refer to Table P.12 for the compatibility of the polyamides with selected corrodents.

## Applications

The polyamides find many diverse applications resulting from their many advantageous properties. A wide range of flexibility permits material to be produced that is soft enough for high-quality bicycle seats and other materials whose strength and rigidity are comparable to those of many metals. Superflexible grades are also available that are used for shoe soles, gaskets, diaphragms, and seals. Because of the high elastic memory of the polyamides, these parts can withstand repeated stretching and flexing over long periods of time.

Since the polyamides can meet specification SAE J844 for airbrake hose, coiled tubing is produced for this purpose for use on trucks. Coiled airbrake hose produced from this material has been used on trucks that have traveled over 2 million miles without a single reported failure. High-pressure hose and fuel lines are also produced from this material.

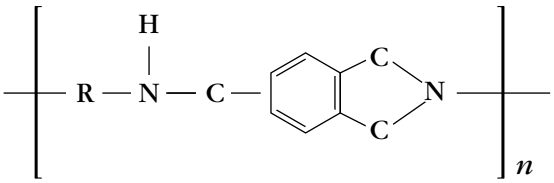
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Corrosion-resistant and wear-resistant coverings for aircraft control cables, automotive cables, and electrical wire are also produced.

See Refs. 7 and 8.

## POLYAMIDE-IMIDE (PAI)

Polyamide-imides are heterocyclic polymers that have an atom of nitrogen in one of the rings of the molecular chain. A typical chemical structure is shown below:




This series of thermoplasts can be used at high and low temperatures and as such finds applications in the extreme environments of space. The temperature range is from –310 to 500°F (–190 to 260°C). The polyamide-imides possess excellent electrical and mechanical properties that are relatively stable from low negative temperatures to high positive temperatures. The physical and mechanical properties are shown in Table P.14.

**Table P.14** Physical and Mechanical Properties of PAI

| Property | Unfilled | Wear-resistant grade | 30% glass-fiber reinforced |
|---|---|---|---|
| Specific gravity | 1.42 | 1.50 | 1.61 |
| Water absorption (24 h at 73°F/23°C) (%) | | | |
| Dielectric strength, short-term (V/mil) | 580 | | 840 |
| Tensile strength at break (psi) | | | |
| Tensile modulus ($\times 10^3$ psi) | 700 | 870 | 1,560 |
| Elongation at break (%) | 15 | 9 | 7 |
| Compressive strength (psi) | 32,100 | 18,300 | 38,300 |
| Flexural strength (psi) | 34,900 | 27,000 | 48,300 |
| Compressive modulus ($\times 10^3$ psi) | | | 1,150 |
| Flexural modulus ($\times 10^3$ psi) at | | | |
| 73°F/23°C | 730 | 910 | 1,700 |
| 200°F/93°C | | | |
| 250°F/121°C | | | |
| lzod impact (ft-lb/in. of notch) | 2.7 | 1.3 | 1.5 |
| Hardness, Rockwell | E86 | E66 | E94 |
| Coefficient of thermal expansion ($10^{-6}$ in./in./°F) | 30.6 | 15 | 16.2 |
| Thermal conductivity ($10^{-4}$cal-cm/s-cm$^2$ °C or Btu/hr/ft$^2$/°F/in.) | 6.2 | | 8.8 |
| Deflection temperature at 264 psi (°F) at 66 psi (°F) | 532 | 532 | 539 |
| Max. operating temperature (°F/°C) | 500/260 | | |
| Limiting oxygen index (%) | | | |
| Flame spread | | | |
| Underwriters Lab rating (Sub. 94) | | | |

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**Table P.15** Compatibility of PAI with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetic acid 10% | 200 | 93 | Cellosolve | 200 | 93 |
| Acetic acid 50% | 200 | 93 | Chlorobenzene | 200 | 93 |
| Acetic acid 80% | 200 | 93 | Chloroform | 120 | 49 |
| Acetic acid glacial | 200 | 93 | Chromic acid 10% | 200 | 93 |
| Acetic anhydride | 200 | 93 | Cyclohexane | 200 | 93 |
| Acetone | 80 | 27 | Cyclohexanol | 200 | 93 |
| Acetyl chloride, dry | 120 | 49 | Dibutyl phthalate | 200 | 93 |
| Aluminum sulfate 10% | 220 | 104 | Ethylene glycol | 200 | 93 |
| Ammonium chloride 10% | 200 | 93 | Hydrochloric acid 20% | 200 | 93 |
| Ammonium hydroxide 25% | 200 | 93 | Hydrochloric acid 38% | 200 | 93 |
| Ammonium hydroxide, sat. | 200 | 93 | Lactic acid 25% | 200 | 93 |
| Ammonium nitrate 10% | 200 | 93 | Lactic acid, conc. | 200 | 93 |
| Ammonium sulfate 10% | 200 | 93 | Magnesium chloride, dry | 200 | 93 |
| Amyl acetate | 200 | 93 | Methyl ethyl ketone | 200 | 93 |
| Aniline | 200 | 93 | Oleum | 120 | 49 |
| Barium chloride 10% | 200 | 93 | Sodium carbonate 10% | 200 | 93 |
| Benzaldehyde | 200 | 93 | Sodium chloride 10% | 200 | 93 |
| Benzene | 80 | 27 | Sodium hydroxide 10% | x | x |
| Benzene sulfonic acid 10% | x | x | Sodium hydroxide 50% | x | x |
| Benzyl chloride | 120 | 49 | Sodium hydroxide, conc. | x | x |
| Bromine gas, moist | 120 | 49 | Sodium hypochlorite 10% | 200 | 93 |
| Butyl acetate | 200 | 93 | Sodium hypochlorite, conc. | x | x |
| Butyl alcohol | 200 | 93 | Sodium sulfide to 50% | x | x |
| *n*-Butylamine | 200 | 93 | Sulfuric acid 10% | 200 | 93 |
| Calcium chloride | 200 | 93 | Sulfuric acid, fuming | 120 | 49 |
| Calcium hypochlorite | x | x | Toluene | 200 | 93 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x.
*Source:* Schweitzer, PA. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

PAI is resistant to acetic acid and phosphoric acid up to 35% and sulfuric acid to 30%. It is not resistant to UV light degradation. Refer to Table P.15 for the compatibility of PAI with selected corrodents.

PAI finds applications in under-the-hood applications and as bearings and pistons in compressors.

## POLYBUTADIENE RUBBER (BR)

Butadiene ($CH_2 = CH - CH = CH_2$) has two unsaturated linkages and can be polymerized readily. When butadiene or its derivatives become polymerized, the units link together to form long chains that contain over 1000 units. Simple butadiene does not yield a good grade of rubber, apparently because the chains are too smooth. Better results are obtained by introducing side groups into the chains either by modifying butadiene or by making a copolymer of butadiene and some other compound.

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**Table P.16** Physical and Mechanical Properties of Polybutadiene (BR)[a]

| | |
|---|---|
| Specific gravity | 0.94 |
| Specific heat, cal/g | 0.45 |
| Brittle point | –68°F (–56°C) |
| Insulation resistance, ohms/cm | $10^{17}$ |
| Coefficient of linear expansion at 32–140°F, in./in.-°F | 0.000036 |
| Dielectric constant at 50 Hz | 2.9 |
| Power factor at 50 Hz | $7 \times 10^{-4}$ |
| Swelling, % by volume | |
| in kerosene at 77°F (25°C) | 200 |
| in benzene at 77°F (25°C) | 200 |
| in acetone at 77°F (25°C) | 25 |
| in mineral oil at 100°F (38°C) | 120 |
| Tensile strength, psi | 2000–3000 |
| Elongation, % at break | 700–750 |
| Hardness, Shore A | 45–80 |
| Abrasion resistance | Excellent |
| Maximum temperature, continuous use | 200°F (93°C) |
| Impact resistance | Excellent |
| Compression set | Good |
| Resilience, % | 90 |
| Tear resistance, psi | 1600 |
| Machining qualities | Can be ground |
| Resistance to sunlight | Deteriorates |
| Resistance to heat | Poor |

[a]These are representative values since they may be altered by compounding.

## Physical and Mechanical Properties

Polybutadiene, designated BR, is very similar to the butadiene–styrene rubbers but is extremely difficult to process. As a result, it is widely used as an admixture with Buna-S and other elastomers. It is rarely used in an amount larger than 75% of the total polymer in a compound.

It has outstanding properties of resilience and hysteresis, almost equivalent to that of natural rubber, excellent abrasion resistance, and good resistance to water adsorption and heat aging. It also possesses good electrical properties. Its tensile strength, tear tolerance, and impermeability are all good. Polyhutadiene has an operating temperature range only slightly greater than that of natural rubber, ranging from –150 to 200°F (–101 to 93°C).

Polybutadiene will burn and has poor flame resistance. Its physical and mechanical properties are given in Table P.16.

## Resistance to Sun, Weather, and Ozone

Although polybutadiene has good weather resistance, it will deteriorate when exposed to sunlight for prolonged periods of time. It also exhibits poor resistance to ozone.

## Chemical Resistance

The chemical resistance of polybutadiene is similar to that of natural rubber. It shows poor resistance to aliphatic and aromatic hydrocarbons, oil, and gasoline but displays fair

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to good resistance in the presence of mineral solids and oxygenated compounds. Refer to Table P.17 for the compatibility of polybutadiene with selected corrodents.

**Table P.17** Compatibility of Polybutadiene (BR) with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Alum | 90 | 32 | Nitric acid 10% | 80 | 27 |
| Alum ammonium | 90 | 32 | Nitric acid 20% | 80 | 27 |
| Alum ammonium sulfate | 90 | 32 | Nitric acid 30% | 80 | 27 |
| Alum chrome | 90 | 32 | Nitric acid 40% | x | x |
| Alum potassium | 90 | 32 | Nitric acid 50% | x | x |
| Aluminum chloride, aqueous | 90 | 32 | Nitric acid 70% | x | x |
| Aluminum sulfate | 90 | 32 | Nitric acid, anhydrous | x | x |
| Ammonia gas | 90 | 32 | Nitrous acid, concentrated | 80 | 27 |
| Ammonium chloride 10% | 90 | 32 | Ozone | x | x |
| Ammonium chloride 28% | 90 | 32 | Phenol | 80 | 27 |
| Ammonium chloride 50% | 90 | 32 | Sodium bicarbonate 20% | 90 | 32 |
| Ammonium chloride, saturated | 90 | 32 | Sodium bisulfate | 80 | 27 |
| Ammonium nitrate | 90 | 32 | Sodium bisulfite | 90 | 32 |
| Ammonium sulfate 10–40% | 90 | 32 | Sodium carbonate | 90 | 32 |
| Calcium chloride, saturated | 80 | 27 | Sodium chlorate | 80 | 27 |
| Calcium hypochlorite, saturated | 90 | 32 | Sodium hydroxide 10% | 90 | 32 |
| Carbon dioxide, wet | 90 | 32 | Sodium hydroxide 15% | 90 | 32 |
| Chlorine gas, wet | x | x | Sodium hydroxide 30% | 90 | 32 |
| Chrome alum | 90 | 32 | Sodium hydroxide 50% | 90 | 32 |
| Chromic acid 10% | x | x | Sodium hydroxide 70% | 90 | 32 |
| Chromic acid 30% | x | x | Sodium hydroxide, concentrated | 90 | 32 |
| Chromic acid 40% | x | x | Sodium hypochlorite to 20% | 90 | 32 |
| Chromic acid 50% | x | x | Sodium nitrate | 90 | 32 |
| Copper chloride | 90 | 32 | Sodium phosphate, acid | 90 | 32 |
| Copper sulfate | 90 | 32 | Sodium phosphate, alkaline | 90 | 32 |
| Fatty acids | 90 | 32 | Sodium phosphate, neutral | 90 | 32 |
| Ferrous chloride | 90 | 32 | Sodium silicate | 90 | 32 |
| Ferrous sulfate | 90 | 32 | Sodium sulfide to 50% | 90 | 32 |
| Hydrochloric acid, dilute | 80 | 27 | Sodium sulfite 10% | 90 | 32 |
| Hydrochloric acid 20% | 90 | 32 | Sodium dioxide, dry | x | x |
| Hydrochloric acid 35% | 90 | 32 | Sulfur trioxide | 90 | 32 |
| Hydrochloric acid 38% | 90 | 32 | Sulfuric acid 10% | 80 | 27 |
| Hydrochloric acid 50% | 90 | 32 | Sulfuric acid 30% | 80 | 27 |
| Hydrochloric acid fumes | 90 | 32 | Sulfuric acid 50% | 80 | 27 |
| Hydrogen peroxide 90% | 90 | 32 | Sulfuric acid 60% | 80 | 27 |
| Hydrogen sulfide, dry | 90 | 32 | Sulfuric acid 70% | 90 | 32 |
| Nitric acid 5% | 80 | 27 | Toluene | x | x |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that the data are unavailable.
*Source:* Schweitzer, PA. *Corrosion Resistance Tables.* 4th ed. Vols l–3. New York: Marcel Dekker, 1995.

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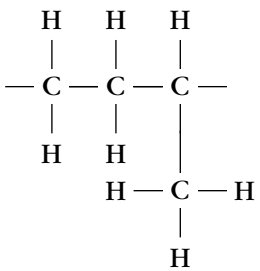
### Applications

Very rarely is polybutadiene used by itself. It is generally used as a blend with other elastomers to impart better resiliency, abrasion resistance, and/or low-temperature properties, particularly in the manufacture of automobile tire treads, shoe heels and soles, gaskets, seals, and belting.

See Refs. 7 and 8.

## POLYBUTYLENE (PB)

Polybutylene is a semicrystalline polyolefin thermoplastic based on poly-1-butene and includes homopolymers and a series of copolymers (butene/ethylene). This thermoplast possesses the combination of stress cracking resistance, chemical resistance, and abrasion resistance. Its structural formula is



Polybutylene maintains its mechanical properties at elevated temperatures. Its long-term strength is greater than that of high-density polyethylene. Polybutylene has an upper temperature limit of 200°F (93°C). It possesses a combination of stress cracking resistance, chemical resistance, and abrasion resistance. Refer to Table P.18 for the physical and mechanical properties of polybutylene. Polybutylene is resistant to acids, bases, soaps, and detergents. It is partially soluble in aromatic and chlorinated hydrocarbons above 140°F (60°C) and is not completely resistant to aliphatic solvents at room temperature. Chlorinated water will cause pitting attack, and therefore it should not be used to handle potable water that has been chlorinated. Refer to Table P.19 for the compatibility of polybutylene with selected corrodents.

Applications include piping, chemical process equipment, and fly ash and bottom ash lines containing abrasive slurries. It is also used for molded appliance parts.

**Table P.18** Physical and Mechanical Properties of PB

| Property | |
|---|---|
| Specific gravity | 0.91–0.925 |
| Water absorption (24 h at 73°F/23°C) (%) | 0.01–0.02 |
| Dielectric strength, short-term (V/mil) | >450 |
| Tensile strength at break (psi) | 3800–4400 |
| Tensile modulus ($\times 10^3$ psi) | 30–40 |
| Elongation at break (%) | 300–380 |

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**Table P.18** Physical and Mechanical Properties of PB (Continued)

| Property | |
|---|---|
| Compressive strength (psi) | |
| Flexural strength (psi) | 2000–2300 |
| Compressive modulus ($\times 10^3$ psi) | 31 |
| Flexural modulus ($\times 10^3$ psi) | |
| at 73°F/23°C | 40–50 |
| at 200°F/93°C | |
| at 250°F/121°C | |
| Izod impact (ft-lb/in. of notch) | No break |
| Hardness, Rockwell | |
| Coefficient of thermal expansion ($10^{-6}$ in./in./ °F) | 128–150 |
| Thermal conductivity ($10^{-4}$cal-cm/s-cm$^2$ °C or Btu/h/ft$^2$/°F/in.) | 5.2 |
| Deflection temperature at 264 psi (°F) | 130–140 |
| at 66 psi (°F) | 215–235 |
| Max. operating temperature (°F/°C) | 200–93 |
| Limiting oxygen index (%) | |
| Flame spread | |
| Underwriters Lab rating (Sub. 94) | |

**Table P.19** Compatibility of PB with Selected Corrodents[a]

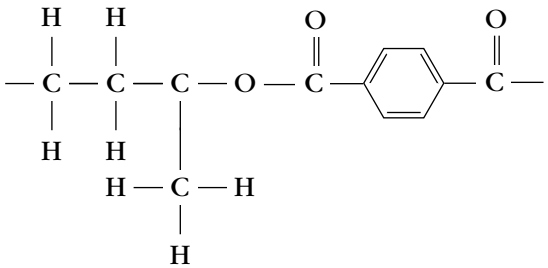
| | | | |
|---|---|---|---|
| Acetic acid | R | Citric acid | R |
| Acetic anhydride | R | Cyclohexane | R |
| Allyl alcohol | x | Detergents | R |
| Aluminum chloride | x | Lactic acid | R |
| Ammonium chloride | x | Malic acid | R |
| Ammonium hydroxide | R | Methyl alcohol | x |
| Amyl alcohol | x | Phenol | R |
| Aniline | R | Picric acid | R |
| Benzaldehyde | R | Propyl alcohol | x |
| Benzene | R | Salicylic acid | R |
| Benzoic acid | R | Soaps | R |
| Boric acid | R | Sodium carbonate | R |
| Butyl alcohol | x | Sodium hydroxide 10% | R |
| Calcium carbonate | R | Sodium hydroxide 50% | R |
| Calcium hydroxide | R | Toluene | R |
| Calcium sulfate | R | Trichloroacetic acid | R |
| Carbonic acid | R | Water (chlorine free) | R |
| Chloracetic acid | R | Xylene | R |
| Chlorobenzene | R | | |

[a]Materials are in the pure state or in a saturated solution unless otherwise specified. R = PB is resistant at 70°F/23°C; x = PB is not resistant.

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## POLYBUTYLENE TEREPHTHALATE (PBT)

PBT is known as a thermoplastic polyester. These thermoplastic polyesters are highly crystalline with a melting point of approximately 430°F (221°C). It has a structural formula as follows:



PBT is fairly translucent in its molded sections and opaque in thick sections but can be extruded into a thin, transparent film. It is available in both unreinforced and reinforced formulations. Unreinforced resins generally

1. Are hard, strong, and extremely tough.
2. Have good chemical resistance, very low moisture absorption, and resistance to cold flow.
3. Have high abrasion resistance and a low coefficient of friction.
4. Have good stress crack and fatigue resistance.
5. Have good electrical properties.
6. Have good surface appearance.

Electrical properties are good up to the rated temperature limits.

The glass-reinforced thermoplastics are unique in that they are the first thermoplastics that can compare with, or are better than, thermoset polymers in electrical, mechanical, dimensional, and creep properties at elevated temperatures (approximately 300°F [149°C]) while having superior impact properties. Refer to Table P.20 for the physical and mechanical properties of PBT.

**Table P.20** Physical and Mechanical Properties of PBT

| Property | Unfilled | 30% glass-fiber reinforced | 30% glass-fiber reinforced flame-retardant grade |
|---|---|---|---|
| Specific gravity | 1.30–1.38 | 1.48–1.58 | 1.63 |
| Water absorption (24 h at 73°F/23°C) (%) | 0.08–0.09 | 0.06–0.08 | 0.06–0.07 |
| Dielectric strength, short-term (V/mil) | 550 | 460–560 | 490 |
| Tensile strength at break (psi) | 8200–8700 | 1400–19,000 | 17,400–20,000 |
| Tensile modulus ($\times 10^3$ psi) | 280–435 | 1300–1450 | 1490–1700 |
| Elongation at break (%) | 50–300 | 2–4 | 2.0–3.0 |
| Compressive strength (psi) | 8600–14,500 | 18,000–23,500 | 18,000 |
| Flexural strength (psi) | 12,000–16,700 | 22,000–29,000 | 30,000 |

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**Table P.20** Physical and Mechanical Properties of PBT (Continued)

| Property | Unfilled | 30% glass-fiber reinforced | 30% glass-fiber reinforced flame-retardant grade |
|---|---|---|---|
| Compressive modulus ($\times 10^3$ psi) | 375 | 700 | |
| Flexural modulus ($\times 10^3$ psi) | | | |
| at 73°F/23°C | 330–400 | 850–1200 | 1300–1500 |
| at 200°F/93°C | | | |
| at 250°F/121°C | | | |
| Izod impact (ft-lb/in. of notch) | 0.7–1.0 | 0.9–2.0 | 1.3–1.6 |
| Hardness, Rockwell | M68–78 | M90 | M88–90 |
| Coefficient of thermal expansion ($10^{-6}$ in./in./°F) | 60–90 | 15–25 | |
| Thermal conductivity ($10^{-4}$cal-cm/s-cm$^2$°C or Btu/h/ft$^2$/°F/in.) | 4.2–6.9 | 7.0 | |
| Deflection temperature | | | |
| at 264 psi (°F) | 122–185 | 385–437 | 400–450 |
| at 66 psi (°F) | 240–375 | 421–500 | 425–490 |
| Max. operating temperature (°F/°C) | | | |
| Limiting oxygen index (%) | | | |
| Flame spread | | | |
| Underwriters Lab rating (Sub. 94) | | | |

PBT exhibits good chemical resistance in general to dilute mineral acids, aliphatic hydrocarbons, aromatic hydrocarbons, ketones, and esters with limited resistance to hot water and washing soda. It is not resistant to chlorinated hydrocarbons and alkalies.

PBT has good weatherability and is resistant to UV degradation. Refer to Table P.21 for the compatibility of PBT with selected corrodents.

**Table P.21** Compatibility of PBT with Selected Corrodents[a]

| Chemical | | Chemical | |
|---|---|---|---|
| Acetic acid 5% | R | Ethanol | R |
| Acetic acid 10% | R | Ether | R |
| Acetone | R | Ethyl acetate | R |
| Ammonia 10% | x | Ethylene chloride | x |
| Benzene | R | Ethylene glycol | R |
| Butyl acetate | R | Formic acid | R |
| Calcium chloride | R | Fruit juice | R |
| Calcium disulfide | R | Fuel oil | R |
| Carbon tetrachloride | R | Gasoline | R |
| Chlorobenzene | x | Glycerine | R |
| Chloroform | x | Heptane/hexane | R |
| Citric acid 10% | R | Hydrochloric acid 2% | R |
| Diesel oil | R | Hydrochloric acid 38% | x |
| Dioxane | R | Hydrogen peroxide 0–5% | R |
| Edible oil | R | Hydrogen peroxide 30% | R |

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**Table P.21** Compatibility of PBT with Selected Corrodents[a] (Continued)

| Chemical | | Chemical | |
|---|---|---|---|
| Ink | R | Sodium bisulfite | R |
| Linseed Oil | R | Sodium carbonate | R |
| Methanol | R | Sodium chloride 10% | R |
| Methyl ethyl ketone | R | Sodium hydroxide 50% | x |
| Methylene chloride | x | Sodium nitrate | R |
| Motor oil | R | Sodium thiosulfate | R |
| Nitric acid 2% | R | Sulfuric acid 2% | R |
| Paraffin oil | R | Sulfuric acid 98% | x |
| Phosphoric acid 10% | R | Toluene | R |
| Potassium dichromate 10% | R | Vaseline | R |
| Potassium hydroxide 50% | x | Water, cold | R |
| Potassium permanganate 10% | R | Water, hot | R |
| Silicone oil | R | Wax, molten | R |
| Soap solution | R | Xylene | R |

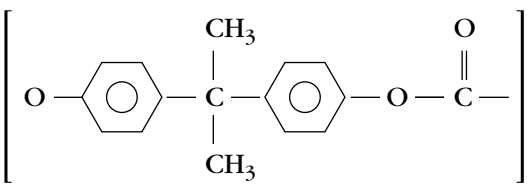
[a]R = Material resistant at 73°F/20°C; x = material not resistant.

The unreinforced resins are used in housings that require excellent impact resistance and in moving parts such as gears, bearings, pulleys, and writing instruments. Flame-retardant formulations find application as television, radio, electronics, business machine, and pump components.

Reinforced resins find application in the automotive, electrical, electronic, and general industrial areas.

## POLYCARBONATE (PC)

This thermoplast is produced under the trade name Lexan by GE Plastics. Its structure is



Because of its extremely high impact resistance and good clarity, it is widely used for windows in chemical equipment and glazing in chemical plants. The exceptional weather ability, corrosion resistance, and high impact strength give it wide use in outdoor energy management devices, network interfaces, electrical wiring blocks, telephone equipment, lighting diffusers, globes, and housings. Table P.22 provides the physical and mechanical properties of PC.

Polycarbonate is resistant to aliphatic hydrocarbons and weak acids and has limited resistance to weak alkalies. It is resistant to most oils and greases. PC will be attacked by strong alkalies and strong acids and is soluble in ketones, esters, and aromatic and chlorinated hydrocarbons.

See Refs. 15 and 16.

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**Table P.22** Physical and Mechanical Properties of PC

| | |
|---|---|
| Specific gravity | 1.2 |
| Water absorption, 24 h at 73°F/23°C, % | 0.15–0.2 |
| Tensile strength at 73°F/23°C, psi $\times 10^3$ | 8–9.5 |
| Modulus of elasticity at 73°F/23°C $\times 10^5$ psi | 3.2–4.5 |
| Compressive strength, psi $\times 10^3$ | 10–14 |
| Flexural strength, psi $\times 10^3$ | 11.5–15 |
| Izod impact strength, notched at 73°F/23°C, ft-lb/in. | 4–16 |
| Coefficient of linear thermal expansion, in./in. °F $\times 10^{-5}$ | 1.79–3.9 |
| Thermal conductivity, Btu/h/ft$^2$/°F/in. | 1.33–1.41 |
| Heat distortion temperature, °F/ °C | |
| at 66 psi | 285/140 |
| at 264 psi | 265/129 |
| Limiting oxygen index, % | 25–31.5 |
| Underwriters Lab rating, Sub 94 | SEO-SEI |

## POLYCARBONATE/ACRYLONITRILE-BUTADIENE-STYRENE ALLOY

See "Cycoloy."

## POLYCARBONATE/POLYBUTYLENE-TEREPHTHALATE ALLOY

See "Xenoy."

## POLYCHLOROPRENE

See "Neoprene."

## POLYESTER (PE) ELASTOMER

This elastomer combines characteristics of thermoplastics and elastomers. It is structurally strong, resilient, and resistant to impact and flexural fatigue. Physical and mechanical properties vary depending upon the hardness of the elastomer. Hardnesses range from 40 to 72 on the Shore D scale. The standard hardnesses to which PE elastomers are formulated are 40, 55, 63, and 72 Shore D. Combined are such features as resilience, high resistance to deformation under moderate strain conditions, outstanding flex-fatigue resistance, good abrasion resistance, retention of flexibility at low temperatures, and good retention of properties at elevated temperatures. Polyester elastomers can successfully replace other thermoset rubbers at lower cost in many applications by taking advantage of their higher strength and using thinner cross-sections.

### Physical and Mechanical Properties

When modulus is an important design consideration, thinner sections of PE elastomer can be used, since its tensile stress at low strain shows higher modulus values than other elastomeric materials. Polyester elastomers yield at approximately 25%

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strain, and beyond the yield point they elongate to 300–500% with some permanent set. To take full advantage of the elastomeric properties of PE, parts should be designed to function with deformations that do not exceed the yield point (up to approximately 20% strain).

The Bashore resilience of PE exceeds 60% for the 40D hardness grade. Even as the hardness approaches that of plastics (63D), these materials still have a resilience of 40%.

The load-bearing properties of PE elastomers under compression are good. As the hardness increases, so does the compression modulus. The compression modulus of PE elastomers is 50–100% greater than that of other rubbers of comparable hardness.

Table P.23 lists the compression set of PE elastomers at constant load (1350 psi) and at varying temperatures. These conditions were chosen because they very closely simulate the conditions under which parts fabricated from PE elastomers operate. The compression set of these rubbers measured for 22 h at 158°F (70°C) with a constant deflection of 25% is 60% for materials having a hardness of 40D and 56% for materials of 55D hardness. Because of the high load-bearing capability of these elastomers, the majority of compression applications employ deflections well below 25%. At 25% deflection, most formulations of PE elastomers are deformed beyond their yield point, or at least beyond the limits of good design practice. Under these conditions, PE elastomers are generally comparable to urethane elastomers. Annealing of PE parts will reduce the compression set values to 40% or less with a 25% deflection.

Very little hysteresis loss is exhibited by PE elastomers when they are stressed below the yield point. Applications at low strain levels can usually be expected to exhibit complete recovery and continue to do so in cyclic applications with little heat buildup. Because of the high resilience and low heat buildup of these elastomers, their resistance to cut growth is outstanding. This means that a part made of PE, engineered to operate at low strain levels, can usually be expected to exhibit complete recovery from deformation and to continue to do so under repeated cycling for extremely long periods of time without heat buildup or distortion.

The mechanical properties of these elastomers are maintained up to 302°F (150°C), better than many rubbers, particularly the harder polymers. Above 248°F (120°C) their tensile strengths far exceed those of other rubbers. Their hot strength and good resistance to hot fluids make PE elastomers suitable for many applications involving fluid containment.

All of the PE formulations have brittle points below –94°F (–70°C) and exhibit high impact strength and resistance to stiffening at temperatures down to –40°F (–40°C). As would be expected, the softer members exhibit the better low-temperature flexibility.

The physical and mechanical properties of polyester elastomers are given in Table P.23.

## Resistance to Sun, Weather, and Ozone

The polyester rubbers possess excellent resistance to ozone. When formulated with appropriate additives, their resistance to sunlight aging is very good. Resistance to general weathering is good.

## Chemical Resistance

In general, the fluid resistance of polyester rubbers increases with increasing hardness. Since these rubbers contain no plasticizers, they are not susceptible to the solvent extraction or

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**Table P.23** Physical and Mechanical Properties of Polyester Elastomer[a]

| | |
|---|---|
| Specific gravity | 1.17–1.25 |
| Brittle point | –94°F (–70°C) |
| Resilience, % | 42–62 |
| Coefficient of linear expansion, in./in.-°C | $2 \times 10^{-5}$ –$21 \times 10^{-5}$ |
| Dielectric strength, V/mil | 645–900 |
| Dielectric constant at 1 kHz | 4.16–6 |
| Permeability to air | Low |
| Tear strength | |
| lb/in. | 631–1055 |
| kn/m | 110–185 |
| Water absorption, %/24 h | 0.6–.03 |
| Tensile strength, psi | 3700–5700 |
| Elongation, % at break | 350–450 |
| Hardness, Shore D | 40–72 |
| Abrasion resistance | Good |
| Maximum temperature, continuous use | 302°F (150°C) |
| Impact resistance | Good |
| Compression set, % | |
| at 73°F (23°C) | 1–11 |
| at 158°F (70°C) | 2–27 |
| at 212°F (100°C) | 4–44 |
| Resistance to sunlight | Good |
| Effect of aging | Nil |
| Resistance to heat | Excellent |
| Flexural modulus, psi | 7000–75,000 |

[a]These are representative values since they may be altered by compounding.

heat volatilization of such additives. Many fluids and chemicals will extract plasticizers from elastomers, causing a significant increase in stiffness (modulus) and volume shrinkage.

Overall, PE elastomers are resistant to the same classes of chemicals and fluids as the polyurethanes are. However, PE has better high-temperature properties than the polyurethanes and can be used satisfactorily at higher temperatures in the same fluids.

Polyester elastomers have excellent resistance to nonpolar materials such as oils and hydraulic fluids, even at elevated temperatures. At room temperature, elastomers are resistant to most polar fluids, such as acids, bases, amines, and glycols. Resistance is very poor at temperatures of 158°F (70°C) or above. These rubbers should not be used in applications requiring continuous exposure to polar fluids at elevated temperatures.

Polyester elastomers also have good resistance to hot, moist atmospheres. Their hydrolytic stability can be further improved by compounding.

## Applications

Applications for PE elastomers are varied. Large quantities of PE materials are used for liners for tanks, ponds, swimming pools, and drums. Because of their low permeability to air, they are also used for inflatables. Their chemical resistance to oils and hydraulic fluids coupled with their high heat resistance make PE elastomers very suitable for automotive hose applications.

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Since the PE elastomers do not contain any plasticizers, hoses and tubing produced from them do not stiffen with age. Other PE products include seals, gaskets, specialty belting, noise damping devices, low-pressure tires, industrial solid tires, wire and cable jacketing, pump parts, electrical connectors, flexible shafts, sports equipment, piping clamps and cushions, gears, flexible couplings, and fasteners.

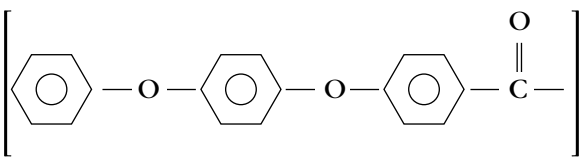
See Refs. 7 and 8.

## POLYESTER FIBERS

Polyester fibers are used primarily as a surfacing mat for the resin-rich inner surfaces of filament-wound or contact-molded thermoset structures. See "Thermoset Reinforcing Materials."

## POLYETHERETHERKETONE (PEEK)

PEEK is a thermoplast suitable for applications that require mechanical strength with the need to resist difficult thermal and chemical environments. Its chemical structure is




PEEK has a continuous maximum service temperature of 480°F (260°C) with excellent mechanical properties retained to temperatures over 570°F (300°C). Table P.24 gives the physical and mechanical properties of PEEK.

PEEK is insoluble in all common solvents and has excellent resistance to a wide range of organic and inorganic liquids. Refer to Table P.25 for the compatibility of PEEK with selected corrodents.

**Table P.24** Physical and Mechanical Properties of PEEK

| | |
|---|---|
| Specific gravity | 1.32 |
| Water absorption, 24 h at 73°F/23°C, % | 0.5 |
| Tensile strength at 73°F/23°C, psi | 14,500 |
| Modulus of elasticity in tension at 73°F/23°C × psi $10^{-5}$ | 4.9 |
| Compressive strength, psi | 17,100 |
| Flexural strength, psi | 24,650 |
| Izod impact strength, notched at 73°F/23°C, ft-lb/in. | 1.57 |
| Coefficient of thermal expansion in/in. °F × $10^{-5}$ | |
| at 0–290°F | 2.6 |
| at 290–500°F | 6.1 |
| Thermal conductivity, Btu/h/ft$^2$/°F/in. | 1.75 |
| Heat distortion temperature, °F/°C | |
| at 264 psi | 320/160 |
| Limiting oxygen index, % | 24 |
| Underwriters Lab rating, Sub 94 | V-O (1.45) |

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**Table P.25** Compatibility of PEEK with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | 80 | 27 | Hydrobromic acid 50% | x | x |
| Acetic acid 10% | 80 | 27 | Hydrochloric acid 20% | 100 | 38 |
| Acetic acid 50% | 140 | 60 | Hydrochloric acid 38% | 100 | 38 |
| Acetic acid 80% | 140 | 60 | Hydrofluoric acid 30% | x | x |
| Acetic acid, glacial | 140 | 60 | Hydrofluoric acid 70% | x | x |
| Acetone | 210 | 99 | Hydrofluoric acid 100% | x | x |
| Acrylic acid | 80 | 27 | Hydrogen sulfide, wet | 200 | 93 |
| Acrylonitrile | 80 | 27 | Ketones, general | 80 | 27 |
| Aluminum sulfate | 80 | 27 | Lactic acid 25% | 80 | 27 |
| Ammonia gas | 210 | 99 | Lactic acid, concentrated | 100 | 38 |
| Ammonium hydroxide, sat. | 80 | 27 | Magnesium hydroxide | 100 | 38 |
| Aniline | 200 | 93 | Methyl alcohol | 80 | 27 |
| Aqua regia 3:1 | x | x | Methyl ethyl ketone | 370 | 188 |
| Benzaldehyde | 80 | 27 | Naphtha | 200 | 93 |
| Benzene | 80 | 27 | Nitric acid 5% | 200 | 93 |
| Benzoic acid | 170 | 77 | Nitric acid 20% | 200 | 93 |
| Boric acid | 80 | 27 | Nitrous acid 10% | 80 | 27 |
| Bromine gas, dry | x | x | Oxalic acid 5% | x | x |
| Bromine gas, moist | x | x | Oxalic acid 10% | x | x |
| Calcium carbonate | 80 | 27 | Oxalic acid, saturated | x | x |
| Calcium chloride | 80 | 27 | Phenol | 140 | 60 |
| Calcium hydroxide, 10% | 80 | 27 | Phosphoric acid 50–80% | 200 | 93 |
| Calcium hydroxide, sat. | 100 | 38 | Potassium bromide 30% | 140 | 60 |
| Carbon dioxide, dry | 80 | 27 | Sodium carbonate | 210 | 99 |
| Carbon tetrachloride | 80 | 27 | Sodium hydroxide 10% | 220 | 104 |
| Carbonic acid | 80 | 27 | Sodium hydroxide 50% | 180 | 82 |
| Chlorine gas, dry | 80 | 27 | Sodium hydroxide, | | |
| Chlorine liquid | x | x | concentrated | 200 | 93 |
| Chlorobenzene | 200 | 93 | Sodium hypochlorite 20% | 80 | 27 |
| Chloroform | 80 | 27 | Sodium hypochlorite, | | |
| Chlorosulfonic acid | 80 | 27 | concentrated | 80 | 27 |
| Chromic acid 10% | 80 | 27 | Sulfuric acid 10% | 80 | 27 |
| Chromic acid 50% | 200 | 93 | Sulfuric acid 50% | 200 | 93 |
| Citric acid, conc. | 170 | 77 | Sulfuric acid 70% | x | x |
| Cyclohexane | 80 | 27 | Sulfuric acid 90% | x | x |
| Ethylene glycol | 160 | 71 | Sulfuric acid 98% | x | x |
| Ferrous chloride | 200 | 93 | Sulfuric acid 100% | x | x |
| Fluorine gas, dry | x | x | Sulfuric acid, fuming | x | x |
| Fluorine gas, moist | x | x | Toluene | 80 | 27 |
| Hydrobromic acid, dilute | x | x | Zinc chloride | 100 | 38 |
| Hydrobromic acid 20% | x | x | | | |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that the data are unavailable.
*Source:* Schweitzer, PA. *Corrosion Resistance Tables.* 4th ed. Vols 1–3. New York: Marcel Dekker, 1995.

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This thermoplast is not subject to hydrolysis at ambient or elevated temperatures in a continuous cycled environment, permitting the material to be steam sterilized using conventional sterilization equipment.

Like most linear polyaromatics, PEEK suffers from the effects of degradation during outdoor weathering. Painting or pigmenting the polymer will provide protection.

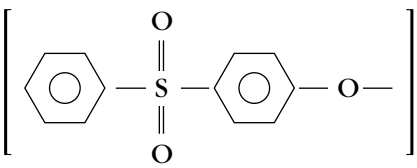
PEEK exhibits excellent resistance to hard (gamma) irradiation, absorbing over 1000 M rads of irradiation without suffering significant damage.

See Refs. 8 and 15.

## POLYETHERSULFONE (PES)

PES is a thermoplast that has a continuous maximum operating temperature of 390°F (200°C). At room temperature, PES is tough, rigid, and strong with outstanding long-term load-bearing properties. Most of these properties are retained at the maximum operating temperature. Table P.26 lists the physical and mechanical properties of PES.

It has the chemical structure



PES has excellent resistance to aliphatic hydrocarbons, some chlorinated hydrocarbons, and aromatics. It is also resistant to most inorganic chemicals. Hydrocarbon and mineral oils, greases, and transmission fluids have no effect on PES.

PES will be attacked by strong oxidizing acids, but glass fiber–reinforced grades are resistant to more dilute acids. It is soluble in highly polar solvents and is subject to stress cracking in ketones and esters.

PES is not resistant to outdoor weathering and is not recommended for outdoor applications unless stabilized by incorporating carbon black or unless painted.

Refer to Table P.27 for the compatibility of PES with selected corrodents.

**Table P.26** Physical and Mechanical Properties of PES

| | |
|---|---|
| Specific gravity | 1.51 |
| Tensile strength at 68°F/20°C, psi | 12,200 |
| Flexural strength, psi | 18,700 |
| Izod impact strength, notched at 73°F/23°C, ft-lb/in. | 1.57 |
| Coefficient of thermal expansion in./in. °F $\times 10^{-5}$ | 5.5 |
| Thermal conductivity, Btu/h/ft$^2$/°F/in. | 1.25 |
| Heat distortion temperature, °F/°C at 264 psi | 397/203 |
| Limiting oxygen index, % | 34 |
| Underwriters Lab rating, Sub 94 | V-O at 0.46 |

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**Table P.27** Compatibility of PES with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetic acid 10% | 80 | 27 | Nitric acid 5% | 80 | 27 |
| Acetic acid 50% | 140 | 60 | Nitric acid 20% | x | x |
| Acetic acid 80% | 200 | 93 | Oxalic acid 5% | 80 | 27 |
| Acetic acid, glacial | 200 | 93 | Oxalic acid 29% | 80 | 27 |
| Acetone | x | x | Oxalic acid, saturated | 80 | 27 |
| Ammonia, gas | 80 | 27 | Phenol | x | x |
| Aniline | x | x | Phosphoric acid 50–80% | 200 | 93 |
| Benzene | 80 | 27 | Potassium bromide 30% | 140 | 60 |
| Benzene sulfonic acid 10% | 100 | 38 | Sodium carbonate | 80 | 27 |
| Benzoic acid | 80 | 27 | Sodium chloride | 80 | 27 |
| Carbon tetrachloride | 80 | 27 | Sodium hydroxide 20% | 80 | 27 |
| Chlorobenzene | x | x | Sodium hydroxide 50% | 80 | 27 |
| Chlorosulfonic acid | x | x | Sodium hypochlorite 20% | 80 | 27 |
| Chromic acid 10% | x | x | Sodium hypochlorite, concentrated | 80 | 27 |
| Chromic acid 50% | x | x | Sulfuric acid 10% | 80 | 27 |
| Citric acid, concentrated | 80 | 27 | Sulfuric acid 50% | x | x |
| Ethylene glycol | 100 | 38 | Sulfuric acid 70% | x | x |
| Ferrous chloride | 100 | 38 | Sulfuric acid 90% | x | x |
| Hydrochloric acid 20% | 140 | 60 | Sulfuric acid 98% | x | x |
| Hydrochloric acid 38% | 140 | 60 | Sulfuric acid 100% | x | x |
| Hydrogen sulfide, wet | 80 | 27 | Sulfuric acid, fuming | x | x |
| Methyl ethyl ketone | x | x | Toluene | 80 | 27 |
| Naphtha | 80 | 27 | | | |

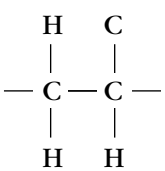
[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x.
*Source:* Material extracted from PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols 1–3. New York: Marcel Dekker, 1995.

Refer to Ref. 8 for a wide range of compatibility of PES with selected corrodents. See also Ref. 15.

## POLYETHYLENE (PE)

See also "Polymers."

Polyethylene is produced in various types that differ in molecular structure, crystallinity, molecular weight, and molecular weight distribution. The basic formula is



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PE is produced by polymerizing ethylene gas obtained from petroleum hydrocarbons. Changes in the polymerizing conditions are responsible for the various types of PE.

The terms low, high, and medium density refer to the ASTM designation based on the unmodified PE. Low-density PE has a specific gravity of 0.91–0.925, medium-density PE has a specific gravity of 0.926–0.940, and high-density PE has a specific gravity of 0.941–0.959. The densities, being related to the molecular structure, are indications of the properties of the final product.

The two grades of polyethylene primarily used for corrosion resistance are the high molecular weight (HMW) and the ultra high molecular weight (UHMW). The HMW material has an average molecular weight of 200,000–500,000, while the UHMW material has an average molecular weight of at least 3.1 million. Table P.28 gives the physical and mechanical properties of UHMW polyethylene.

If exposed to ultraviolet radiation, from the sun or other source, photo or light oxidation will occur. To prevent this, it is necessary to incorporate carbon black into the resin to stabilize it. Other stabilizers will not provide complete protection. PE does not support biological growth.

Polyethylene is resistant to a wide variety of acids, bases, inorganic salts, and many fertilizer solutions.

The compatibility of UHMW polyethylene with selected corrodents is given in Table P.29.

See Refs. 8 and 10.

**Table P.28** Physical and Mechanical Properties of UHMW PE

| | |
|---|---|
| Specific gravity | 0.94–0.96 |
| Water absorption 24 h at 73°F (23°C), % | <0.01 |
| Tensile strength at 73°F (23°C), psi | 3100–3500 |
| Modulus of elasticity in tension at 73°F (23°C) $\times 10^5$ | 1.18 |
| Flexural modulus, psi $\times 10^5$ | 1.33 |
| Izod impact strength, notched at 73°F (23°C) | 0.4–6.0 |
| Coefficient of thermal expansion | |
| in./in.–°F $\times 10^{-5}$ | 11.1 |
| in./10°F/100 ft | 0.111 |
| Thermal conductivity, Btu/h/sq ft/°F/in. | 0.269 |
| Heat distortion temperature, °F/°C | |
| at 66 psi | 150/66 |
| at 264 psi | 250/121 |
| Resistance to heat at continuous drainage, °F/°C | 180/82 |
| Flame spread | slow burning |

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**Table P.29** Compatibility of UHMW PE with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde 40% | 90 | 32 | Antimony trichloride | 140 | 60 |
| Acetamide | | | Aqua regia 3:1 | 130 | 54 |
| Acetic acid 10% | 140 | 60 | Barium carbonate | 140 | 60 |
| Acetic acid 50% | 140 | 60 | Barium chloride | 140 | 60 |
| Acetic acid 80% | 80 | 27 | Barium hydroxide | 140 | 60 |
| Acetic acid, glacial | | | Barium sulfate | 140 | 60 |
| Acetic anhydride | x | x | Barium sulfide | 140 | 60 |
| Acetone | 120 | 49 | Benzaldehyde | x | x |
| Acetyl chloride | | | Benzene | x | x |
| Acrylic acid | | | Benzene sulfonic acid 10% | 140 | 60 |
| Acrylonitrile | 150 | 66 | Benzoic acid | 140 | 60 |
| Adipic acid | 140 | 60 | Benzyl alcohol | 170 | 77 |
| Allyl alcohol | 140 | 60 | Benzyl chloride | | |
| Allyl chloride | 80 | 27 | Borax | 140 | 60 |
| Alum | 140 | 60 | Boric acid | 140 | 60 |
| Aluminum acetate | | | Bromine gas, dry | x | x |
| Aluminum chloride, aqueous | 140 | 60 | Bromine gas, moist | x | x |
| Aluminum chloride, dry | 140 | 60 | Bromine liquid | x | x |
| Aluminum fluoride | 140 | 60 | Butadiene | x | x |
| Aluminum hydroxide | 140 | 60 | Butyl acetate | 90 | 32 |
| Aluminum nitrate | | | Butyl alcohol | 140 | 60 |
| Aluminum oxychloride | | | *n*-Butylamine | x | x |
| Aluminum sulfate | 140 | 60 | Butyl phthalate | 80 | 27 |
| Ammonia gas | 140 | 60 | Butyric acid | 130 | 54 |
| Ammonium bifluoride | | | Calcium bisulfide | 140 | 60 |
| Ammonium carbonate | 140 | 60 | Calcium bisulfite | 80 | 27 |
| Ammonium chloride 10% | 140 | 60 | Calcium carbonate | 140 | 60 |
| Ammonium chloride 50% | 140 | 60 | Calcium chlorate | 140 | 60 |
| Ammonium chloride, sat. | 140 | 60 | Calcium chloride | 140 | 60 |
| Ammonium fluoride 10% | 140 | 60 | Calcium hydroxide 10% | 140 | 60 |
| Ammonium fluoride 25% | 140 | 60 | Calcium hydroxide, sat. | 140 | 60 |
| Ammonium hydroxide 25% | 140 | 60 | Calcium hypochlorite | 140 | 60 |
| Ammonium hydroxide, sat. | 140 | 60 | Calcium nitrate | 140 | 60 |
| Ammonium nitrate | 140 | 60 | Calcium oxide | 140 | 60 |
| Ammonium persulfate | 140 | 60 | Calcium sulfate | 140 | 60 |
| Ammonium phosphate | 80 | 27 | Caprylic acid | | |
| Ammonium sulfate 10–40% | 140 | 60 | Carbon bisulfide | x | x |
| Ammonium sulfide | 140 | 60 | Carbon dioxide, dry | 140 | 60 |
| Ammonium sulfite | | | Carbon dioxide, wet | 140 | 60 |
| Amyl acetate | 140 | 60 | Carbon disulfide | x | x |
| Amyl alcohol | 140 | 60 | Carbon monoxide | 140 | 60 |
| Amyl chloride | x | x | Carbon tetrachloride | x | x |
| Aniline | 130 | 54 | Carbonic acid | 140 | 60 |

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**Table P.29** Compatibility of UHMW PE with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Cellosolve | | | Hydrofluoric acid 70% | x | x |
| Chloracetic acid | x | x | Hydrofluoric acid 100% | x | x |
| Chloracetic acid, 50% in water | x | x | Hypochlorous acid | | |
| Chlorine gas, dry | 80 | 27 | Iodine solution 10% | 80 | 27 |
| Chlorine gas, wet, 10% | 120 | 49 | Ketones, general | x | x |
| Chlorine, liquid | x | x | Lactic acid 25% | 140 | 60 |
| Chlorobenzene | x | x | Lactic acid, concentrated | 140 | 60 |
| Chloroform | 80 | 27 | Magnesium chloride | 140 | 60 |
| Chlorosulfonic acid | x | x | Malic acid | 100 | 38 |
| Chromic acid 10% | 140 | 60 | Manganese chloride | 80 | 27 |
| Chromic acid 50% | 90 | 32 | Methyl chloride | x | x |
| Chromyl chloride | | | Methyl ethyl ketone | x | x |
| Citric acid 15% | 140 | 60 | Methyl isobutyl ketone | 80 | 27 |
| Citric acid, conc. | 140 | 60 | Muriatic acid | 140 | 60 |
| Copper acetate | | | Nitric acid 5% | 140 | 60 |
| Copper carbonate | | | Nitric acid 20% | 140 | 60 |
| Copper chloride | 140 | 60 | Nitric acid 70% | x | x |
| Copper cyanide | 140 | 60 | Nitric acid, anhydrous | x | x |
| Copper sulfate | 140 | 60 | Nitrous acid, concentrated | | |
| Cresol | 80 | 27 | Oleum | | |
| Cupric chloride 5% | 80 | 27 | Perchloric acid 10% | 140 | 60 |
| Cupric chloride 50% | | | Perchloric acid 70% | x | x |
| Cyclohexane | 130 | 54 | Phenol | 100 | 38 |
| Cyclohexanol | 170 | 77 | Phosphoric acid 50–80% | 100 | 38 |
| Dichloroacetic acid | 73 | 23 | Picric acid | 100 | 38 |
| Dichloroethane (ethylene dichloride) | x | x | Potassium bromide 30% | 140 | 60 |
| Ethylene glycol | 140 | 60 | Salicylic acid | | |
| Ferric chloride | 140 | 60 | Silver bromide 10% | | |
| Ferric chloride 50% in water | 140 | 60 | Sodium carbonate | 140 | 60 |
| Ferric nitrate 10–50% | 140 | 60 | Sodium chloride | 140 | 60 |
| Ferrous chloride | 140 | 60 | Sodium hydroxide 10% | 170 | 77 |
| Ferrous nitrate | 140 | 60 | Sodium hydroxide 50% | 170 | 17 |
| Fluorine gas, dry | x | x | Sodium hydroxide, concentrated | | |
| Fluorine gas, moist | x | x | Sodium hypochlorite 20% | 140 | 60 |
| Hydrobromic acid, dilute | 140 | 60 | Sodium hypochlorite, concentrated | 140 | 60 |
| Hydrobromic acid 20% | 140 | 60 | Sodium sulfide to 50% | 140 | 60 |
| Hydrobromic acid 50% | 140 | 60 | Stannic chloride | 140 | 60 |
| Hydrochloric acid 20% | 140 | 60 | Stannous chloride | 140 | 60 |
| Hydrochloric acid 38% | 140 | 60 | Sulfuric acid 10% | 140 | 60 |
| Hydrocyanic acid 10% | 140 | 60 | Sulfuric acid 50% | 140 | 60 |
| Hydrofluoric acid 30% | 80 | 27 | Sulfuric acid 70% | 80 | 27 |

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**Table P.29** Compatibility of UHMW PE with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Sulfuric acid 90% | x | x | Thionyl chloride | x | x |
| Sulfuric acid 98% | x | x | Toluene | x | x |
| Sulfuric acid 100% | x | x | Trichloroacetic acid | 140 | 60 |
| Sulfuric acid, fuming | x | x | White liquor | | |
| Sulfurous acid | 140 | 60 | Zinc chloride | 140 | 60 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that the data are unavailable.
*Source:* Schweitzer, PA. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

## POLYMERS

Also see "Thermoplasts," "Thermoset Polymers," "Elastomers," and individual compounds.

Polymers are better known as "plastics." This is really a misnomer since the term plastic as defined in the dictionary is "a material capable of being molded," such as putty or wet clay. Many of the so-called plastic materials available today are not capable of being molded or, once formed, of being reshaped. Consequently, the term polymer is more descriptive.

Polymers can be classified into three categories: thermoplastic polymers. commonly called thermoplasts; thermosetting polymers, commonly called thermosets; and elastomers, commonly called rubbers.

Thermoplasts are long-chain linear molecules that can easily be formed by heat and pressure at temperatures above a critical temperature known as the "glass temperature." Since this critical temperature is below room temperature for many polymers, these polymers are brittle at room temperature. However these polymers can be reheated and reformed into new shapes and can therefore be recycled.

Thermosets are polymers that take on a permanent shape or "set" when heated, although some will set at room temperature. An example of the latter are epoxies, which result from combining an epoxy polymer with a curing agent or catalyst at room temperature. Thermosets will decompose on heating and therefore cannot be reformed or recycled.

An elastomer is generally considered to be any material, either natural or synthetic, that is elastic or resilient and in general resembles natural rubber in feeling and appearance. A more technical definition is provided by ASTM, which states, "An elastomer is a polymeric material which at room temperature can be stretched to at least twice its original length and upon immediate release of the stress will return quickly to its original length."

In general, elastomers must be cooled to below room temperature to be made brittle.

Metallic materials undergo a specific corrosion rate as a result of an electrochemical reaction. Because of this, it is possible to predict the life of a metal when in contact with a specific corrodent under a given set of conditions. This is not the case with polymeric

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materials. Plastic materials do not experience a specific corrosion rate. They are usually completely resistant to chemical attack or they deteriorate rapidly. They are attacked either by chemical reaction or by solvation. Solvation is the penetration of the plastic by a corrodent, which causes softening, swelling, and ultimate failure. Corrosion of plastics can be classified in the following ways as to the attack mechanism:

1. Disintegration or degradation of a physical nature due to absorption, permeation, solvent action, or other factors
2. Oxidation, where chemical bonds are attacked
3. Hydrolysis, where ester linkages are attacked
4. Radiation
5. Thermal degradation involving depolymerization and possibly repolymerization
6. Dehydration (rather uncommon)
7. Any combination of the above

Results of such attacks will appear in the form of softening, charring, crazing, delamination, embrittlement, discoloration, dissolving, or swelling.

The corrosion resistance of polymer matrix composites is also affected by two other factors: the nature of the laminate and, in the case of the thermoset resins, the cure. Improper or insufficient cure time will adversely affect the corrosion resistance, while proper cure time and procedures will generally improve the corrosion resistance.

All of the polymers are compounded. The final product is produced to certain specific properties for a specific application. When the corrosion resistance of a polymer is discussed, the data referred to are that of the pure polymer. In many instances, other ingredients are blended with the polymer to enhance certain properties, which in many cases will reduce the ability of the polymer to resist the attack of some media. Therefore, it is essential to know the makeup of any polymer prior to its use.

## Thermoplasts

A general rule as to the differences in the corrosion resistance of the thermoplasts may be derived from the periodic table. In the periodic table, the basic elements of nature are organized by atomic structure as well as by chemical nature. The elements are placed into classes with similar properties, i.e., elements and compounds that exhibit similar behavior. These classes are the alkali metals, alkaline earth metals, transition metals, rare earth series, other metals, nonmetals. and noble (inert) gases.

The category known as halogens is of particular importance and interest in the case of thermoplasts. These elements include fluorine, chlorine, bromine, and iodine. They are the most electronegative elements in the periodic table, making them the most likely to attract an electron from another element and become a stable structure. Of all the halogens, fluorine is the most electronegative, permitting it to bond strongly with carbon and hydrogen atoms but not well with itself. The carbon–fluorine bond is predominant in PVDF and is responsible for the important properties of these materials. These are among the strongest known organic compounds. The fluorine acts like a protective shield for other bonds of lesser strength within the main chain of the polymer. The carbon–hydrogen bond, of which such plastics as PE and PP are composed, is considerably weaker. The carbon–chlorine bond, a key bond in PVC, is still weaker.

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The arrangement of the elements in the molecule, the symmetry of the structure, and the degree of branching of the polymer chains are as important as the specific elements contained in the molecule. Plastics containing the carbon–hydrogen bonds, such as PP and PE, and carbon–chlorine bonds, such as PVC, ECTFE, and CTFE, are different in the important property of chemical resistance from a fully fluorinated plastic such as PTFE.

The fluoroplastic materials are divided into two groups: fully fluorinated fluorocarbon polymers such as PTFE, FEP, and PFA, called perfluoropolymers, and the partially fluorinated polymers such as ETFE, PVDF and ECTFE, which are called fluoropolymers. The polymeric characteristics within each group are similar, but there are important differences between the groups.

The abbreviations used for the common thermoplasts are given in Table P.30 while Table P.31 gives the heat distortion temperatures. Table P.32 provides the tensile strength of the thermoplasts.

Refer to individual thermoplasts for additional information.

**Table P.30** Abbreviations Used for Thermoplasts

| | |
|---|---|
| ABS | Acrylonitrile–butadiene–styrene |
| CPVC | Chlorinated polyvinyl chloride |
| CR | Chloroprene rubber (Neoprene) |
| CSM | Chlorine sulfonyl polyethylene (Hypalon) |
| ECTFE | Ethylene-chlorotrifluoroethylene |
| EP | Epoxide epoxy |
| EPDM | Ethylene propylene rubber |
| ETFE | Ethylene-tetrafluoroethylene |
| FEP | Perfluoroethylenepropylene |
| FPM | Fluorine rubber (Viton[a]) |
| HDPE | High-density polyethylene |
| HP | Isobutene isoprene (butyl) rubber |
| LPDE | Low density polyethylene |
| NBR | Nitrile (butadiene) rubber |
| NR | Natural rubber |
| PA | Polyamide |
| PB | Polybutylene |
| PC | Polycarbonate |
| PCTFE | Polychlorotrifluoroethylene |
| PF | Phenol-formaldehyde |
| PFA | Perfluoroalkoxy resin |
| PP | Polypropylene |
| PTFE | Polytetrafluoroethylene (Teflon[a]) |
| PVC | Polyvinyl chloride |
| PVDC | Polyvinylidene chloride |
| PVDF | Polyvinylidene fluoride |
| UHMWPE | Ultra high molecular weight polyethylene |

[a]Registered trademark of E. I. DuPont.

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**Table P.31** Heat Distortion Temperature of the Common Thermoplasts

| | Pressure | | |
|---|---|---|---|
| Polymer | 66 psi | 264 psi | Melt point |
| PTFE | 250°F/121°C | 132°F/56°C | 620°F/327°C |
| PVC | 135°F/57°C | 140°F/60°C | 285°F/I41°C |
| LDPE | — | 104°F/40°C | 221°F/105°C |
| UHMW PE | 155°F/68°C | I10°F/43°C | 265°F/129°C |
| PP | 225°F/107°C | 120°F/49°C | 330°F/166°C |
| PFA | 164°F/73°C | 118°F/48°C | 590°F/310°C |
| FEP | 158°F/70°C | 124°F/51°C | 554°F/290°C |
| PVDF | 298°F/148°C | 235°F/113°C | 352°F/178°C |
| ECTFE | 240°F/116°C | 170°F/77°C | 464°F/240°C |
| PCTFE | 258°F/I26°C | 167°F/75°C | 424°F/218°C |
| ETFE | 220°F/104°C | 165°F/74°C | 518°F/270°C |

**Table P.32** Tensile Strength of Thermoplasts at 83°F (25°C) at Break

| Polymer | Strength (psi) |
|---|---|
| PVDF | 8000 |
| ETFE | 6500 |
| PCTFE | 4500–6000 |
| PFA | 4000–4300 |
| ECTFE | 7000 |
| PTFE | 2500–6000 |
| FEP | 2700–3100 |
| PVC | 6000–7500 |
| PE | 1200–4550 |
| PP | 4500–6000 |
| UHMW PE | 5600 |

## Polyvinyl Chloride (PVC)

There are two basic types of PVC produced: type 1, which is a rigid unplasticized PVC that has optimum chemical resistance, and type 2, which has optimum impact resistance but reduced chemical resistance. Unplasticized PVC resists attack by most acids and strong alkalies as well as gasoline, kerosene, aliphatic alcohols, and hydrocarbons. It is particularly useful in the handling of inorganic materials such as hydrochloric acid. It has been approved by the National Sanitation Foundation for the handling of potable water. Type 2 PVC's resistance to oxidizing and highly alkaline media is reduced.

PVC can be attacked by aromatics, chlorinated organic compounds, and lacquer solvents. Refer to "Polyvinyl Chloride" for additional information.

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## Chlorinated Polyvinyl Chloride (CPVC)

Although the corrosion resistance of CPVC is similar to that of PVC, there are enough differences that prevent CPVC from being used in all environments where PVC is used. In general, CPVC cannot be used in the presence of most polar organic materials, including chlorinated or aromatic hydrocarbons, esters, and ketones.

It is compatible for use with most acids, alkalies, salts, halogens, and many corrosive wastes. Refer to "Chlorinated Polyvinyl Chloride" for additional information.

## Polypropylene

Polypropylene is available as a homopolymer or a copolymer. The homopolymers are generally long-chain high-molecular-weight molecules with a minimum of random molecular orientation, thus optimizing their chemical, thermal, and physical properties. For maximum corrosion resistance, homopolymers should be used.

Polypropylene is resistant to salt water, crude oil, sulfur-bearing compounds, caustic, solvents, acids, and other organic chemicals. It is not recommended for use with oxidizing-type acids, detergents, low-boiling hydrocarbons, alcohols, aromatics, and some chlorinated organic materials. Unpigmented polypropylene is degraded by ultraviolet light. Refer to "Polypropylene" for additional information.

## Polyethylene (PE)

Polyethylene material varies from type to type depending upon the molecular structure and its crystallinity, molecular weight, and molecular weight distribution. The terms low-, high-, and medium-density refer to the ASTM designations based on unmodified polyethylene. The densities, being related to the molecular structure, are indicators of the properties of the final product. High molecular weight (HMW) and ultra high molecular weight (UHMW) are the two forms most often used for corrosion resistance. When PE is exposed to ultraviolet radiation, usually from the sun, photo or light oxidation will occur. In order to protect against this, it is necessary to incorporate carbon black into the resin to stabilize it. Other types of stabilizers will not provide complete protection.

PE exhibits a wide range of corrosion resistance ranging from potable water to corrosive wastes. It is resistant to most mineral acids, including sulfuric up to 70% concentration; inorganic salts, including chlorides; alkalies; and many organic acids.

It is not resistant to bromine, aromatics, or chlorinated hydrocarbons. Refer to "Polyethylene" for additional information.

## Polybutylene

The combination of stress cracking resistance, chemical resistance, and abrasion resistance makes this polymer extremely useful. It is resistant to acids, bases, soaps, and detergents up to 200°F (93°C). It is not resistant to aliphatic solvents at room temperatures and is partially soluble in aromatic and chlorinated hydrocarbons. Chlorinated water will cause pitting attack. Refer to "Polybutylene" for additional information.

## Polyphenylene Sulfide (PPS) (Ryton)

This thermoplast exhibits good resistance to aqueous inorganic salts and bases and is inert to many organic solvents. It also finds applications in oxidizing environments. Refer to "Polyphenylene Sulfide" for additional information.

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### Polycarbonate

Polycarbonate has exceptional weatherability and good corrosion resistance to mineral acids. Organic solvents will attack the polymer. Strong alkalies will decompose it. It is sold under the trade name Lexan. Refer to "Polycarbonate" for additional information.

### Polyetheretherketone (PEEK)

PEEK exhibits excellent corrosion resistance to a wide range of organic and inorganic chemicals. It is resistant to acetic, nitric, hydrochloric, phosphoric, and sulfuric acids, among others. Refer to "Polyetheretherketone" for additional information.

### Polyethersulfone (PES)

PES resists most inorganic chemicals but is attacked by strong oxidizing acids. PES has excellent resistance to aliphatic hydrocarbons and aromatics. It is soluble in highly polar solvents and is subject to stress cracking in certain solvents, notably ketones and esters.

Hydrocarbons and mineral oils, greases, and transmission fluids have no effect on PES. Refer to "Polyethersulfone" for additional information.

### Phenolics

The phenolics are relatively inert to acids but have little alkaline or bleach resistance. They exhibit a wider range of corrosion resistance as a composite material with a glass filling. Refer to "Phenolic Resins" for additional information.

### ABS

This thermoplastic resin is resistant to aliphatic hydrocarbons but not resistant to aromatic and chlorinated hydrocarbons. Refer to "Acrylonitrile-Butadiene-Styrene" for additional information.

### Vinylidene Fluoride (PVDF)

Vinylidene fluoride is chemically resistant to most acids, bases, and organic solvents. It also has the ability to handle wet or dry chlorine, bromine, and other halogens.

PVDF is not suitable for use with strong alkalies, fuming acids, polar solvents, amines, ketones, and esters. When used with strong alkalies, it is subject to stress cracking. Refer to "Vinylidene Fluoride Elastomers" for additional information.

### Ethylene-Chlorotrifluoroethylene (ECTFE)

The chemical resistance of ECTFE is outstanding. It is resistant to strong mineral and oxidizing acids, alkalies, metal etchants, liquid oxygen, and practically all organic solvents except hot amines such as aniline, dimethylamine, etc. Severe stress tests have shown that ECTFE is not subject to chemically induced stress cracking from strong acids, bases, or solvents. Some halogenated solvents can cause ECTFE to become slightly plasticized when it comes into contact with them. Upon removal of the solvent from contact, and upon drying, the mechanical properties of ECTFE return to their original values, indicating that no chemical attack has taken place.

ECTFE will be attacked by metallic sodium and potassium and fluorine. Refer to "Ethylene-Chlorotrifluoroethylene Elastomer" for additional information.

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### Ethylene-Tetrafluoroethylene (ETFE)

ETFE is inert to strong mineral acids, inorganic bases, halogens, and metal salt solutions. Even carboxylic acids, anhydrides, aromatic and aliphatic hydrocarbons, alcohols, aldehydes, ketones, ethers, esters, chlorocarbons, and classic polymer solvents have little effect on ETFE.

Very strong oxidizing acids, such as nitric, near their boiling points at high concentration, will attack ETFE in varying degrees, as will organic bases such as amines and sulfonic acids. Refer to "Ethylene-Tetrafluoroethylene" for additional information.

### Polytetrafluoroethylene (PTFE)

PTFE is unique in its corrosion-resistant properties. There are very few chemicals that will attack PTFE within normal-use temperature. Elemental sodium in intimate contact removes fluorine from the polymer molecule. The other alkali metals (potassium, lithium, etc.) react in a similar manner.

Fluorine and related compounds (e.g., chlorine trifluoride) are absorbed into PTFE resin with such intimate contact that the mixture becomes sensitive to a source of ignition such as impact. These potent oxidizers should only be handled with great care and a recognition of the potential hazards.

The handling of 80% sodium hydroxide, aluminum chloride, ammonia, and certain amines at high temperatures may produce the same effect as elemental sodium. Also, slow oxidative attack can be produced by 70% nitric acid under pressure and at 480°F (250°C). Refer to "Polytetrafluoroethylene" for additional information.

### Fluorinated Ethylene Propylene (FEP)

FEP basically exhibits the same corrosion resistance as PTFE, with a few exceptions, but at a lower operating temperature. It is resistant to practically all chemicals, exceptions being the extremely potent oxidizing agents such as chlorine trifluoride and related compounds. Some chemicals will attack FEP when present in high concentrations at or near the service temperature limit of 400°F (200°C). Refer to "Fluorinated Ethylene Propylene" for additional information.

### Perfluoroalkoxy (PFA)

PFA is inert to strong mineral acids, inorganic bases, inorganic oxidizers, aromatics, some aliphatic hydrocarbons, alcohols, aldehydes, ketones, ethers, esters, chlorocarbons, fluorocarbons, and mixtures of these.

PFA will be attacked by certain halogenated complexes containing fluorine. These include chlorine trifluoride, bromine trifluoride, iodine pentachloride, and fluorine. It can also be attacked by such metals as sodium or potassium, particularly in their molten state. Refer to "Perfluoroalkoxy" for additional information.

### Thermosets

Thermoset resins are "families" of compounds rather than unique individual compounds. Similar to the thermoplast resins, they can be formulated to improve certain specific properties but often at the expense of another property. In the chemical corrosion field, there are four families of thermoset resins that are of importance:

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The polyesters
The epoxies
The vinyl esters
The furans

Refer to the specific resins for additional information.

### Polyester Resins

The members of this family of resins that are of greatest importance for their corrosion resistance are the following:

Isophthalic resins
Bisphenol A–fumarate resins
Hydrogenated bisphenol A–bisphenol A resins
Halogenated resins
Terephthalate resins

### Elastomers

See also individual elastomers. Elastomeric materials fail in the same manner as other polymeric materials. When an elastomer is used as a lining material for a tank or piping, additional consideration must be given to the problems of permeation and absorption.

Physical properties of the elastomer determine the reaction of the elastomer to such physical actions as permeation and absorption. If a lining material is subject to permeation by a corrosive chemical, it is possible for the base metal to be attacked and corroded even though the lining material itself is unaffected. Because of this, permeation and absorption must be taken into account when specifying a lining material. See "Permeation" and "Absorption."

### Environmental Stress Cracking

When a tough polymer is stressed for a long period of time under loads that are small relative to the polymer's yield point, stress cracks develop. Crystallinity is an important factor affecting stress corrosion cracking. The less the crystallization that takes place, the less the likelihood of stress cracking. Unfortunately, the lower the crystallinity, the greater the likelihood of permeation.

The presence of contaminants in the fluid may act as an accelerant for stress corrosion cracking. For example, polypropylene can safely handle sulfuric and hydrochloric acids. However, iron or copper contamination in concentrated sulfuric or hydrochloric acid can result in stress cracking of polypropylene.

### Outdoor Use

Elastomers in outdoor use can be subject to degradation as a result of the action of ozone, oxygen, and sunlight. These three weathering agents can greatly affect the properties and appearance of a large number of elastomeric materials. Surface cracking, discoloration of colored stocks, and serious loss of tensile strength, elongation, and other rubber-like properties are the result of this attack.

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### Natural Rubber (NR)

Cold water preserves natural rubber, but if exposed to air, particularly in sunlight, rubber tends to become hard and brittle. It has only fair resistance to ozone. In general, it has poor weathering and aging properties.

Natural rubber offers excellent resistance to most inorganic salt solutions, alkalies, and nonoxidizing acids. Hydrochloric acid will react with rubber to form rubber hydrochloride. Strong oxidizing media such as nitric acid, concentrated sulfuric acid, permanganates, dichromates, chlorine dioxide, and sodium hypochlorite will severely attack rubber. Mineral and vegetable oils, gasoline, benzene, toluene, and chlorinated hydrocarbons also affect rubber. Natural rubber offers good resistance to radiation and alcohols. Refer to "Natural Rubber" for additional information.

### Isoprene Rubber (IR)

This is the synthetic form of natural rubber and, as such, can be used in the same applications as natural rubber. For additional information, refer to "Isoprene Rubber."

### Neoprene (CR)

Neoprene possesses excellent resistance to sun, weather, and ozone. Because of its low rate of oxidation, neoprene has a high resistance to both outdoor and indoor aging. If severe ozone is to be expected, as for example around electrical equipment, neoprene can be compounded to resist thousands of parts per million of ozone for hours without surface cracking. Natural rubber will crack within minutes when exposed to ozone concentrations of only 50 ppm.

Neoprene provides excellent resistance to attack from solvents, fats, waxes, oils, greases, and many other petroleum-based products. A minimum amount of swelling and relatively little loss of strength is experienced when in contact with aliphatic compounds (methyl and ethyl alcohols, ethylene glycols, etc.), aliphatic hydrocarbons, and most refrigerants. Neoprene is also resistant to dilute mineral acids, inorganic salt solutions, and alkalies.

Neoprene has only limited serviceability when exposed to chlorinated and aromatic hydrocarbons, organic esters, aromatic hydroxy compounds, and certain ketones. Highly oxidizing acid and salt solutions cause surface deterioration and loss of strength. This includes such materials as nitric acid and concentrated sulfuric acid. Refer to "Neoprene" for additional information.

### Butadiene-Styrene Rubber (SBR, BUNA-S, GR-S)

Buna-S has poor weathering and aging properties. Sunlight will cause it to deteriorate. It does have better water resistance than natural rubber.

The chemical resistance of Buna-S is similar to that of natural rubber. It is resistant to water and exhibits fair to good resistance to dilute acids, alkalies, and alcohol. It is not resistant to oils, gasoline, hydrocarbons, or oxidizing agents. Refer to "Butadiene-Styrene Rubber" for additional information.

### Butyl Rubber (IRR) and Chlorobutyl Rubber (CIIR)

Butyl rubber has excellent resistance to sun, weather, and ozone. Its resistance to water absorption and its weathering qualities are outstanding.

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Butyl rubber is resistant to dilute mineral acids, alkalies, phosphate ester oils, acetone, ethylene, ethylene glycol, and water. It is resistant to swelling by vegetable and animal oils.

Butyl rubber is not resistant to concentrated nitric and sulfuric acids, petroleum oils, gasoline, and most solvents, except oxygenated solvents.

Chlorobutyl rubber exhibits the same general resistance as natural rubber but can be used at a higher temperature. It cannot be used with hydrochloric acid even though butyl rubber is suitable. Refer to "Butyl Rubber and Chlorobutyl Rubber" for additional information.

### Chlorosulfonated Polyethylene Rubber (Hypalon)

Hypalon is one of the most weather-resistant elastomers available. Sunlight and ultraviolet light have little if any adverse effect on its physical properties. Many elastomers are degraded by ozone concentrations of 1 ppm in air, while Hypalon is unaffected by concentrations as high as 1 ppm per 100 parts of air.

Hypalon is capable of resisting attack by hydrocarbon oils and fats and by such oxidizing chemicals as sodium hypochlorite, sodium peroxide, ferric chloride, and sulfuric, chromic, and hydrofluoric acids. Concentrated hydrochloric acid (37%) at temperatures above 158°F (70°C) will attack Hypalon, but it can be handled in all concentrations below this temperature. Nitric acid at room temperature and up to 60% concentration can also be handled without adverse effects. Hypalon is also resistant to salt solutions, alcohols, and both weak and concentrated alkalies and is generally unaffected by soil chemicals, moisture, and other deteriorating factors associated with burial in the earth.

Hypalon has poor resistance to aliphatic, aromatic, and chlorinated hydrocarbons, aldehydes, and ketones. Refer to "Chlorosulfonated Polyethylene Rubber" for additional details.

### Polybutadiene Rubber (BR)

Polybutadiene has good weather resistance but will deteriorate when exposed to sunlight for extended periods of time. It also has poor resistance to ozone.

In general, the chemical resistance of BR is similar to that of natural rubber. For additional information, refer to "Polybutadiene."

### Ethylene-Acrylic Rubber (EA)

The EA elastomers have extremely good resistance to sun, weather, and ozone. Its resistance to water absorption is very good.

The EA elastomers exhibit good resistance to hot oils, hydrocarbon- or glycol-based lubricants, and transmission and power-steering fluids. Good resistance is also displayed to dilute acids, aliphatic hydrocarbons, gasoline, and animal and vegetable oils.

The EA elastomers will be attacked by esters, ketones, highly aromatic hydrocarbons, and concentrated acids. Refer to "Ethylene-Acrylic Rubber" for additional information.

### Acrylate-Butadiene Rubber (ABR) and Acrylic Ester-Acrylic Halide Rubbers (ACM)

These rubbers exhibit good resistance to sun, weather, and ozone.

They have excellent resistance to aliphatic hydrocarbons (gasoline, kerosene) and offer good resistance to water, acids, synthetic lubricants, and silicate hydraulic fluids.

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These rubbers will be attacked when exposed to alkalies, aromatic hydrocarbons (benzene, toluene), halogenated hydrocarbons, alcohol, and phosphate hydraulic fluids. Refer to "Acrylic-Butadiene Rubber and Acrylic Ester–Acrylic Halide Rubbers" for additional information.

### Ethylene-Propylene Rubber (EPDM and EPT)

Ethylene-propylene rubbers are particularly resistant to sun, weather, and ozone attack. Ozone resistance is inherent in the polymer, and for all practical purposes it can be considered immune to ozone attack. It is not necessary to add any compounding ingredients to produce the immunity.

Ethylene-propylene rubbers are resistant to oxygenated solvents, such as acetone, methyl ethyl ketone, ethyl acetate, weak acids and alkalies, detergents, phosphate esters, alcohols, and glycols.

The elastomer will be attacked by hydrocarbon solvents and oils, chlorinated hydrocarbons, and turpentine. EPT rubbers, in general, are resistant to most of the same corrodents as EPDM. Refer to "Ethylene-Propylene Rubbers" for additional information.

### Styrene-Butadiene-Styrene Rubber (SBS)

The SBS rubbers are not resistant to sun, weather, or ozone. Their chemical resistance is similar to that of natural rubber. They have excellent resistance to water, acids, and bases. Refer to "Styrene-Butadiene-Styrene Rubber" for additional information.

### Styrene-Ethylene-Butylene-Styrene Rubber (SEBS)

The SEBS rubbers possess excellent resistance to ozone. For prolonged outdoor exposure the addition of an ultraviolet light absorber, a carbon black pigment, or both is required. The chemical resistance of the SEBS rubbers is similar to that of natural rubber, and they possess excellent resistance to water, acids, and bases. Refer to "Styrene-Ethylene-Butylene-Styrene Rubber" for additional information.

### Polysulfide Rubbers (ST and FA)

FA polysulfide rubbers possess excellent resistance to ozone, weathering, and ultraviolet light. ST polysulfide rubber, compounded with carbon black, is resistant to ultraviolet light and sunlight. It also has satisfactory weather resistance.

The polysulfide rubbers exhibit excellent resistance to oils, gasoline, and aliphatic and aromatic hydrocarbon solvents, good water and alkali resistance, and fair acid resistance. The FA polysulfide rubbers are more resistant to solvents than the ST polysulfide rubbers. The ST rubbers exhibit better resistance to chlorinated organics than the FA rubbers.

The polysulfide rubbers are not resistant to strong concentrated inorganic acids such as sulfuric, nitric, and hydrochloric. Refer to "Polysulfide Rubbers" for additional information.

### Urethane Rubbers (AU)

The urethane rubbers exhibit excellent resistance to ozone attack and have good resistance to weathering. Extended exposure to ultraviolet light will cause the rubbers to darken and will reduce their physical properties. The addition of pigments or ultraviolet-screening agents will prevent this.

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The urethane rubbers are resistant to most mineral and vegetable oils, grease and fuels, and aliphatic, aromatic, and chlorinated hydrocarbons.

Aromatic hydrocarbons, polar solvents, esters, ethers, and ketones will attack the urethane rubbers. The urethane rubbers have limited service in weak acid solutions and cannot be used in concentrated acids. They are also not resistant to caustic or steam. Refer to "Urethane Rubbers" for additional information.

## Polyamides

Of the many varieties of polyamides (nylons) produced, only grades 11 and 12 find application as elastomeric materials. They are resistant to sun, weather, and ozone.

The polyamides are resistant to most inorganic alkalies, particularly ammonium hydroxide and ammonia at elevated temperatures and sodium and potassium hydroxide at ambient temperatures. They are also resistant to almost all inorganic salts and almost all hydrocarbons and petroleum-based fuels. At normal temperatures they are also resistant to organic acids (citric, lactic, oleic, oxalic, stearic, tartaric, and uric) and most aldehydes and ketones.

The polyamides have limited resistance to hydrochloric, sulfonic, and phosphoric acids at ambient temperatures.

Refer to "Polyamides" for additional information.

## Polyester Elastomer (PE)

The polyesters exhibit excellent resistance to ozone and good resistance to weathering. When formulated with proper additives, they are capable of exhibiting very good resistance to sunlight and aging.

Polyester elastomers have excellent resistance to nonpolar materials such as oils and hydraulic fluids, even at elevated temperatures. At room temperature they are resistant to most polar fluids such as acids, bases, amines, and glycols. Resistance is very poor at temperatures of 158°F (70°C) or higher. Refer to "Polyester Elastomer" for additional information.

## Thermoplastic Elastomers, Olefinic Type (TPE)

The TPEs exhibit good resistance to sun, weather, and ozone. Their water resistance is excellent, showing essentially no property changes after prolonged exposure to water at elevated temperatures.

The TPEs display reasonably good resistance to oils and automotive fluids, comparable to that of neoprene. However, they do not have the outstanding oil resistance of the polyester elastomers. Refer to "Thermoplastic Elastomers" for additional information.

## Silicone (SI) and Fluorosilicone (FSI) Rubbers

The SI and FSI rubbers show excellent resistance to sun, weathering, and ozone, even after long-term exposure.

The silicone rubbers are resistant to dilute acids and alkalies, alcohols, animal and vegetable oils, and lubricating oils and aliphatic hydrocarbons. Aromatic solvents such as benzene, toluene, gasoline, and chlorinated solvents, and high-temperature steam will attack SI rubbers.

The FSI rubbers have better chemical resistance than the SI rubbers. They possess excellent resistance to aliphatic hydrocarbons and good resistance to aromatic hydrocarbons,

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oil and gasoline, animal and vegetable oils, dilute acids and alkalies, and alcohols. Refer to "Silicone and Fluorosilicone Rubbers" for additional information.

### Vinylidene Fluoride (PVDF)

PVDF is highly resistant to the chlorinated solvents, aliphatic solvents, weak bases and salts, strong acids, halogens, strong oxidants, and aromatic solvents.

Strong bases will attack PVDF. Sodium hydroxide can cause stress cracking. Refer to "Vinylidene Fluoride Elastomers" for additional information.

### Ethylene-Tetrafluoroethylene Elastomer (ETFE)

Because of ETFE's outstanding resistance to sunlight, ozone, and weather, coupled with its wide range of corrosion resistance, it is ideally suited for outdoor applications subject to atmospheric corrosion.

ETFE is inert to strong mineral acids, inorganic bases, halogens, and metal salt solutions. Carboxylic acids, anhydrides, aromatic and aliphatic hydrocarbons, alcohols, aldehydes, ketones, esters, ethers, chlorocarbons, and classic polymer solvent have little effect on ETFE.

Strong oxidizing acids near their boiling points, such as nitric acid at high concentrations, organic bases such as amines, and sulfonic acids will have a deleterious effect on ETFE. Refer to "Ethylene-Tetrafluoroethylene Elastomer" for additional information.

### Ethylene-Chlorotrifluoroethylene Elastomer (ECTFE)

ECTFE is extremely resistant to sun, weather, and ozone attack.

Ethylene-chlorotrifluoroethylene is resistant to strong mineral and oxidizing acids, alkalies, metal etchants, liquid oxygen, and practically all organic solvents except hot amines (aniline, dimethylamine, etc.).

ECTFE will be attacked by metallic sodium and potassium. Refer to "Ethylene-Chlorotrifluoroethylene Elastomer" for additional information.

### Perfluoroelastomers (FPM)

The FPM elastomers have excellent resistance to sun, weather, and ozone, even after long-term exposure.

The perfluoroelastomers are resistant to polar solvents (ketones, esters, ethers), strong organic solvents (benzene, dimethyl formamide), inorganic and organic acids (hydrochloric, nitric, sulfuric) and bases, strong oxidizing agents (fuming nitric acid), metal halides, chlorine (wet and dry), inorganic salt solutions, hydraulic fluids, and heat transfer fluids. Refer to "Perfluoroelastomers" for additional information.

See Refs. 9, 8, 10, 7, 17, and 15.

## POLYMER CONCRETES

Polymer concretes are totally chemical-resistant synthetic resin compounds. They pass the total immersion test at varying temperatures for extended periods of time. Polymer concretes are not to be confused with polymer modified portland cement concrete. Polymer modified portland cement concrete can use some of the same generic resins used in polymer concretes, but with different results.

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The polymer concretes are usually formulated from the following resins:

1. Furan
2. Epoxy
3. Polyester
4. Acrylics
5. Sulfur
6. Vinyl ester

The major advantage of the polymer concretes is their wide range of corrosion resistance. The polymer modified portland cement concretes offer the following advantages:

1. Thinner concrete cross-sections can be applied.
2. They lower absorption of concrete.
3. They improve impact resistance.
4. They provide improved adhesion for pours onto existing concrete.
5. They provide improved corrosion resistance to salt but not to aggressive corrosive chemicals such as hydrochloric acid.

Polymer concretes are usually installed at thicknesses of greater than $\frac{1}{2}$ inch.

A monolithic surfacing or topping is usually installed at thicknesses of $\frac{1}{16}$ to $\frac{1}{2}$ inch. The most popular monolithic surfacings are formulated from the following resins:

1. Epoxy
2. Polyester
3. Vinyl ester
4. Acrylic
5. Urethane

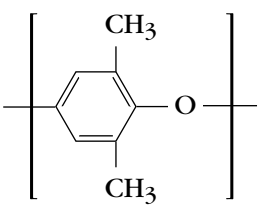
Monolithic surfacings are versatile materials used primarily as flooring systems.

The chemical resistance of monolithic surfacings and polymer concretes is the same as the chemical resistance of their mortar counterparts. Refer to "Mortars."

See Refs. 8, 18, 19, and 20.

## POLYPHENYLENE OXIDE (PPO)

Noryls, patented by G. E. Plastics, are amorphous modified polyphenylene oxide resins. The basic phenylene oxide structure is as follows:




Several grades of the resin are produced to provide a choice of performance characteristics to meet a wide range of engineering application requirements.

PPO maintains excellent mechanical properties over a temperature range of below −40°F/−40°C to above 300°F/149°C. It possesses excellent dimensional stability, is

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**Table P.33** Physical and Mechanical Properties of PPO Alloy with Polystyrenes

| Property | Impact-modified | 10% glass fiber reinforced |
|---|---|---|
| Specific gravity | 1.27–1.36 | 1.14–1.31 |
| Water absorption (24 h at 73°F/23°C) (%) | 0.01–0.07 | 0.06–0.07 |
| Dielectric strength, short-term (V/mil) | 530 | 420 |
| Tensile strength at break (psi) | 7000–8000 | 10,000–12,000 |
| Tensile modulus (psi $\times 10^3$) | 345–360 | |
| Elongation at break (%) | 35 | 5–8 |
| Compressive strength (psi) | 10,000 | |
| Flexural strength (psi) | 8200–11,000 | 20,000–23,000 |
| Compressive modulus (psi $\times 10^3$) | | |
| Flexural modulus (psi $\times 10^3$) | | |
| at 73°F/23°C | 325–345 | 760 |
| at 200°F/93°C | | |
| at 250°F/121°C | | |
| Izod impact (ft-lb/in. of notch) | 6.8 | 1.1–1.3 |
| Hardness, Rockwell | R119 | R121 |
| Coefficient of thermal expansion ($10^{-6}$ in./in./°F) | 33 | 14 |
| Thermal conductivity ($10^{-4}$cal-cm/s-cm$^2$ °C or Btu/h/ft$^2$/°F/in.) | 1.32 | |
| Deflection temperature | | |
| at 264 psi (°F) | 190–275 | 252–260 |
| at 66 psi (°F) | 205–245 | 273–280 |
| Max. operating temperature (°F/°C) | 120–230/50–110 | 230/110 |
| Limiting oxygen index (%) | 22–39 | 26–36 |
| Flame spread | | |
| Underwriters Lab rating (Sub. 94) | V-1 | V-1 |

self-extinguishing with nonsagging characteristics, and has low creep, high modulus, low water absorption, good electrical properties, and excellent impact strength. The physical and mechanical properties of PPO are shown in Table P.33.

PPO has excellent resistance to aqueous environments, dilute mineral acids, and dilute alkalies. It is not resistant to aliphatic hydrocarbons, aromatic hydrocarbons, ketones, esters, or chlorinated hydrocarbons. Refer to Table P.34 for the compatibility of PPO with selected corrodents.

PPO finds application in business equipment, appliances, electronics, and electrical devices.

**Table P.34** Compatibility of PPO with Selected Corrodents[a]

| | | | |
|---|---|---|---|
| Acetic acid 5% | R | Citric acid 10% | R |
| Acetic acid 10% | R | Copper sulfate | R |
| Acetone | x | Cyclohexane | x |
| Ammonia 10% | R | Cyclohexanone | x |
| Benzene | x | Diesel oil | R |
| Carbon tetrachloride | x | Dioxane | x |
| Chlorobenzene | x | Edible oil | R |
| Chloroform | x | Ethanol | R |

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**Table P.34** Compatibility of PPO with Selected Corrodents[a] (Continued)

| | | | |
|---|---|---|---|
| Ethyl acetate | R | Paraffin oil | R |
| Ethylene chloride | x | Phosphoric acid 10% | R |
| Ethylene glycol | R | Potassium hydroxide 50% | R |
| Formaldehyde 30% | R | Potassium dichromate | R |
| Formic acid | R | Potassium permanganate 10% | R |
| Fruit juice | R | Silicone oil | R |
| Fuel oil | R | Soap solution | R |
| Gasoline | R | Sodium carbonate 10% | R |
| Glycerine | R | Sodium chloride 10% | R |
| Hexane/heptane | R | Sodium hydroxide 5% | R |
| Hydrochloric acid 2% | R | Sodium hydroxide 50% | R |
| Hydrochloric acid 38% | R | Styrene | x |
| Hydrogen peroxide 0–5% | R | Sulfuric acid 2% | R |
| Hydrogen peroxide 30% | R | Sulfuric acid 98% | R |
| Hydrogen sulfide | R | Trichloroethylene | x |
| Linseed oil | R | Urea, aqueous | R |
| Methanol | R | Water, cold | R |
| Methyl ethyl ketone | x | Water, hot | R |
| Milk | R | Wax, molten | R |
| Motor oil | R | Xylene | x |
| Nitric acid 2% | R | | |

[a]R = material resistant at 73°F/20°C; x = material not resistant.

## POLYPHENYLENE SULFIDE (PPS)

See also "Polymers."

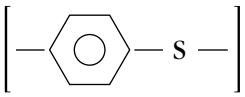
Polyphenylene sulfide is a thermoplastic capable of being used at high temperatures. It has a maximum service rating of 450°F (230°C). As the temperature increases, there is a corresponding increase in toughness. Table P.35 provides the physical and mechanical properties of PPS.

**Table P.35** Physical and Mechanical Properties of PPS

| | |
|---|---|
| Specific gravity | 1.34 |
| Water absorption 24 h at 73°F/23°C, % | 0.01 |
| Tensile strength at 73°F/23°C, psi | 10,800 |
| Modulus of elasticity in tension at 73°F/23°C psi $\times 10^5$ | 4.8–6.3 |
| Compressive strength, psi | 16,000 |
| Flexural modulus, psi $\times 10^5$ | 11–20 |
| Izod impact strength, notched at 73°F/23°C, ft-lb/in. | 0.03 |
| Coefficient of thermal expansion in./in. °F $\times 10^{-5}$ | 2.7–3.0 |
| Thermal conductivity, Btu/h/ft$^2$/°F/in. | 2.0 |
| Heat distortion temperature, °F/°C at 264 psi | 275/135 |
| Limiting oxygen index, % | 47 |
| Underwriters Lab rating, Sub 94 | SEO |

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The structure is



Polyphenylene sulfide offers excellent resistance to aqueous inorganic salts and bases and many organic solvents. It can also be used under highly oxidizing conditions. Relatively few materials react with PPS at high temperatures. PPS is resistant to organic solvents except for chlorinated solvents, some halogenated gases, and alkyl amines. It stress cracks in chlorinated solvents. Weak and strong alkalies have no effect on PPS. Polyphenylene sulfide is resistant to weak acids with the exception of hydrochloric. Strong oxidizing acids such as sulfuric, nitric, chromic, and 10% perchloric will attack PPS. Refer to Table P.36 for the compatibility of PPS (Ryton) with selected corrodents.

**Table P.36** Compatibility of Polyphenylene Sulfide with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetaldehyde | 230 | 110 | Ammonium phosphate 65% | 300 | 149 |
| Acetamide | 250 | 121 | Ammonium sulfate 10–40% | 300 | 149 |
| Acetic acid 10% | 250 | 121 | Amyl acetate | 300 | 149 |
| Acetic acid 50% | 250 | 121 | Amyl alcohol | 210 | 99 |
| Acetic acid 80% | 250 | 121 | Amyl chloride | 200 | 93 |
| Acetic acid, glacial | 190 | 88 | Aniline | 300 | 149 |
| Acetic anhydride | 280 | 138 | Barium carbonate | 200 | 93 |
| Acetone | 260 | 127 | Barium chloride | 200 | 93 |
| Acrylic acid 25% | 100 | 38 | Barium hydroxide | 200 | 93 |
| Acrylonitrile | 130 | 54 | Barium sulfate | 220 | 104 |
| Adipic acid | 300 | 149 | Barium sulfide | 200 | 93 |
| Alum | 300 | 149 | Benzaldehyde | 250 | 121 |
| Aluminum acetate | 210 | 99 | Benzene | 300 | 149 |
| Aluminum chloride, aqueous | 300 | 149 | Benzene sulfonic acid 10% | 250 | 121 |
| Aluminum chloride, dry | 270 | 132 | Benzoic acid | 230 | 110 |
| Aluminum hydroxide | 250 | 121 | Benzyl alcohol | 200 | 93 |
| Aluminum nitrate | 250 | 121 | Benzyl chloride | 300 | 149 |
| Aluminum oxychloride | 460 | 238 | Borax | 210 | 99 |
| Ammonia gas | 250 | 121 | Boric acid | 210 | 99 |
| Ammonium carbonate | 460 | 238 | Bromine gas, dry | x | x |
| Ammonium chloride 10% | 300 | 149 | Bromine gas, moist | x | x |
| Ammonium chloride 50% | 300 | 149 | Bromine liquid | x | x |
| Ammonium chloride, sat. | 300 | 149 | Butadiene | 100 | 38 |
| Ammonium hydroxide 25% | 250 | 121 | Butyl acetate | 250 | 121 |
| Ammonium hydroxide, sat. | 250 | 121 | Butyl alcohol | 200 | 93 |
| Ammonium nitrate | 250 | 121 | *n*-Butylamine | 200 | 93 |

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**Table P.36** Compatibility of Polyphenylene Sulfide with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Butyric acid | 240 | 116 | Hydrobromic acid, dilute | 200 | 93 |
| Calcium bisulfite | 200 | 93 | Hydrobromic acid 20% | 200 | 93 |
| Calcium carbonate | 300 | 149 | Hydrobromic acid 50% | 200 | 93 |
| Calcium chloride | 300 | 149 | Hydrochloric acid 20% | 230 | 110 |
| Calcium hydroxide 10% | 300 | 149 | Hydrochloric acid 38% | 210 | 99 |
| Calcium hydroxide, sat. | 300 | 149 | Hydrocyanic acid 10% | 250 | 121 |
| Carbon bisulfide | 200 | 93 | Hydrofluoric acid 30% | 200 | 93 |
| Carbon dioxide, dry | 200 | 93 | Lactic acid 25% | 250 | 121 |
| Carbon disulfide | 200 | 93 | Lactic acid, concentrated | 250 | 121 |
| Carbon tetrachloride | 120 | 49 | Magnesium chloride | 300 | 149 |
| Cellosolve | 220 | 104 | Methyl ethyl ketone | 200 | 93 |
| Chloracetic acid | 190 | 88 | Methyl isobutyl ketone | 250 | 121 |
| Chlorine gas, dry | x | x | Muriatic acid | 210 | 99 |
| Chlorine gas, wet | x | x | Nitric acid 5% | 150 | 66 |
| Chlorine liquid | 200 | 93 | Nitric acid 20% | 100 | 38 |
| Chloroform | 150 | 66 | Oleum | 80 | 27 |
| Chlorosulfonic acid | x | x | Phenol 88% | 300 | 149 |
| Chromic acid 10% | 200 | 93 | Phosphoric acid 50–80% | 220 | 104 |
| Chromic acid 50% | 200 | 93 | Potassium bromide 30% | 200 | 93 |
| Citric acid 15% | 250 | 121 | Sodium carbonate | 300 | 149 |
| Citric acid, conc. | 250 | 121 | Sodium chloride | 300 | 149 |
| Copper acetate | 300 | 149 | Sodium hydroxide 10% | 210 | 99 |
| Copper chloride | 220 | 104 | Sodium hydroxide 50% | 210 | 99 |
| Copper cyanide | 210 | 99 | Sodium hypochlorite 5% | 200 | 93 |
| Copper sulfate | 250 | 121 | Sodium hypochlorite, concentrated | 250 | 121 |
| Cresol | 200 | 93 | Sodium sulfide to 50% | 230 | 110 |
| Cupric chloride 5% | 300 | 149 | Stannic chloride | 210 | 99 |
| Cyclohexane | 190 | 88 | Sulfuric acid 10% | 250 | 121 |
| Cyclohexanol | 250 | 121 | Sulfuric acid 50% | 250 | 121 |
| Dichloroethane (ethylene dichloride) | 210 | 99 | Sulfuric acid 70% | 250 | 121 |
| Ethylene glycol | 300 | 149 | Sulfuric acid 90% | 220 | 104 |
| Ferric chloride | 210 | 99 | Sulfuric acid, fuming | 80 | 27 |
| Ferric chloride 50% in water | 210 | 99 | Sulfurous acid 10% | 200 | 93 |
| Ferric nitrate 10–50% | 210 | 99 | Thionyl chloride | x | x |
| Ferrous chloride | 210 | 99 | Toluene | 300 | 149 |
| Ferrous nitrate | 210 | 99 | Zinc chloride 70% | 250 | 121 |
| Fluorine gas, dry | x | x | | | |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that the data are unavailable.

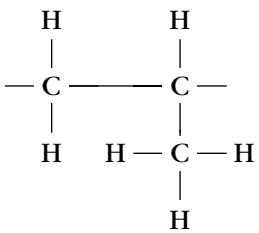
*Source:* Schweitzer, PA. *Corrosion Resistance Tables.* 4th ed. Vols 1–3. New York: Marcel Dekker, 1995.

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## POLYPROPYLENE (PP)

See also "Polymers."

Polypropylene is one of the most common and versatile thermoplastics. It is closely related to polyethylene, both of which are members of a group known as "polyolefins." The polyolefins are composed of only carbon and hydrogen. When unmodified, PP is the lightest of the common thermoplastics, having a specific gravity of 0.91. In addition to its light weight, it has the advantages of high heat resistance, stiffness, and a wide range of chemical resistance. Within the chemical structure of PP, a distinction is made between isotactic PP and atactic PP; the isotactic form accounts for 97% of the PP. This form is highly ordered:



Atactic PP is a viscous liquid–type PP having a PP polymer matrix.

Polypropylene can be produced either as a homopolymer or as a copolymer with polyethylene. The copolymer is less brittle than the homopolymer and is able to withstand impact forces down to –20°F (–29°C), while the homopolymer is extremely brittle below 40°F (4°C). The physical and mechanical properties are shown in Table P.37.

Although the copolymers have increased impact resistance, their tensile strength and stiffness are considerably lower, increasing the potential for distortion and cold flow, particularly at elevated temperatures.

**Table P.37** Physical and Mechanical Properties of Copolymer and Homopolymer PP

| Property | Homopolymer | Copolymer |
|---|---|---|
| Specific gravity | 0.905 | 0.91 |
| Water absorption, 24 h at 73°F/23°C, % | 0.02 | 0.03 |
| Tensile strength at 73°F/23°C, psi | 5000 | 4000 |
| Modulus of elasticity in tension at 73°F/23°C psi $\times 10^5$ | 1.7 | 1.5 |
| Compressive strength, psi | 9243 | 8500 |
| Flexural strength, psi | 7000 | — |
| Izod impact strength, notched at 73°F/23°C, ft-lb/in. | 1.3 | 8 |
| Coefficient of thermal expansion in./in. °F $\times 10^{-5}$ | 5.0 | 6.1 |
| Thermal conductivity, Btu/h/ft$^2$/°F/in. | 1.2 | 1.3 |
| Heat distortion temperature °F/°C | | |
| at 66 psi | 220/107 | 220/107 |
| at 264 psi | 140/60 | 124/49 |
| Limiting oxygen index, % | 17 | — |
| Flame spread | Slow burning | |
| Underwriters Lab rating, Sub 94 | 94 HB | |

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The homopolymers, being long-chain, high-molecular-weight molecules with a minimum of random orientation, have optimum chemical, thermal, and physical properties. For this reason, homopolymer material is preferred for difficult chemical, thermal, and physical conditions.

Polypropylene is subject to degradation by ultraviolet light. Therefore, if it is exposed to sunlight, an ultraviolet absorber or screening agent must be used to protect the material. It is not affected by most inorganic chemicals, except the halogens and severe oxidizing conditions. PP can be used with sulfur-bearing compounds, caustics, solvents, acids, and other organic chemicals.

It should not be used with oxidizing-type acids, detergents, low-boiling hydrocarbons, alcohols, aromatics, and some chlorinated organic materials. Refer to Table P.38 for the compatibility of polypropylene with selected corrodents. Reference 8 provides a wider range of corrodents and the compatibility of PP with them.

See Refs. 8 and 10.

**Table P.38** Compatibility of PP with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | 120 | 49 | Ammonium fluoride 10% | 210 | 99 |
| Acetamide | 110 | 43 | Ammonium fluoride 25% | 200 | 93 |
| Acetic acid 10% | 220 | 104 | Ammonium hydroxide 25% | 200 | 93 |
| Acetic acid 50% | 200 | 93 | Ammonium hydroxide, sat. | 200 | 93 |
| Acetic acid 80% | 200 | 93 | Ammonium nitrate | 200 | 93 |
| Acetic acid, glacial | 190 | 88 | Ammonium persulfate | 220 | 104 |
| Acetic anhydride | 100 | 38 | Ammonium phosphate | 200 | 93 |
| Acetone | 220 | 104 | Ammonium sulfate 10–40% | 200 | 93 |
| Acetyl chloride | x | x | Ammonium sulfide | 220 | 104 |
| Acrylic acid | x | x | Ammonium sulfite | 220 | 104 |
| Acrylonitrile | 90 | 32 | Amyl acetate | x | x |
| Adipic acid | 100 | 38 | Amyl alcohol | 200 | 93 |
| Allyl alcohol | 140 | 60 | Amyl chloride | x | x |
| Allyl chloride | 140 | 60 | Aniline | 180 | 82 |
| Alum | 220 | 104 | Antimony trichloride | 180 | 82 |
| Aluminum acetate | 100 | 38 | Aqua regia 3:1 | x | x |
| Aluminum chloride, aqueous | 200 | 93 | Barium carbonate | 200 | 93 |
| Aluminum chloride, dry | 220 | 104 | Barium chloride | 220 | 104 |
| Aluminum fluoride | 200 | 93 | Barium hydroxide | 200 | 93 |
| Aluminum hydroxide | 200 | 93 | Barium sulfate | 200 | 93 |
| Aluminum nitrate | 200 | 93 | Barium sulfide | 200 | 93 |
| Aluminum oxychloride | 220 | 104 | Benzaldehyde | 80 | 27 |
| Aluminum sulfate | | | Benzene | 140 | 60 |
| Ammonia gas | 150 | 66 | Benzene sulfonic acid 10% | 180 | 82 |
| Ammonium bifluoride | 200 | 93 | Benzoic acid | 190 | 88 |
| Ammonium carbonate | 220 | 104 | Benzyl alcohol | 140 | 60 |
| Ammonium chloride 10% | 180 | 82 | Benzyl chloride | 80 | 27 |
| Ammonium chloride 50% | 180 | 82 | Borax | 210 | 99 |
| Ammonium chloride, sat. | 200 | 93 | Boric acid | 220 | 104 |

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**Table P.38** Compatibility of PP with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Bromine gas, dry | x | x | Copper carbonate | 200 | 93 |
| Bromine gas, moist | x | x | Copper chloride | 200 | 93 |
| Bromine liquid | x | x | Copper cyanide | 200 | 93 |
| Butadiene | x | x | Copper sulfate | 200 | 93 |
| Butyl acetate | x | x | Cresol | x | x |
| Butyl alcohol | 200 | 93 | Cupric chloride 5% | 140 | 60 |
| *n*-Butylamine | 90 | 32 | Cupric chloride 50% | 140 | 60 |
| Butyl phthalate | 180 | 82 | Cyclohexane | x | x |
| Butyric acid | 180 | 82 | Cyclohexanol | 150 | 66 |
| Calcium bisulfide | 210 | 99 | Dichloroacetic acid | 100 | 38 |
| Calcium bisulfite | 210 | 99 | Dichloroethane | | |
| Calcium carbonate | 210 | 99 | (ethylene dichloride) | 80 | 27 |
| Calcium chlorate | 220 | 104 | Ethylene glycol | 210 | 99 |
| Calcium chloride | 220 | 104 | Ferric chloride | 210 | 99 |
| Calcium hydroxide 10% | 200 | 93 | Ferric chloride 50% in water | 210 | 99 |
| Calcium hydroxide, sat. | 220 | 104 | Ferric nitrate 10–50% | 210 | 99 |
| Calcium hypochlorite | 210 | 99 | Ferrous chloride | 210 | 99 |
| Calcium nitrate | 210 | 99 | Ferrous nitrate | 210 | 99 |
| Calcium oxide | 220 | 104 | Fluorine gas, dry | x | x |
| Calcium sulfate | 220 | 104 | Fluorine gas, moist | x | x |
| Caprylic acid | 140 | 60 | Hydrobromic acid, dilute | 230 | 110 |
| Carbon bisulfide | x | x | Hydrobromic acid 20% | 200 | 93 |
| Carbon dioxide, dry | 220 | 104 | Hydrobromic acid, 50% | 190 | 88 |
| Carbon dioxide, wet | 140 | 60 | Hydrochloric acid 20% | 220 | 104 |
| Carbon disulfide | x | x | Hydrochloric acid 38% | 200 | 93 |
| Carbon monoxide | 220 | 104 | Hydrocyanic acid 10% | 150 | 66 |
| Carbon tetrachloride | x | x | Hydrofluoric acid 30% | 180 | 82 |
| Carbonic acid | 220 | 104 | Hydrofluoric acid 70% | 200 | 93 |
| Cellosolve | 200 | 93 | Hydrofluoric acid 100% | 200 | 93 |
| Chloracetic acid | 180 | 82 | Hypochlorous acid | 140 | 60 |
| Chloracetic acid, 50% water | 80 | 27 | Iodine solution 10% | x | x |
| Chlorine gas, dry | x | x | Ketones, general | 110 | 43 |
| Chlorine gas, wet | x | x | Lactic acid 25% | 150 | 66 |
| Chlorine liquid | x | x | Lactic acid, concentrated | 150 | 66 |
| Chlorobenzene | x | x | Magnesium chloride | 210 | 99 |
| Chloroform | x | x | Malic acid | 130 | 54 |
| Chlorosulfonic acid | x | x | Manganese chloride | 120 | 49 |
| Chromic acid 10% | 140 | 60 | Methyl chloride | x | x |
| Chromic acid 50% | 150 | 66 | Methyl ethyl ketone | x | x |
| Chromyl chloride | 140 | 60 | Methyl isobutyl ketone | 80 | 27 |
| Citric acid 15% | 220 | 104 | Muriatic acid | 200 | 93 |
| Citric acid, con. | 220 | 104 | Nitric acid 5% | 140 | 60 |
| Copper acetate | 80 | 27 | Nitric acid 20% | 140 | 60 |

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**Table P.38** Compatibility of PP with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Nitric acid 70% | x | x | Sodium hypochlorite, | | |
| Nitric acid, anhydrous | x | x | concentrated | 110 | 43 |
| Nitrous acid, concentrated | x | x | Sodium sulfide to 50% | 190 | 88 |
| Oleum | x | x | Stannic chloride | 150 | 66 |
| Perchloric acid 10% | 140 | 60 | Stannous chloride | 200 | 93 |
| Perchloric acid 70% | x | x | Sulfuric acid 10% | 200 | 93 |
| Phenol | 180 | 82 | Sulfuric acid 50% | 200 | 93 |
| Phosphoric acid 50–80% | 210 | 99 | Sulfuric acid 70% | 180 | 82 |
| Picric acid | 140 | 60 | Sulfuric acid 90% | 180 | 82 |
| Potassium bromide 30% | 210 | 99 | Sulfuric acid 98% | 120 | 49 |
| Salicylic acid | 130 | 54 | Sulfuric acid 100% | x | x |
| Silver bromide 10% | 170 | 77 | Sulfuric acid, fuming | x | x |
| Sodium carbonate | 220 | 104 | Sulfurous acid | 180 | 82 |
| Sodium chloride | 200 | 93 | Thionyl chloride | 100 | 38 |
| Sodium hydroxide 10% | 220 | 104 | Toluene | x | x |
| Sodium hydroxide 50% | 220 | 104 | Trichloroacetic acid | 150 | 66 |
| Sodium hydroxide, | | | White liquor | 220 | 104 |
| concentrated | 140 | 60 | Zinc chloride | 200 | 93 |
| Sodium hypochlorite 20% | 120 | 49 | | | |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that the data are unavailable.
*Source:* Schweitzer, PA. *Corrosion Resistance Tables.* 4th ed. Vols 1–3. New York: Marcel Dekker, 1995.

## POLYSILOXANE RUBBER

See "Silicone and Fluorosilicone Rubbers."

## POLYSULFIDE RUBBERS (ST AND FA)

Polysulfide rubbers are manufactured by combining ethylene ($CH_2 = CH_2$) with an alkaline polysulfide. The sulfur forms a part of the polymerized molecule. They are also known as Thiokol rubbers. In general, these elastomers do not have great elasticity, but they do have good resistance to most solvents. Compared with nitrile rubber they have poor tensile strength, a pungent odor, poor rebound, high creep under strain, and poor abrasion resistance.

Modified organic polysulfides are made by substituting other unsaturated compounds for ethylene, which results in compounds that have little objectionable odor.

### Physical and Mechanical Properties

ST polysulfide rubber is prepared from bis(2-chloroethyl) formal and sodium polysulfide. Products made from these rubbers have good low-temperature properties and exhibit

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outstanding resistance to oils and solvents, to gas permeation, and to weathering. Pure gum vulcanizates possess poor physical properties, and as a result all practical compounds contain reinforcing fillers, usually carbon blacks.

Compounds can be used continuously at temperatures of 212°F (100°C) and intermittently at temperatures up to 300°F (149°C). The polymer does not melt or soften at elevated temperatures, but a gradual shortening in elongation and drop in tensile strength do occur. As the temperature increases, the effect becomes more pronounced. With the addition of plasticizers, ST compounds can be made to remain flexible at temperatures below –60°F (–51°C).

Compression set values for ST elastomers are shown in Table P.39. The use of ST rubber in compressive applications should be limited to those applications in which service temperatures do not exceed 200°F (93°C).

ST polysulfide rubber is blended with nitrile rubber (NBR) and neoprene to obtain a balance of properties unattainable with either polymer alone. High ratios of ST to NBR or neoprene W decrease the swelling from aromatics, fuels, ketones, and esters. The low-temperature flexibility is also improved. Higher ratios of NBR or neoprene W to ST result in improvements in physical properties, tear strength, and compressive set resistance before and after heat aging.

The electrical insulating properties of ST are poor, as is its flame resistance.

Table P.39 lists the physical and mechanical properties of ST polysulfide.

**Table P.39** Physical and Mechanical Properties of Polysulfide ST Rubber[a]

| | | | |
|---|---|---|---|
| Specific gravity | | 1.27 | |
| Brittle point | | –60°F (–51°C) | |
| Permeability | | | |
| to helium gas, $cm^3/s\text{-}in.^2$, 0.1-in, thick film | | 1.5 | |
| to solvents, fl oz/in.-24 h-$ft^2$ | 75°F (24°C) | | 180°F (82°C) |
| methanol | 0.005 | | 0.140 |
| tetrachloride | 0.042 | | 0.210 |
| acetate | 0.150 | | 0.510 |
| benzene | 0.540 | | 1.800 |
| diisobutylene | 0.0 | | 0.001 |
| methyl ethyl ketone | 0.28 | | 0.65 |
| Tensile strength, psi | | 500–1750 | |
| Elongation, % at break | | 230–450 | |
| Hardness, Shore A | | 30–90 | |
| Abrasion resistance | | Good | |
| Maximum temperature, continuous use | | 212°F (100°C) | |
| Compression set, % after 22 h | | | |
| at 158°F (70°C) | | 15 | |
| at 212°F (100°C) | | 75 | |
| Machining qualities | | Excellent | |
| Resistance to sunlight | | Excellent | |
| Effect of aging | | None | |
| Resistance to heat | | Fair | |

[a]These are representative values since they may be altered by compounding.

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FA polysulfide is prepared by reacting a mixture of bis(2-chloroethyl) formal and ethylene dichloride with sodium polysulfide. Cured compounds are particularly noted for outstanding volume swell resistance to aliphatic and aromatic solvents; resistance to alcohols, ketones, and esters; exceptional low permeability to gases, water, and organic liquids; and excellent low-temperature flexibility.

FA polysulfide rubbers that contain no plasticizers are flexible at temperatures as low as –50°F (–45°C), and they retain their excellent flexing characteristics at subnormal temperatures even when oil and solvent are present. With the addition of plasticizers or reinforcing pigments, a wide range of hardness can be achieved. Depending on the hardness, tensile strengths up to 1500 psi can be developed. When the materials are immersed in solvents, they retain a very high percentage of this tensile strength. The FA polysulfide rubbers have a wider operating temperature range than the ST elastomers. The FA series remain serviceable over a range of –50 to 250°F (–45 to 121°C).

The electrical properties of the FA polysulfide rubbers are good, but their flame resistance is poor. Table P.40 lists the physical and mechanical properties of PA polysulfide rubber.

**Table P.40** Physical and Mechanical Properties of Polysulfide FA Rubber[a]

| | |
|---|---|
| Specific gravity | 1.34 |
| Refractive index | 1.65 |
| Brittle point | –30°F (–35°C) |
| Dielectric constant | |
| at 1 kHz | 7.3 |
| at 1 MHz | 6.8 |
| Dissipation factor | |
| at 1 kHz | $5.3 \times 10^{-3}$ |
| at 1MHz | $5.2 \times 10^{13}$ |
| Volume resistivity, ohm-cm | |
| at 73°F (23°C) | $5 \times 10^{13}$ |
| at 140°F (60°C) | $2 \times 10^{12}$ |
| Surface resistivity, ohms | |
| at 73°F (23°C) | $7 \times 10^{14}$ |
| at 140°F (60°C) | $2 \times 10^{14}$ |
| Permeability at 75°F (24°C)[b] | |
| to methanol | 0.001 |
| to carbon tetrachloride | 0.01 |
| to ethyl acetate | 0.04 |
| to benzene | 0.14 |
| Permeability at room temperature[c] | |
| to hydrogen | $14.8 \times 10^{-6}$ |
| to helium | $9.4 \times 10^{-6}$ |
| Swelling, % by volume | |
| in kerosene at 77°F (25°C) | 4 |
| in benzene at 77°F (25°C) | 50 |
| in acetone at 77°F (25°C) | 25 |
| in mineral oil at 158°F (70°C) | 1 |

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**Table P.40** Physical and Mechanical Properties of Polysulfide FA Rubber[a] (Continued)

| | |
|---|---|
| Tensile strength, psi | 150–1200 |
| Elongation, % at break | 210–700 |
| Hardness, Shore A | 25–90 |
| Abrasion resistance | Fair |
| Maximum temperature, continuous use | 250°F (121°C) |
| Machining qualities | Excellent |
| Resistance to sunlight | Excellent |
| Effect of aging | None |

[a]These are representative values since they may be altered by compounding.
[b]1/16-in. (1.6 mm), sheet, in.-oz.-in.$^2$ (24 h)-ft.
[c]0.25-mm thick sheet in cm$^3$/cm$^2$-min.

ST polysulfide rubber compounded with carbon black is resistant to ultraviolet light and sunlight. Its resistance to ozone is good but can be improved by the addition of NBC, though this addition can degrade the material's compression set. ST polysulfide rubber also possesses satisfactory weather resistance.

## Chemical Resistance

The polysulfide rubbers possess outstanding resistance to solvents. They exhibit excellent resistance to oils, gasoline, and aliphatic and aromatic hydrocarbon solvents, very good water resistance, good alkali resistance, and fair acid resistance. FA polysulfide rubbers are somewhat more resistant to solvents than the ST rubbers. Compounding of the FA polymers with NBR will provide high resistance to aromatic solvents and improve the physical properties of the blend. For high resistance to esters and ketones, neoprene W is compounded with FA polysulfide rubber to produce improved physical properties.

ST polysulfide rubbers exhibit better resistance to chlorinated organics than the FA polysulfide rubbers. Contact of either rubber with strong, concentrated inorganic acids such as sulfuric, nitric, or hydrochloric should be avoided. Refer to Table P.41 for the compatibility of polysulfide ST rubber with selected corrodents.

**Table P.41** Compatibility of Polysulfide ST Rubber with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetamide | x | x | Ammonium chloride, sat. | 90 | 32 |
| Acetic acid 10% | 80 | 27 | Ammonium hydroxide 10% | x | x |
| Acetic acid 50% | 80 | 27 | Ammonium hydroxide 25% | x | x |
| Acetic acid 80% | 80 | 27 | Ammonium hydroxide, sat. | x | x |
| Acetic acid, glacial | 80 | 27 | Ammonium sulfate 10–40% | x | x |
| Acetone | 80 | 27 | Amyl alcohol | 80 | 27 |
| Ammonia gas | x | x | Aniline | x | x |
| Ammonium chloride 10% | 150 | 66 | Benzene | x | x |
| Ammonium chloride 28% | 150 | 66 | Benzoic acid | 150 | 66 |
| Ammonium chloride 50% | 150 | 66 | Bromine water, dilute | 80 | 27 |

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**Table P.41** Compatibility of Polysulfide ST Rubber with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Bromine water, sat. | 80 | 27 | Hydrochloric acid 20% | x | x |
| Butane | 150 | 66 | Hydrochloric acid 35% | x | x |
| Butyl acetate | 80 | 66 | Hydrochloric acid 38% | x | x |
| Butyl alcohol | 80 | 66 | Hydrochloric acid 50% | x | x |
| Calcium chloride dilute | 150 | 66 | Hydrofluoric acid, dilute | x | x |
| Calcium chloride, sat. | 150 | 66 | Hydrofluoric acid 30% | x | x |
| Calcium hydroxide 10% | x | x | Hydrofluoric acid 40% | x | x |
| Calcium hydroxide 20% | x | x | Hydrofluoric acid 50% | x | x |
| Calcium hydroxide 30% | x | x | Hydrofluoric acid 70% | x | x |
| Calcium hydroxide, sat. | x | x | Hydrofluoric acid 100% | x | x |
| Cane sugar liquors | x | x | Hydrogen peroxide, | | |
| Carbon bisulfide | x | x | all concentrations | x | x |
| Carbon tetrachloride | x | x | Lactic acid, | | |
| Carbonic acid | 150 | 66 | all concentrations | x | x |
| Castor oil | 80 | 66 | Methyl ethyl ketone | 150 | 66 |
| Cellosolve | 80 | 66 | Methyl isobutyl ketone | 80 | 27 |
| Chlorine water, sat. | x | x | Monochlorobenzene | x | x |
| Chlorobenzene | x | x | Muriatic acid | x | x |
| Chloroform | x | x | Nitric acid, all concentrations | x | x |
| Chromic acid 10% | x | x | Oxalic acid, all concentrations | x | x |
| Chromic acid 30% | x | x | Phenol, all concentrations | x | x |
| Chromic acid 40% | x | x | Phosphoric acid, | | |
| Chromic acid 50% | x | x | all concentrations | x | x |
| Citric acid 5% | x | x | Potassium hydroxide to 50% | 80 | 27 |
| Citric acid 10% | x | x | Potassium sulfate 10% | 90 | 32 |
| Citric acid 15% | x | x | Propane | 150 | 66 |
| Citric acid, conc. | x | x | Silicone oil | x | x |
| Copper sulfate | x | x | Sodium carbonate | x | x |
| Corn oil | 90 | 32 | Sodium chloride | 80 | 27 |
| Cottonseed oil | 90 | 32 | Sodium hydroxide, | | |
| Cresol | x | x | all concentrations | x | x |
| Diacetone alcohol | 80 | 27 | Sodium hypochlorite, | | |
| Dibutyl phthalate | 80 | 27 | all concentrations | x | x |
| Ethers, general | 90 | 32 | Sulfuric acid, | | |
| Ethyl acetate | 80 | 27 | all concentrations | x | x |
| Ethyl alcohol | 80 | 27 | Toluene | x | x |
| Ethylene chloride | 80 | 27 | Trichloroethylene | x | x |
| Ethylene glycol | 150 | 66 | Water, demineralized | 80 | 27 |
| Formaldehyde dilute | 80 | 27 | Water, distilled | 80 | 27 |
| Formaldehyde 37% | 80 | 27 | Water, salt | 80 | 27 |
| Formaldehyde 50% | 80 | 27 | Water, sea | 80 | 27 |
| Glycerine | 80 | 27 | Whiskey | x | x |
| Hydrochloric acid, dilute | x | x | Zinc chloride | x | x |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that the data are unavailable.

*Source:* Schweitzer, PA. *Corrosion Resistance Tables.* 4th ed. VoIs 1–3. New York: Marcel Dekker, 1995.

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### Applications

FA polysulfide rubber is one of the elastomeric materials commonly used for the fabrication of rubber rollers for printing and coating equipment. The major reason for this is its high degree of resistance to the many types of solvents, including ketones, esters, aromatic hydrocarbons, and plasticizers, that are used as vehicles for the various printing inks and coatings.

Applications are also found in the fabrication of hose and hose liners for the handling of aromatic solvents, esters, ketones, oils, fuels, gasolines, paints, lacquers, and thinners. Large amounts of material are also used to produce caulking compounds, cement, paint can gaskets, seals, and flexible mountings.

The impermeability of the polysulfide rubbers to air and gas has promoted the use of these materials for inflatable products such as life jackets, life rafts, balloons, and other items.

### Resistance to Sun, Weather, and Ozone

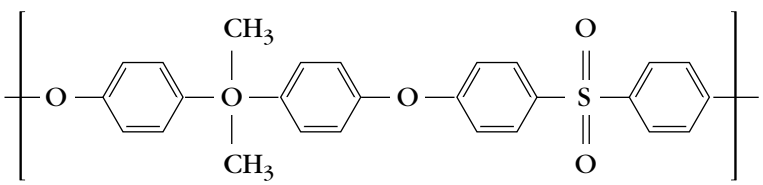
FA polysulfide rubber compounds display excellent resistance to ozone, weathering, and exposure to ultraviolet light. Their resistance is superior to that of the ST polysulfide rubbers. If high concentrations of ozone are to be present, the use of 0.5 parts of nickel dibutyldithiocarbamate (NBC) per 100 parts of FA polysulfide rubber will improve the ozone resistance.

ST polysulfide rubber compounded with carbon black is resistant to ultraviolet light and sunlight. Its resistance to ozone is good but can be improved by the addition of NBC, though this addition can degrade the material's compression set. ST polysulfide rubber also possesses satisfactory weather resistance.

See Refs. 7, 8, and 21.

## POLYSULFONE (PSF)

Polysulfone is an engineering polymer that can be used at elevated temperatures. It has the following chemical structure:




The linkages connecting the benzene rings are hydrolytically stable.

PSF has high tensile strength and stress-strain behavior, which is typical of that found in a ductile material. In addition, as temperatures increase, flexural modulus remains high. These resins also remain stable at elevated temperatures, resisting creep and deformation under continuous load. PSF has an operating temperature range of –150 to 300°F (–101 to 146°C).

PSF also exhibits excellent electrical properties that remain stable over a wide temperature range up to 350°F/177°C. Refer to Table P.42 for its physical and mechanical properties.

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**Table P.42** Physical and Mechanical Properties of Unfilled PSF

| Property | Flame retardant | Unfilled |
|---|---|---|
| Specific gravity | 1.24–1.25 | 1.24 |
| Water absorption (24 hr at 73°F/23°C) (%) | 0.3 | 0.62 |
| Dielectric strength, short-term (V/mil) | 425 | 20 |
| Tensile strength at break (psi) | | 10,200 |
| Tensile modulus (psi $\times 10^3$) | 360–390 | 390 |
| Elongation at break (%) | 50–100 | 40–80 |
| Compressive strength (psi) | 40,000 | |
| Flexural strength (psi) | 15,400–17,500 | 17,500 |
| Compressive modulus (psi $\times 10^3$) | 374 | |
| Flexural modulus (psi $\times 10^3$) | | |
| at 73°F/23°C | 390 | 370 |
| at 200°F/93°C | 370 | |
| at 250°F/121°C | 350 | |
| Izod impact (ft-lb/in. of notch) | 1.0–1.3 | 1.0–1.2 |
| Hardness, Rockwell | M69 | R120 |
| Coefficient of thermal expansion ($10^{-6}$ in./in./°F) | 56 | 31 |
| Thermal conductivity ($10^{-4}$cal-cm/s-cm$^2$ °C or Btu/h/ft$^2$/°F/in.) | 6.2 | 1.8 |
| Deflection temperature | | |
| at 264 psi (°F) | 345 | 340 |
| at 66 psi (°F) | 358 | 360 |
| Max. operating temperature (°F/°C) | | 300/149 |
| Limiting oxygen index (%) | | |
| Flame spread | | |
| Underwriters Lab rating (Sub. 94) | V-O | |

Polysulfone can be reinforced with glass fiber to improve its mechanical properties, as shown in Table P.43.

**Table P.43** Physical and Mechanical Properties of Glass–Fiber Reinforced PSF

| Property | 10% reinforcing | 30% reinforcing |
|---|---|---|
| Specific gravity | 1.31 | 1.46–1.49 |
| Water absorption (24 h at 73°F/23°C) (%) | | 0.3 |
| Dielectric strength, short-term (V/mil) | | |
| Tensile strength at break (psi) | 14,500 | 14,500–18,100 |
| Tensile modulus (psi $\times 10^3$) | 667–670 | 1360–1450 |
| Elongation at break (%) | 4.2 | 1.5–1.8 |
| Compressive strength (psi) | | 19,000 |
| Flexural strength (psi) | 20,000 | 20,000–23,500 |
| Compressive modulus (psi $\times 10^3$) | | |
| Flexural modulus (psi $\times 10^3$) | | |
| at 73°F/23°C | 600 | 1050–1250 |
| at 200°F/93°C | | |
| at 250°F/121°C | | |

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**Table P.43** Physical and Mechanical Properties of Glass–Fiber Reinforced PSF (Continued)

| Property | 10% reinforcing | 30% reinforcing |
|---|---|---|
| Izod impact (ft-lb/in. of notch) | 1.3 | 1.1–1.5 |
| Hardness, Rockwell | M79 | M87–100 |
| Coefficient of thermal expansion ($10^{-6}$ in./in./°F) | 18–32 | 20–25 |
| Thermal conductivity ($10^{-4}$cal-cm/s-cm$^2$°C or Btu/h/ft$^2$/°F in.) | | |
| Deflection temperature | | |
| at 264 psi (°F) | 361 | 350–365 |
| at 66 psi (°F) | 367 | 360–372 |
| Max. operating temperature (°F/°C) | | |
| Limiting oxygen index (%) | | |
| Flame spread | | |
| Underwriters Lab rating (Sub. 94) | | |

PSF is resistant to repeated sterilization by several techniques including steam, dry heat, ethylene oxide, certain chemicals, and radiation. It will withstand exposure to soap, detergent solutions, and hydrocarbon oils, even at elevated temperatures and under moderate stress levels. Polysulfone is unaffected by hydrolysis and has a very high resistance to mineral acids, alkali, and salt solutions.

PSF is not resistant to polar organic solvents such as ketones, chlorinated hydrocarbons, and aromatic hydrocarbons.

Polysulfone has good weatherability and is not degraded by UV radiation. Refer to Table P.44 for the compatibility of PSF with selected corrodents. Reference 8 provides a more detailed listing.

**Table P.44** Compatibility of PSF with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetaldehyde | x | x | Ammonium chloride 10% | 200 | 93 |
| Acetic acid 10% | 200 | 93 | Ammonium chloride 50% | 200 | 93 |
| Acetic acid 50% | 200 | 93 | Ammonium chloride, sat. | 200 | 93 |
| Acetic acid 80% | 200 | 93 | Ammonium hydroxide 25% | 200 | 93 |
| Acetic acid, glacial | 200 | 93 | Ammonium hydroxide, sat. | 200 | 93 |
| Acetone | x | x | Ammonium nitrate | 200 | 93 |
| Acetyl chloride | x | x | Ammonium phosphate | 200 | 93 |
| Aluminum chloride, aqueous | 200 | 93 | Ammonium sulfate to 40% | 200 | 93 |
| Aluminum chloride, dry | 200 | 93 | Amyl acetate | x | x |
| Aluminum fluoride | 200 | 93 | Amyl alcohol | 200 | 93 |
| Aluminum oxychloride | 150 | 66 | Aniline | x | x |
| Aluminum sulfate | 200 | 93 | Aqua regia 3:1 | x | x |
| Ammonia gas | x | x | Barium carbonate | 200 | 93 |
| Ammonium carbonate | 200 | 93 | Barium chloride 10% | 200 | 93 |

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**Table P.44** Compatibility of PSF with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Barium hydroxide | 200 | 93 | Dibutyl phthalate | 180 | 82 |
| Barium sulfate | 200 | 93 | Ethylene glycol | 200 | 93 |
| Benzaldehyde | x | x | Ferric chloride | 200 | 93 |
| Benzene | x | x | Ferric nitrate | 200 | 93 |
| Benzoic acid | x | x | Ferrous chloride | 200 | 93 |
| Benzyl chloride | x | x | Hydrobromic acid, dilute | 300 | 149 |
| Borax | 200 | 93 | Hydrobromic acid 20% | 200 | 93 |
| Boric acid | 200 | 93 | Hydrochloric acid 20% | 140 | 60 |
| Bromine gas, moist | 200 | 93 | Hydrochloric acid 38% | 140 | 60 |
| Butyl acetate | x | x | Hydrofluoric acid 30% | 80 | 27 |
| Butyl alcohol | 200 | 93 | Ketones, general | x | x |
| *n*-Butylamine | x | x | Lactic acid 25% | 200 | 93 |
| Calcium bisulfite | 200 | 93 | Lactic acid, conc. | 200 | 93 |
| Calcium chloride | 200 | 93 | Methyl chloride | x | x |
| Calcium hypochlorite | 200 | 93 | Methyl ethyl ketone | x | x |
| Calcium nitrate | 200 | 93 | Nitric acid 20% | x | x |
| Calcium sulfate | 200 | 93 | Nitric acid 5% | x | x |
| Carbon bisulfide | x | x | Nitric acid 70% | x | x |
| Carbon disulfide | x | x | Nitric acid, anhydrous | x | x |
| Carbon tetrachloride | x | x | Phosphoric acid 50–80% | 80 | 27 |
| Carbonic acid | 200 | 93 | Potassium bromide 30% | 200 | 93 |
| Cellosolve | x | x | Sodium carbonate | 200 | 93 |
| Chlorine liquid | x | x | Sodium chloride | 200 | 93 |
| Chloroacetic acid | x | x | Sodium hydroxide 10% | 200 | 93 |
| Chlorobenzene | x | x | Sodium hydroxide 50% | 200 | 93 |
| Chloroform | x | x | Sodium hypochlorate 20% | 300 | 149 |
| Chlorosulfonic acid | x | x | Sodium hypochlorite, conc. | 300 | 149 |
| Chromic acid 10% | 140 | 60 | Sodium sulfite to 50% | 200 | 93 |
| Chromic acid 50% | x | x | Stannic chloride | 200 | 93 |
| Citric acid 15% | 100 | 38 | Sulfuric acid 10% | 300 | 149 |
| Citric acid 40% | 80 | 27 | Sulfuric acid 50% | 300 | 149 |
| Copper cyanide | 200 | 93 | Sulfuric acid 70% | x | x |
| Copper sulfate | 200 | 93 | Sulfuric acid 90% | x | x |
| Cresol | x | x | Sulfuric acid 98% | x | x |
| Cupric chloride 5% | 200 | 93 | Sulfuric acid 100% | x | x |
| Cupric chloride 50% | 200 | 93 | Sulfuric acid, fuming | x | x |
| Cyclohexane | 200 | 93 | Sulfurous acid | 200 | 93 |
| Cyclohexanol | 200 | 93 | Toluene | x | x |

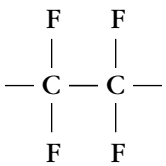
[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x.
*Source:* Schweitzer, PA. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

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Polysulfone finds application as hot-water piping, lenses, iron handles, switches, and circuit breakers. Its rigidity and high-temperature performance make it ideal for medical, microwave, and electronic application.

## POLYTETRAFLUOROETHYLENE (PTFE)

Also see "Permeation." PTFE is a fully fluorinated thermoplastic having the formula



It has an operating temperature range of –20°F (–29°C) to 450°F (232°C). This temperature range is based on the physical/mechanical properties of PTFE. When handling certain aggressive chemicals, it may be necessary to reduce the upper temperature limit. PTFE is a relatively weak material and tends to creep under stress at elevated temperatures. The physical and mechanical properties are shown in Table P.45.

PTFE is unique in its corrosion-resistant properties. It is chemically inert in the presence of most materials. There are very few materials that will attack PTFE within normal-use temperatures. Among materials that will attack PTFE are the most violent oxidizing and reducing agents known. Elemental sodium removes fluorine from the polymer molecule. The other alkali metals (potassium, lithium, etc.) act in a similar manner.

Fluorine and related compounds (e.g., chlorine trifluoride) are absorbed into the PTFE resin with such intimate contact that the mixture becomes sensitive to a source of ignition such as impact. These potent oxidizers should only be handled with great care and a recognition of the potential hazards.

The handling of 80% sodium hydroxide, aluminum chloride, ammonia, and certain amines at high temperatures have the same effect as elemental sodium. Slow oxidative attack can be produced by 70% nitric acid under pressure at 480°F (250°C). Refer to Table P.46 for the compatibility of PTFE with selected corrodents.

See Ref. 8.

**Table P.45** Physical and Mechanical Properties of PTFE

| | |
|---|---|
| Specific gravity | 2.13–2.2 |
| Water absorption, 24 h at 73°F/23°C, % | 0.01 |
| Tensile strength at 73°F/23°C, psi | 2000–6500 |
| Compressive strength, psi | 1700 |
| Flexural strength, psi | No break |
| Flexural modulus, psi $\times 10^{-5}$ | 0.7–1.1 |
| Izod impact strength, notched at 73°F/23°C, ft-lb/in. | 3 |
| Coefficient of thermal expansion, in./in. °F $\times 10^{-5}$ | 5.5 |
| Heat distortion temperature at 66 psi, °F/°C | 250/121 |
| Low-temperature embrittlement, °F/°C | –450/–268 |

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**Table P.46** Compatibility of PTFE with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | 450 | 232 | Barium carbonate | 450 | 232 |
| Acetamide | 450 | 232 | Barium chloride | 450 | 232 |
| Acetic acid 10% | 450 | 232 | Barium hydroxide | 450 | 232 |
| Acetic acid 50% | 450 | 232 | Barium sulfate | 450 | 232 |
| Acetic acid 80% | 450 | 232 | Barium sulfide | 450 | 232 |
| Acetic acid, glacial | 450 | 232 | Benzaldehyde | 450 | 232 |
| Acetic anhydride | 450 | 232 | Benzene sulfonic acid 10% | 450 | 232 |
| Acetone | 450 | 232 | Benzene[b] | 450 | 232 |
| Acetyl chloride | 450 | 232 | Benzoic acid | 450 | 232 |
| Acrylonitrile | 450 | 232 | Benzyl alcohol | 450 | 232 |
| Adipic acid | 450 | 232 | Benzyl chloride | 450 | 232 |
| Allyl alcohol | 450 | 232 | Borax | 450 | 232 |
| Allyl chloride | 450 | 232 | Boric acid | 450 | 232 |
| Alum | 450 | 232 | Bromine gas, dry[b] | 450 | 232 |
| Aluminum chloride, aqueous | 450 | 232 | Bromine liquid[b] | 450 | 232 |
| Aluminum fluoride | 450 | 232 | Butadiene[b] | 450 | 232 |
| Aluminum hydroxide | 450 | 232 | Butyl acetate | 450 | 232 |
| Aluminum nitrate | 450 | 232 | Butyl alcohol | 450 | 232 |
| Aluminum oxychloride | 450 | 232 | *n*-Butylamine | 450 | 232 |
| Aluminum sulfate | 450 | 232 | Butyl phthalate | 450 | 232 |
| Ammonia gas[b] | 450 | 232 | Butyric acid | 450 | 232 |
| Ammonium bifluoride | 450 | 232 | Calcium bisulfide | 450 | 232 |
| Ammonium carbonate | 450 | 232 | Calcium bisulfite | 450 | 232 |
| Ammonium chloride 10% | 450 | 232 | Calcium carbonate | 450 | 232 |
| Ammonium chloride 50% | 450 | 232 | Calcium chlorate | 450 | 232 |
| Ammonium chloride, sat. | 450 | 232 | Calcium chloride | 450 | 232 |
| Ammonium fluoride 10% | 450 | 232 | Calcium hydroxide 10% | 450 | 232 |
| Ammonium fluoride 25% | 450 | 232 | Calcium hydroxide, sat. | 450 | 232 |
| Ammonium hydroxide 25% | 450 | 232 | Calcium hypochlorite | 450 | 232 |
| Ammonium hydroxide, sat. | 450 | 232 | Calcium nitrate | 450 | 232 |
| Ammonium nitrate | 450 | 232 | Calcium oxide | 450 | 232 |
| Ammonium persulfate | 450 | 232 | Calcium sulfate | 450 | 232 |
| Ammonium phosphate | 450 | 232 | Caprylic acid | 450 | 232 |
| Ammonium sulfate 10–40% | 450 | 232 | Carbon bisulfide[b] | 450 | 232 |
| Ammonium sulfide | 450 | 232 | Carbon dioxide, dry | 450 | 232 |
| Amyl acetate | 450 | 232 | Carbon dioxide, wet | 450 | 232 |
| Amyl alcohol | 450 | 232 | Carbon disulfide | 450 | 232 |
| Amyl chloride | 450 | 232 | Carbon monoxide | 450 | 232 |
| Aniline | 450 | 232 | Carbon tetrachloride[c] | 450 | 232 |
| Antimony trichloride | 450 | 232 | Carbonic acid | 450 | 232 |
| Aqua regia 3:1 | 450 | 232 | Chloracetic acid | 450 | 232 |

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**Table P.46** Compatibility of PTFE with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Chloracetic acid, 50% water | 450 | 232 | Hypochlorous acid | 450 | 232 |
| Chlorine gas, dry | x | x | Iodine solution 10%[b] | 450 | 232 |
| Chlorine gas, wet[b] | 450 | 232 | Ketones, general | 450 | 232 |
| Chlorine, liquid | x | x | Lactic acid 25% | 450 | 232 |
| Chlorobenzene[b] | 450 | 232 | Lactic acid, concentrated | 450 | 232 |
| Chloroform[b] | 450 | 232 | Magnesium chloride | 450 | 232 |
| Chlorosulfonic acid | 450 | 232 | Malic acid | 450 | 232 |
| Chromic acid 10% | 450 | 232 | Methyl chloride[b] | 450 | 232 |
| Chromic acid 50% | 450 | 232 | Methyl ethyl ketone[b] | 450 | 232 |
| Chromyl chloride | 450 | 232 | Methyl isobutyl ketone[c] | 450 | 232 |
| Citric acid 15% | 450 | 232 | Muriatic acid[b] | 450 | 232 |
| Citric acid, concentrated | 450 | 232 | Nitric acid 20%[b] | 450 | 232 |
| Copper carbonate | 450 | 232 | Nitric acid 5%[b] | 450 | 232 |
| Copper chloride | 450 | 232 | Nitric acid 70%[b] | 450 | 232 |
| Copper cyanide 10% | 450 | 232 | Nitric acid, anhydrous[b] | 450 | 232 |
| Copper sulfate | 450 | 232 | Nitrous acid 10% | 450 | 232 |
| Cresol | 450 | 232 | Oleum | 450 | 232 |
| Cupric chloride 5% | 450 | 232 | Perchloric acid 10% | 450 | 232 |
| Cupric chloride 50% | 450 | 232 | Perchloric acid 70% | 450 | 232 |
| Cyclohexane | 450 | 232 | Phenol[b] | 450 | 232 |
| Cyclohexanol | 450 | 232 | Phosphoric acid 50–80% | 450 | 232 |
| Dichloroacetic acid | 450 | 232 | Picric acid | 450 | 232 |
| Dichloroethane (ethylene dichloride)[b] | 450 | 232 | Potassium bromide 30% | 450 | 232 |
| | | | Salicylic acid | 450 | 232 |
| Ethylene glycol | 450 | 232 | Sodium carbonate | 450 | 232 |
| Ferric chloride | 450 | 232 | Sodium chloride | 450 | 232 |
| Ferric chloride 50% in water | 450 | 232 | Sodium hydroxide 10% | 450 | 232 |
| Ferric nitrate 10–50% | 450 | 232 | Sodium hydroxide 50% | 450 | 232 |
| Ferrous chloride | 450 | 232 | Sodium hydroxide, concentrated | 450 | 232 |
| Ferrous nitrate | 450 | 232 | | | |
| Fluorine gas, dry | x | x | Sodium hypochlorite 20% | 450 | 232 |
| Fluorine gas, moist | x | x | Sodium hypochlorite, concentrated | 450 | 232 |
| Hydrobromic acid, dilute[b,c] | 450 | 232 | | | |
| Hydrobromic acid 20%[c] | 450 | 232 | Sodium sulfide to 50% | 450 | 232 |
| Hydrobromic acid 50%[c] | 450 | 232 | Stannic chloride | 450 | 232 |
| Hydrochloric acid 20%[c] | 450 | 232 | Stannous chloride | 450 | 232 |
| Hydrochloric acid 38%[c] | 450 | 232 | Sulfuric acid 10% | 450 | 232 |
| Hydrocyanic acid 10% | 450 | 232 | Sulfuric acid 50% | 450 | 232 |
| Hydrofluoric acid 30%[b] | 450 | 232 | Sulfuric acid 70% | 450 | 232 |
| Hydrofluoric acid 70%[b] | 450 | 232 | Sulfuric acid 90% | 450 | 232 |
| Hydrofluoric acid 100%[b] | 450 | 232 | Sulfuric acid 98% | 450 | 232 |

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**Table P.46** Compatibility of PTFE with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Sulfuric acid 100% | 450 | 232 | Toluene[b] | 450 | 232 |
| Sulfuric acid, fuming[b] | 450 | 232 | Trichloroacetic acid | 450 | 232 |
| Sulfurous acid | 450 | 232 | White liquor | 450 | 232 |
| Thionyl chloride | 450 | 232 | Zinc chloride[d] | 450 | 232 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that the data are unavailable.
[b]Material will permeate.
[c]Material will cause stress cracking.
[d]Material will be absorbed.
*Source:* Schweitzer, PA. *Corrosion Resistance Tables.* 4th ed. Vols 1–3 New York: Marcel Dekker, 1995.

## POLYURETHANE (PUR)

Polyurethanes are produced from either polyesters or polyethers. Those produced from polyether are more resistant to hydrolysis and have higher resilience, good energy-absorption characteristics, good hysteresis characteristics, and good all-around chemical resistance. The polyester-based urethanes are generally stiffer and will have higher compression and tensile moduli, higher tear strength and cut resistance, higher operating temperature, lower compression set, optimum abrasion resistance, and good fuel and oil resistance. Refer to Fig. P.2 for the structural formula

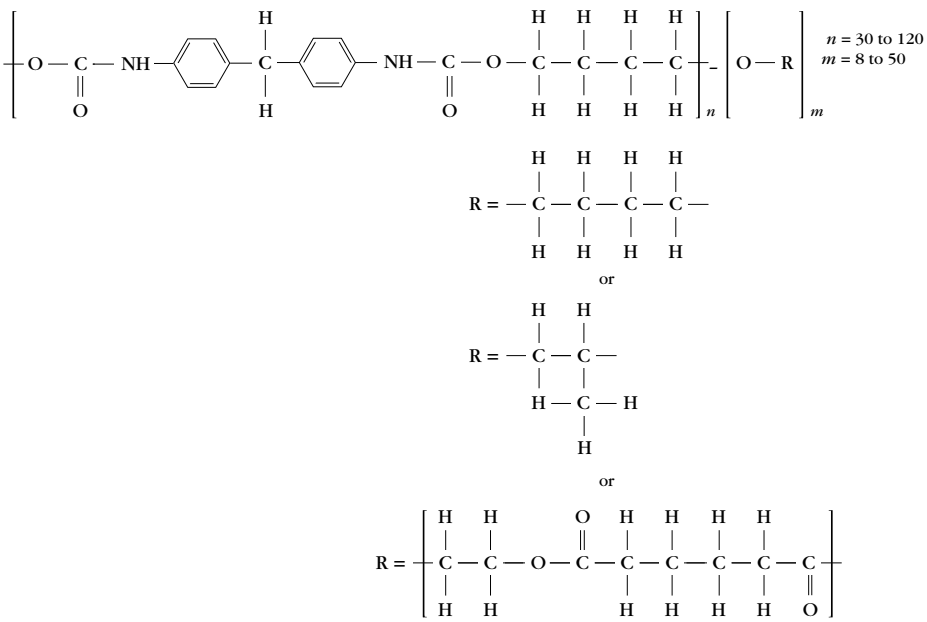



**Figure P.2** Chemical structure of PUR.

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**Table P.47** Physical and Mechanical Properties of PUR

| Property | Unfilled | 10–20% glass fiber reinforced |
|---|---|---|
| Specific gravity | 1.12–1.24 | 1.22–1.36 |
| Water absorption (24 h at 73°F/23°C) (%) | 0.15–0.19 | 0.4–0.55 |
| Dielectric strength, short-term (V/mil) | 400 | 600 |
| Tensile strength at break (psi) | 4500–9000 | 4800–7500 |
| Tensile modulus (psi $\times 10^3$) | 190–300 | 0.6–1.40 |
| Elongation at break (%) | 60–560 | 3–70 |
| Compressive strength (psi) | | 5000 |
| Flexural strength (psi) | 10,200–15,000 | 1700–6200 |
| Compressive modulus (psi $\times 10^3$) | | |
| Flexural modulus (psi $\times 10^3$) | | |
| at 73°F/23°C | 4–310 | 40–90 |
| at 200°F/93°C | | |
| at 250°F/121°C | | |
| Izod impact (ft-lb/in. of notch) | No break, 1.5–1.8 | No break, 10–14 |
| Hardness, Rockwell | >R100, M48 | R45–55 |
| Coefficient of thermal expansion ($10^{-6}$ in./in./°F) | 0.5–0.8 | 34 |
| Thermal conductivity ($10^{-4}$cal-cm/s-cm$^2$ °C or Btu/h/ft$^2$/°F/in.) | | |
| Deflection temperature | | |
| at 264 psi (°F) | 158–260 | 115–130 |
| at 66 psi (°F) | 115–275 | 140–145 |
| Max. operating temperature (°F/°C) | | |
| Limiting oxygen index (%) | | |
| Flame spread | | |
| Underwriters Lab rating (Sub. 94) | | |

Polyurethanes can be formulated to produce a range of materials, from soft elastomers with a Shore A of 5 to tough solids with a Shore D of 90. PURs can have extremely high abrasion resistance and tear strength, excellent shock absorption, and good electrical properties. Polyurethanes can also be reinforced with glass filler. Refer to Table P.47 for the physical and mechanical properties of PUR.

Polyurethanes exhibit excellent resistance to oxygen aging but have limited life in high-humidity and high-temperature applications. Water affects PUR in two ways: temporary plastization and permanent degradation. Moisture plastization results in a slight reduction in hardness and tensile strength. When the absorbed water is removed, the original properties are restored. Hydrolytic degradation causes a permanent reduction in physical and electrical properties.

Since polyurethane is a polar material, it is resistant to nonpolar organic fluids such as oils, fuels, and greases but will be readily attacked and even dissolved by polar organic liquids such as dimethylformamide and dimethyl sulfoxide.

Table P.48 provides the compatibility of PUR with selected corrodents.

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**Table P.48** Compatibility of PUR with Selected Corrodents[a]

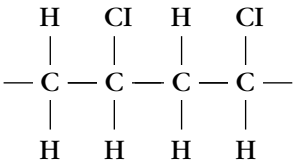
| Chemical | | Chemical | |
|---|---|---|---|
| Acetaldehyde | x | Carbonic acid | R |
| Acetamine | x | Chlorine gas, dry | x |
| Acetic acid 10% | x | Chlorine gas, wet | x |
| Acetic acid 50% | x | Chloroacetic acid | x |
| Acetic acid 80% | x | Chlorobenzene | x |
| Acetic acid, glacial | x | Chloroform | x |
| Acetic anhydride | x | Chlorosulfonic acid | x |
| Acetone | x | Chromic acid 10% | x |
| Acetyl chloride | x | Chromic acid 50% | x |
| Ammonium carbonate | R | Copper chloride | R |
| Ammonium chloride 10% | R | Copper cyanide | R |
| Ammonium chloride 50% | R | Copper sulfate | R |
| Ammonium chloride, sat. | R | Cresol | x |
| Ammonium hydroxide 25% | R | Cyclohexane | R |
| Ammonium hydroxide, sat. | R | Ethylene glycol | R |
| Ammonium persulfate | x | Ferric chloride | R |
| Amyl acetate | x | Ferric chloride 50% | R |
| Amyl alcohol | x | Ferric nitrate 10–50% | R |
| Aniline | x | Hydrochloric acid 20% | R |
| Aqua regia 3:1 | x | Hydrochloric acid 38% | x |
| Barium chloride | R | Magnesium chloride | R |
| Barium hydroxide | R | Methyl chloride | x |
| Barium sulfide | R | Methyl ethyl ketone | x |
| Benzaldehyde | x | Methyl isobutyl ketone | x |
| Benzene | x | Nitric acid 5% | x |
| Benzene sulfonic acid | x | Nitric acid 20% | x |
| Benzoic acid | x | Nitric acid 70% | x |
| Benzyl alcohol | x | Nitric acid, anhydrous | x |
| Benzyl chloride | x | Oleum | x |
| Borax | R | Perchloric acid 10% | x |
| Boric acid | R | Perchloric acid 70% | x |
| Bromine, liquid | x | Phenol | x |
| Butadiene | x | Potassium bromide 30% | R |
| Butyl acetate | x | Sodium chloride | R |
| Calcium chloride | R | Sodium hydroxide 50% | R |
| Calcium hydroxide 10% | R | Sodium hypochlorite, conc. | x |
| Calcium hydroxide, sat. | R | Sulfuric acid 10% | x |
| Calcium hypochlorite | x | Sulfuric acid 50% | x |
| Calcium nitrate | R | Sulfuric acid 70% | x |
| Carbon bisulfide | R | Sulfuric acid 90% | x |
| Carbon dioxide, dry | R | Sulfuric acid 98% | x |
| Carbon dioxide, wet | R | Sulfuric acid 100% | x |
| Carbon monoxide | R | Toluene | x |
| Carbon tetrachloride | x | | |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility at 90°F/32°C is shown by an R. Incompatibility is shown by an x.

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## POLYVINYL CHLORIDE (PVC)

See also "Polymers." Polyvinyl chloride is the most widely used of any of the thermoplasts. PVC is polymerized vinyl chloride, which is produced from acetylene and anhydrous hydrochloric acid. The structure is



PVC is stronger and more rigid than other thermoplastic materials. It has a high tensile strength and modulus of elasticity. Additives are used to further specific end uses, such as thermal stabilizers, lubricity, impact modifiers, and pigmentation.

Two types of PVC are produced, normal impact (type 1) and high impact (type 2). Type 1 is a rigid unplasticized PVC having normal impact with optimum chemical resistance. Type 2 has optimum impact resistance and reduced chemical resistance. Table P.49 lists the physical and mechanical properties of PVC.

Type I (unplasticized PVC) resists attack by most acids and strong alkalies, gasoline, kerosene, aliphatic alcohols, and hydrocarbons. It is particularly useful in the handling of hydrochloric acid.

PVC may be attacked by aromatics, chlorinated organic compounds, and lacquer solvents. Refer to Table P.50 for the compatibility of PVC with selected corrodents. Reference 8 provides a wider listing of the compatibility of PVC with a variety of corrodents.

See Refs. 8, 10 and 21.

**Table P.49** Physical and Mechanical Properties of PVC

| Property | Type 1 | Type 2 |
|---|---|---|
| Specific gravity | 1.45 | 1.38 |
| Water absorption (24 h at 73°F (23°C), % | 0.04 | 0.05 |
| Tensile strength at 73°F (23°C), psi | 6800 | 5500 |
| Modulus of elasticity in tension at 73°F (23°C) $\times 10^5$ | 5.0 | 4.2 |
| Compressive strength, psi | 10,000 | 7900 |
| Flexural strength, psi | 14,000 | 11,000 |
| Izod impact strength, notched at 73°F (23°C) | 0.88 | 12.15 |
| Coefficient of thermal expansion | | |
| in./in.–°F $\times 10^{-5}$ | 4.0 | 6.0 |
| in./10 °F/l00 ft | 0.40 | 0.60 |
| Thermal conductivity Btu/h/sq ft/°F/in | 1.33 | 1.62 |
| Heat distortion temperature, °F (°C) | | |
| at 66 psi | 130/54 | 135/57 |
| at 264 psi | 155/68 | 160/71 |
| Resistance to heat, °F (°C) at continuous drainage | 150/66 | 140/60 |
| Limiting oxygen index, % | | 43 |
| Flame spread | | 15–20 |
| Underwriters Lab rating (Sub 94) | | 94V-O |

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**Table P.50** Compatibility of Type 2 PVC with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | x | x | Barium chloride | 140 | 60 |
| Acetamide | x | x | Barium hydroxide | 140 | 60 |
| Acetic acid 10% | 100 | 38 | Barium sulfate | 140 | 60 |
| Acetic acid 50% | 90 | 32 | Barium sulfide | 140 | 60 |
| Acetic acid 80% | x | x | Benzaldehyde | x | x |
| Acetic acid, glacial | x | x | Benzene | x | x |
| Acetic anhydride | x | x | Benzene sulfonic acid 10% | 140 | 60 |
| Acetone | x | x | Benzoic acid | 140 | 60 |
| Acetyl chloride | x | x | Benzyl alcohol | x | x |
| Acrylic acid | x | x | Borax | 140 | 60 |
| Acrylonitrile | x | x | Boric acid | 140 | 60 |
| Adipic acid | 140 | 60 | Bromine gas, dry | x | x |
| Allyl alcohol | 90 | 32 | Bromine gas, moist | x | x |
| Allyl chloride | x | x | Bromine liquid | x | x |
| Alum | 140 | 60 | Butadiene | 60 | 16 |
| Aluminum acetate | 100 | 38 | Butyl acetate | x | x |
| Aluminum chloride, aqueous | 140 | 60 | Butyl alcohol | x | x |
| Aluminum fluoride | 140 | 60 | *n*-Butylamine | x | x |
| Aluminum hydroxide | 140 | 60 | Butyric acid | x | x |
| Aluminum nitrate | 140 | 60 | Calcium bisulfide | 140 | 60 |
| Aluminum oxychloride | 140 | 60 | Calcium bisulfite | 140 | 60 |
| Aluminum sulfate | 140 | 60 | Calcium carbonate | 140 | 60 |
| Ammonia gas | 140 | 60 | Calcium chlorate | 140 | 60 |
| Ammonium bifluoride | 90 | 32 | Calcium chloride | 140 | 60 |
| Ammonium carbonate | 140 | 60 | Calcium hydroxide 10% | 140 | 60 |
| Ammonium chloride 10% | 140 | 60 | Calcium hydroxide, sat. | 140 | 60 |
| Ammonium chloride 50% | 140 | 60 | Calcium hypochlorite | 140 | 60 |
| Ammonium chloride, sat. | 140 | 60 | Calcium nitrate | 140 | 60 |
| Ammonium fluoride 10% | 90 | 32 | Calcium oxide | 140 | 60 |
| Ammonium fluoride 25% | 90 | 32 | Calcium sulfate | 140 | 60 |
| Ammonium hydroxide 25% | 140 | 60 | Carbon bisulfide | x | x |
| Ammonium hydroxide, sat. | 140 | 60 | Carbon dioxide, dry | 140 | 60 |
| Ammonium nitrate | 140 | 60 | Carbon dioxide, wet | 140 | 60 |
| Ammonium persulfate | 140 | 60 | Carbon disulfide | x | x |
| Ammonium phosphate | 140 | 60 | Carbon monoxide | 140 | 60 |
| Ammonium sulfate 10–40% | 140 | 60 | Carbon tetrachloride | x | x |
| Ammonium sulfide | 140 | 60 | Carbonic acid | 140 | 60 |
| Amyl acetate | x | x | Cellosolve | x | x |
| Amyl alcohol | x | x | Chloracetic acid | 105 | 40 |
| Amyl chloride | x | x | Chlorine gas, dry | 140 | 60 |
| Aniline | x | x | Chlorine gas, wet | x | x |
| Antimony trichloride | 140 | 60 | Chlorine liquid | x | x |
| Aqua regia 3:1 | x | x | Chlorobenzene | x | x |
| Barium carbonate | 140 | 60 | Chloroform | x | x |

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**Table P.50** Compatibility of Type 2 PVC with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Chlorosulfonic acid | 60 | 16 | Nitric acid 5% | 100 | 38 |
| Chromic acid 10% | 140 | 60 | Nitric acid 20% | 140 | 60 |
| Chromic acid 50% | x | x | Nitric acid 70% | 70 | 23 |
| Citric acid 15% | 140 | 60 | Nitric acid, anhydrous | x | x |
| Citric acid, con. | 140 | 60 | Nitrous acid, concentrated | 60 | 16 |
| Copper carbonate | 140 | 60 | Oleum | x | x |
| Copper chloride | 140 | 60 | Perchloric acid 10% | 60 | 16 |
| Copper cyanide | 140 | 60 | Perchloric acid 70% | 60 | 16 |
| Copper sulfate | 140 | 60 | Phenol | x | x |
| Cresol | x | x | Phosphoric acid 50–80% | 140 | 60 |
| Cyclohexanol | x | x | Picric acid | x | x |
| Dichloroacetic acid | 120 | 49 | Potassium bromide 30% | 140 | 60 |
| Dichloroethane | | | Salicylic acid | x | x |
| (ethylene dichloride) | x | x | Silver bromide 10% | 105 | 40 |
| Ethylene glycol | 140 | 60 | Sodium carbonate | 140 | 60 |
| Ferric chloride | 140 | 60 | Sodium chloride | 140 | 60 |
| Ferric nitrate 10–50% | 140 | 60 | Sodium hydroxide 10% | 140 | 60 |
| Ferrous chloride | 140 | 60 | Sodium hydroxide 50% | 140 | 60 |
| Ferrous nitrate | 140 | 60 | Sodium hydroxide, | | |
| Fluorine gas, dry | x | x | concentrated | 140 | 60 |
| Fluorine gas, moist | x | x | Sodium hypochlorite 20% | 140 | 60 |
| Hydrobromic acid, dilute | 140 | 60 | Sodium hypochlorite, | | |
| Hydrobromic acid 20% | 140 | 60 | concentrated | 140 | 60 |
| Hydrobromic acid 50% | 140 | 60 | Sodium sulfide to 50% | 140 | 60 |
| Hydrochloric acid 20% | 140 | 60 | Stannic chloride | 140 | 60 |
| Hydrochloric acid 38% | 140 | 60 | Stannous chloride | 140 | 60 |
| Hydrocyanic acid 10% | 140 | 60 | Sulfuric acid 10% | 140 | 60 |
| Hydrofluoric acid 30% | 120 | 49 | Sulfuric acid 50% | 140 | 60 |
| Hydrofluoric acid 70% | 68 | 20 | Sulfuric acid 70% | 140 | 60 |
| Hypochlorous acid | 140 | 60 | Sulfuric acid 90% | x | x |
| Ketones, general | x | x | Sulfuric acid 98% | x | x |
| Lactic acid 25% | 140 | 60 | Sulfuric acid 100% | x | x |
| Lactic acid, concentrated | 80 | 27 | Sulfuric acid, fuming | x | x |
| Magnesium chloride | 140 | 60 | Sulfurous acid | 140 | 60 |
| Malic acid | 140 | 60 | Thionyl chloride | x | x |
| Methyl chloride | x | x | Toluene | x | x |
| Methyl ethyl ketone | x | x | Trichloroacetic acid | x | x |
| Methyl isobutyl ketone | x | x | White liquor | 140 | 60 |
| Muriatic acid | 140 | 60 | Zinc chloride | 140 | 60 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that the data are unavailable.

*Source:* Schweitzer, PA. *Corrosion Resistance Tables.* 4th ed. Vols 1–3. New York: Marcel Dekker, 1995.

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## POLYVINYLIDENE CHLORIDE (SARAN)

Saran (polyvinylidene chloride) is manufactured by Dow Chemical. The resin is a proprietary product of Dow. It has found wide application in the plating industry and for handling deionized water, pharmaceuticals, food processing, and other applications where stream purity protection is critical. The material complies with FDA regulations for food processing and potable water and also with regulations prescribed by the Meat Inspection Division of the Department of Agriculture for transporting fluids used in meat production. In applications such as plating solutions, chlorines, and certain other chemicals, Saran is superior to polypropylene and finds many applications in the handling of municipal water supplies and waste waters. Refer to Table P.51 for the physical and mechanical properties. Refer to Table P.52 for the compatibility of Saran with selected corrodents.

**Table P.51** Physical and Mechanical Properties of Polyvinylidene Chloride

| | |
|---|---|
| Specific gravity | 1.75–1.85 |
| Water absorption 24 h at 73°F (23°C), % | nil |
| Tensile strength at 73°F (23°C), psi | 2700–3700 |
| Coefficient of thermal expansion | |
| in./in.-°F (°C) $\times 10^{-5}$ | 3.9 to 5 |
| in./10 °F/100 ft | 0.039 to 0.05 |
| Thermal conductivity, Btu/h/sq ft/°F/in. | 1.28 |
| Flame spread | self-extinguishing |

**Table P.52** Compatibility of Polyvinylidene Chloride (Saran) with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetaldehyde | 150 | 66 | Ammonium bifluoride | 140 | 60 |
| Acetic acid 10% | 150 | 66 | Ammonium carbonate | 180 | 82 |
| Acetic acid 50% | 130 | 54 | Ammonium chloride, sat. | 160 | 71 |
| Acetic acid 80% | 130 | 54 | Ammonium fluoride 10% | 90 | 32 |
| Acetic acid, glacial | 140 | 60 | Ammonium fluoride 25% | 90 | 32 |
| Acetic anhydride | 90 | 32 | Ammonium hydroxide 25% | x | x |
| Acetone | 90 | 32 | Ammonium hydroxide, sat. | x | x |
| Acetyl chloride | 130 | 54 | Ammonium nitrate | 120 | 49 |
| Acrylonitrile | 90 | 32 | Ammonium persulfate | 90 | 32 |
| Adipic acid | 150 | 66 | Ammonium phosphate | 150 | 66 |
| Allyl alcohol | 80 | 27 | Ammonium sulfate 10–40% | 120 | 49 |
| Alum | 180 | 82 | Ammonium sulfide | 80 | 27 |
| Aluminum chloride, aqueous | 150 | 66 | Amyl acetate | 120 | 49 |
| Aluminum fluoride | 150 | 66 | Amyl alcohol | 150 | 66 |
| Aluminum hydroxide | 170 | 77 | Amyl chloride | 80 | 27 |
| Aluminum nitrate | 180 | 82 | Aniline | x | x |
| Aluminum oxychloride | 140 | 60 | Antimony trichloride | 150 | 66 |
| Aluminum sulfate | 180 | 82 | Aqua regia 3:1 | 120 | 49 |
| Ammonia gas | x | x | Barium carbonate | 180 | 82 |

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**Table P.52** Compatibility of Polyvinylidene Chloride (Saran) with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Barium chloride | 180 | 82 | Copper carbonate | 180 | 82 |
| Barium hydroxide | 180 | 82 | Copper chloride | 180 | 82 |
| Barium sulfate | 180 | 82 | Copper cyanide | 130 | 54 |
| Barium sulfide | 150 | 66 | Copper sulfate | 180 | 82 |
| Benzaldehyde | x | x | Cresol | 150 | 66 |
| Benzene | x | x | Cupric chloride 5% | 160 | 71 |
| Benzene sulfonic acid 10% | 120 | 49 | Cupric chloride 50% | 170 | 77 |
| Benzoic acid | 120 | 49 | Cyclohexane | 120 | 49 |
| Benzyl chloride | 80 | 27 | Cyclohexanol | 90 | 32 |
| Boric acid | 170 | 77 | Dichloroacetic acid | 120 | 49 |
| Bromine liquid | x | x | Dichloroethane | | |
| Butadiene | x | x | (ethylene dichloride) | 80 | 27 |
| Butyl acetate | 120 | 49 | Ethylene glycol | 180 | 82 |
| Butyl alcohol | 150 | 66 | Ferric chloride | 140 | 60 |
| Butyl phthalate | 180 | 82 | Ferric chloride 50% in water | 140 | 60 |
| Butyric acid | 80 | 27 | Ferric nitrate 10–50% | 130 | 54 |
| Calcium bisulfite | 80 | 27 | Ferrous chloride | 130 | 54 |
| Calcium carbonate | 180 | 82 | Ferrous nitrate | 80 | 27 |
| Calcium chlorate | 160 | 71 | Fluorine gas, dry | x | x |
| Calcium chloride | 180 | 82 | Fluorine gas, moist | x | x |
| Calcium hydroxide 10% | 160 | 71 | Hydrobromic acid, dilute | 120 | 49 |
| Calcium hydroxide, sat. | 180 | 82 | Hydrobromic acid 20% | 120 | 49 |
| Calcium hypochlorite | 120 | 49 | Hydrobromic acid 50% | 130 | 54 |
| Calcium nitrate | 150 | 66 | Hydrochloric acid 20% | 180 | 82 |
| Calcium oxide | 180 | 82 | Hydrochloric acid 38% | 180 | 82 |
| Calcium sulfate | 180 | 82 | Hydrocyanic acid 10% | 120 | 49 |
| Caprylic acid | 90 | 32 | Hydrofluoric acid 30% | 160 | 71 |
| Carbon bisulfide | 90 | 32 | Hydrofluoric acid 100% | x | x |
| Carbon dioxide, dry | 180 | 82 | Hypochlorous acid | 120 | 49 |
| Carbon dioxide, wet | 80 | 27 | Ketones, general | 90 | 32 |
| Carbon disulfide | 80 | 27 | Lactic acid, concentrated | 80 | 27 |
| Carbon monoxide | 180 | 82 | Magnesium chloride | 180 | 82 |
| Carbon tetrachloride | 140 | 60 | Malic acid | 80 | 27 |
| Carbonic acid | 180 | 82 | Methyl chloride | 80 | 27 |
| Cellosolve | 80 | 27 | Methyl ethyl ketone | x | x |
| Chloracetic acid | 120 | 49 | Methyl isobutyl ketone | 80 | 27 |
| Chloracetic acid, 50% water | 120 | 49 | Muriatic acid | 180 | 82 |
| Chlorine gas, dry | 80 | 27 | Nitric acid 5% | 90 | 32 |
| Chlorine gas, wet | 80 | 27 | Nitric acid 20% | 150 | 66 |
| Chlorine liquid | x | x | Nitric acid 70% | x | x |
| Chlorobenzene | 80 | 27 | Nitric acid, anhydrous | x | x |
| Chloroform | x | x | Oleum | x | x |
| Chlorosulfonic acid | x | x | Perchloric acid 10% | 130 | 54 |
| Chromic acid 10% | 180 | 82 | Perchloric acid 70% | 120 | 49 |
| Chromic acid 50% | 180 | 82 | Phenol | x | x |
| Citric acid 15% | 180 | 82 | Phosphoric acid 50–80% | 130 | 54 |
| Citric acid, concentrated | 180 | 82 | Picric acid | 120 | 49 |

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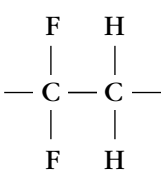
**Table P.52** Compatibility of Polyvinylidene Chloride (Saran) with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Potassium bromide 30% | 110 | 43 | Stannous chloride | 180 | 82 |
| Salicylic acid | 130 | 54 | Sulfuric acid 10% | 120 | 49 |
| Sodium carbonate | 180 | 82 | Sulfuric acid 50% | x | x |
| Sodium chloride | 180 | 82 | Sulfuric acid 70% | x | x |
| Sodium hydroxide 10% | 90 | 32 | Sulfuric acid 90% | x | x |
| Sodium hydroxide 50% | 150 | 66 | Sulfuric acid 98% | x | x |
| Sodium hydroxide, concentrated | x | x | Sulfuric acid 100% | x | x |
| Sodium hypochlorite 10% | 130 | 54 | Sulfuric acid, fuming | x | x |
| Sodium hypochlorite concentrated | 120 | 49 | Sulfurous acid | 80 | 27 |
| Sodium sulfide to 50% | 140 | 60 | Thionyl chloride | x | x |
| Stannic chloride | 180 | 82 | Toluene | 80 | 27 |
| | | | Trichloroacetic acid | 80 | 27 |
| | | | Zinc chloride | 170 | 77 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that the data are unavailable.
*Source:* Schweitzer, PA. *Corrosion Resistance Tables.* 4th ed. Vols 1–3. New York: Marcel Dekker, 1995.

## POLYVINYLIDENE FLUORIDE (PVDF)

Vinylidene fluoride is a crystalline, high-molecular-weight thermoplastic polymer containing 59% fluorine. It is similar in chemical structure to PTFE except that it is not fully fluorinated. The chemical structure is



Much of the strength and chemical-resistant properties are maintained through an operating range of –40 to 320°F (–40 to 160°C). It has high tensile strength and heat deflection temperature and is resistant to the permeation of gases. Approval has been granted by the Food and Drug Administration for repeated use in contact with food, as in food handling and processing equipment. The physical and mechanical properties can be found in Table P.53.

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**Table P.53** Physical and Mechanical Properties of PVDF

| | |
|---|---|
| Specific gravity | 1.76 |
| Water absorption 24 h at 73°F (23°C), % | <0.04 |
| Tensile strength at 73°F (23°C), psi | 6000 |
| Modulus of elasticity in tension at 73°F (23°C) $\times 10^5$ | 2.1 |
| Compressive strength, psi | 11,600 |
| Flexural strength, psi | 10,750 |
| Izod impact strength, notched at 73°F (23°C) | 3.8 |
| Coefficient of thermal expansion | |
| in./in.-°F $\times 10^{-5}$ | 7.9 |
| in./10 °F/l00 ft | 0.079 |
| Thermal conductivity, Btu/h/sq ft/°F/in. | 0.79 |
| Heat distortion temperature, °F/°C | |
| at 66 psi | 284/140 |
| at 264 psi | 194/90 |
| Resistance to heat at continuous drainage, °F/°C | 280/138 |
| Limiting oxygen index, % | 44 |
| Flame spread | 0 |
| Underwriters Lab rating (Sub 94) | 94V-O |

PVDF is chemically resistant to most acids, bases, and organic solvents. It is also resistant to wet or dry chlorine, bromine, and other halogens.

It should not be used with strong alkalies, fuming acids, polar solvents, amines, ketones, or esters. When used with strong alkalies, it stress cracks. Refer to Table P.54 for the compatibility of PVDF with selected corrodents.

**Table P.54** Compatibility of PVDF with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetaldehyde | 150 | 66 | Aluminum chloride, dry | 270 | 132 |
| Acetamide | 90 | 32 | Aluminum fluoride | 300 | 149 |
| Acetic acid 10% | 300 | 149 | Aluminum hydroxide | 260 | 127 |
| Acetic acid 50% | 300 | 149 | Aluminum nitrate | 300 | 149 |
| Acetic acid 80% | 190 | 88 | Aluminum oxychloride | 290 | 143 |
| Acetic acid, glacial | 190 | 88 | Aluminum sulfate | 300 | 149 |
| Acetic anhydride | 100 | 38 | Ammonia gas | 270 | 132 |
| Acetone | x | x | Ammonium bifluoride | 250 | 121 |
| Acetyl chloride | 120 | 49 | Ammonium carbonate | 280 | 138 |
| Acrylic acid | 150 | 66 | Ammonium chloride 10% | 280 | 138 |
| Acrylonitrile | 130 | 54 | Ammonium chloride 50% | 280 | 138 |
| Adipic acid | 280 | 138 | Ammonium chloride, sat. | 280 | 138 |
| Allyl alcohol | 200 | 93 | Ammonium fluoride 10% | 280 | 138 |
| Allyl chloride | 200 | 93 | Ammonium fluoride 25% | 280 | 138 |
| Alum | 180 | 82 | Ammonium hydroxide 25% | 280 | 138 |
| Aluminum acetate | 250 | 121 | Ammonium hydroxide, sat. | 280 | 138 |
| Aluminum chloride, aqueous | 300 | 149 | Ammonium nitrate | 280 | 138 |

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**Table P.54** Compatibility of PVDF with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Ammonium persulfate | 280 | 138 | Carbon disulfide | 80 | 27 |
| Ammonium phosphate | 280 | 138 | Carbon monoxide | 280 | 138 |
| Ammonium sulfate 10–40% | 280 | 138 | Carbon tetrachloride | 280 | 138 |
| Ammonium sulfide | 280 | 138 | Carbonic acid | 280 | 138 |
| Ammonium sulfite | 280 | 138 | Cellosolve | 280 | 138 |
| Amyl acetate | 190 | 88 | Chloracetic acid | 200 | 93 |
| Amyl alcohol | 280 | 138 | Chloracetic acid, 50% water | 210 | 99 |
| Amyl chloride | 280 | 138 | Chlorine gas, dry | 210 | 99 |
| Aniline | 200 | 93 | Chlorine gas, wet, 10% | 210 | 99 |
| Antimony trichloride | 150 | 66 | Chlorine liquid | 210 | 99 |
| Aqua regia 3:1 | 130 | 54 | Chlorobenzene | 220 | 104 |
| Barium carbonate | 280 | 138 | Chloroform | 250 | 121 |
| Barium chloride | 280 | 138 | Chlorosulfonic acid | 110 | 43 |
| Barium hydroxide | 280 | 138 | Chromic acid 10% | 220 | 104 |
| Barium sulfate | 280 | 138 | Chromic acid 50% | 250 | 121 |
| Barium sulfide | 280 | 138 | Chromyl chloride | 110 | 43 |
| Benzaldehyde | 120 | 49 | Citric acid 15% | 250 | 121 |
| Benzene | 150 | 66 | Citric acid, concentrated | 250 | 121 |
| Benzene sulfonic acid 10% | 100 | 38 | Copper acetate | 250 | 121 |
| Benzoic acid | 250 | 121 | Copper carbonate | 250 | 121 |
| Benzyl alcohol | 280 | 138 | Copper chloride | 280 | 138 |
| Benzyl chloride | 280 | 138 | Copper cyanide | 280 | 138 |
| Borax | 280 | 138 | Copper sulfate | 280 | 138 |
| Boric acid | 280 | 138 | Cresol | 210 | 99 |
| Bromine gas, dry | 210 | 99 | Cupric chloride 5% | 270 | 132 |
| Bromine gas, moist | 210 | 99 | Cupric chloride 50% | 270 | 132 |
| Bromine liquid | 140 | 60 | Cyclohexane | 250 | 121 |
| Butadiene | 280 | 138 | Cyclohexanol | 210 | 99 |
| Butyl acetate | 140 | 60 | Dichloroacetic acid | 120 | 49 |
| Butyl alcohol | 280 | 138 | Dichloroethane | | |
| *n*-Butylamine | x | x | (ethylene dichloride) | 280 | 138 |
| Butyl phthalate | 80 | 27 | Ethylene glycol | 280 | 138 |
| Butyric acid | 230 | 110 | Ferric chloride | 280 | 138 |
| Calcium bisulfide | 280 | 138 | Ferric chloride 50% in water | 280 | 138 |
| Calcium bisulfite | 280 | 138 | Ferrous chloride | 280 | 138 |
| Calcium carbonate | 280 | 138 | Ferrous nitrate | 280 | 138 |
| Calcium chlorate | 280 | 138 | Ferrous nitrate 10–50% | 280 | 138 |
| Calcium chloride | 280 | 138 | Fluorine gas, dry | 80 | 27 |
| Calcium hydroxide 10% | 270 | 132 | Fluorine gas, moist | 80 | 27 |
| Calcium hydroxide, sat. | 280 | 138 | Hydrobromic acid, dilute | 260 | 127 |
| Calcium hypochlorite | 280 | 138 | Hydrobromic acid 20% | 280 | 138 |
| Calcium nitrate | 280 | 138 | Hydrobromic acid 50% | 280 | 138 |
| Calcium oxide | 250 | 121 | Hydrochloric acid 20% | 280 | 138 |
| Calcium sulfate | 280 | 138 | Hydrochloric acid 38% | 280 | 138 |
| Caprylic acid | 220 | 104 | Hydrocyanic acid 10% | 280 | 138 |
| Carbon bisulfide | 80 | 27 | Hydrofluoric acid 30% | 260 | 127 |
| Carbon dioxide, dry | 280 | 138 | Hydrofluoric acid 70% | 200 | 93 |
| Carbon dioxide, wet | 280 | 138 | Hydrofluoric acid 100% | 200 | 93 |

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**Table P.54** Compatibility of PVDF with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Hypochlorous acid | 280 | 138 | Sodium carbonate | 280 | 138 |
| Iodine solution 10% | 250 | 121 | Sodium chloride | 280 | 138 |
| Ketones, general | 110 | 43 | Sodium hydroxide 10% | 230 | 110 |
| Lactic acid 25% | 130 | 54 | Sodium hydroxide 50% | 220 | 104 |
| Lactic acid, concentrated | 110 | 43 | Sodium hydroxide, | | |
| Magnesium chloride | 280 | 138 | concentrated[b] | 150 | 66 |
| Malic acid | 250 | 121 | Sodium hypochlorite 20% | 280 | 138 |
| Manganese chloride | 280 | 138 | Sodium hypochlorite, | 280 | 138 |
| Methyl chloride | x | x | concentrated | | |
| Methyl ethyl ketone | x | x | Sodium sulfide to 50% | 280 | 138 |
| Methyl isobutyl ketone | 110 | 43 | Stannic chloride | 280 | 138 |
| Muriatic acid | 280 | 138 | Stannous chloride | 280 | 138 |
| Nitric acid 5% | 200 | 93 | Sulfuric acid 10% | 250 | 121 |
| Nitric acid 20% | 180 | 82 | Sulfuric acid 50% | 220 | 104 |
| Nitric acid 70% | 120 | 49 | Sulfuric acid 70% | 220 | 104 |
| Nitric acid, anhydrous | 150 | 66 | Sulfuric acid 90% | 210 | 99 |
| Nitrous acid, concentrated | 210 | 99 | Sulfuric acid 98% | 140 | 60 |
| Oleum | x | x | Sulfuric acid 100% | x | x |
| Perchloric acid 10% | 210 | 99 | Sulfuric acid, fuming | x | x |
| Perchloric acid 70% | 120 | 49 | Sulfurous acid | 220 | 104 |
| Phenol | 200 | 93 | Thionyl chloride | x | x |
| Phosphoric acid 50–80% | 220 | 104 | Toluene | x | x |
| Picric acid | 80 | 27 | Trichloroacetic acid | 130 | 54 |
| Potassium bromide 30% | 280 | 138 | White liquor | 80 | 27 |
| Salicylic acid | 220 | 104 | Zinc chloride | 260 | 127 |
| Silver bromide 10% | 250 | 121 | | | |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that the data are unavailable.
*Source:* Schweitzer, PA. *Corrosion Resistance Tables.* 4th ed. Vols 1–3. New York: Marcel Dekker, 1995.

PVDF is manufactured under the trade name Kynar by Elf Atochem, Solef by Solvay, Hylar by Ausimont USA, and Super Pro 230 and ISO by Asahi/America.

See Refs. 8, 15 and 21.

## POTENTIAL–pH DIAGRAMS (POURBAIX DIAGRAMS)

Potential–pH diagrams represent graphically the stability of a metal and its corrosion products as a function of the potential and pH (acidity or alkalinity) of an aqueous solution. The pH is shown on the horizontal axis and the potential on the vertical axis.

In order to trace such a diagram, the concentration of the dissolved material must be fixed. The thermodynamic possibilities for reaction between zinc and the atmosphere with its various constituents can be determined in potential–pH diagrams.

Zinc is a relatively base metal. The stability areas of various zinc-containing species in the system Zn–$CO_2$–$H_2O$ at 77°F (25°C) are shown in Fig. P.3. The diagram takes

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into account the formation of zinc hydroxide, of $Zn^{2+}$, and of the zincate ions $HZnO_2$ and $ZnO^{2-}$. The numbers indicate the $H_2CO_3$ content in the moisture film in mole/liter. The broken lines indicate the area of thermodynamic stability of water.

Pourbaix diagrams are widely used in corrosion because they permit easy identification of the predominant materials at equilibrium for a given potential and pH. However, they do not give any information as to the possible rate of corrosion.

## POULTICE CORROSION

Poultice corrosion is a special form of crevice corrosion. It is the gradual collection of hydroscopic particulate matter on ledges and the like. This is a typical type of corrosion experienced on vehicle body parts due to the collection of road salts and debris on ledges and in pockets that are kept moist by weather and washing.

Poultice corrosion is also early initiation of corrosion occurring beneath a hygroscopic attachment or insert. Poultice corrosion is also referred to as deposit corrosion and deposit attack.

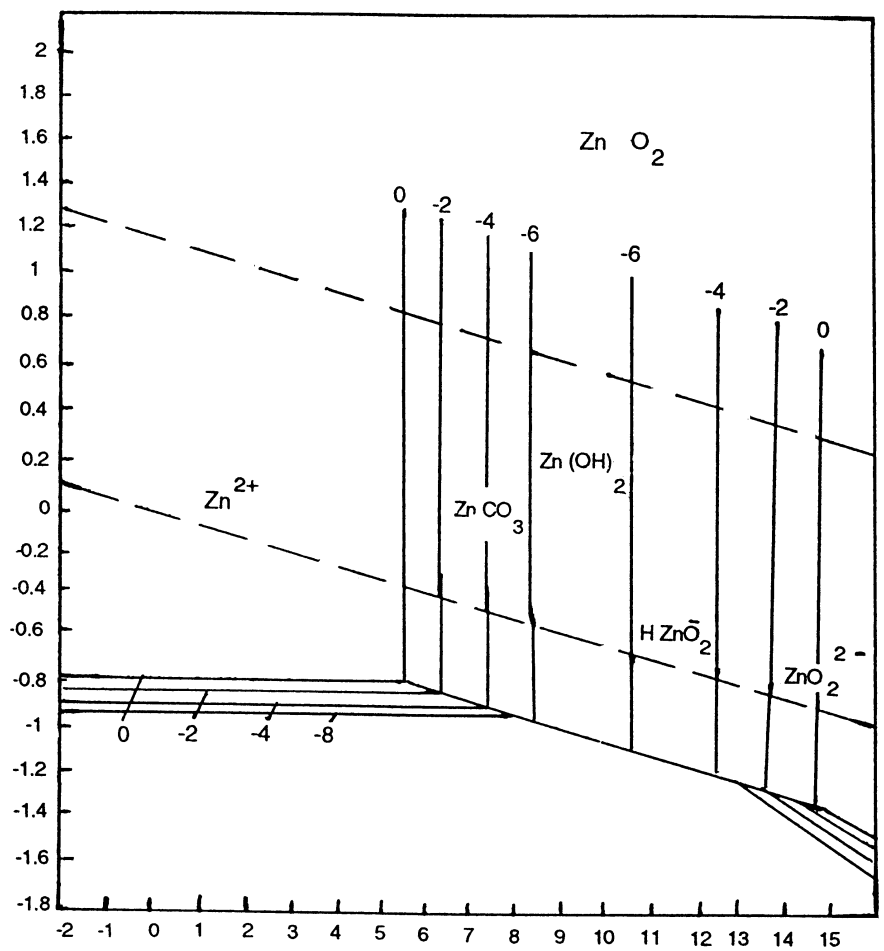



**Figure P.3** Potential pH diagram for the system Zn–$CO_2$–$H_2O$ at 77°/25°C.

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## PRECIPITATION-HARDENING STAINLESS STEELS

This family of stainless alloys utilizes a thermal treatment to intentionally precipitate phases, which causes a strengthening of the alloy. Precipitation-hardening stainless steels have high strength and relatively good ductility and corrosion resistance at high temperatures.

Precipitation-hardenable (PH) stainless steels are themselves divided into three alloy types: martensitic, austenitic, and semiaustenitic. An illustration of the relationship between these alloys is shown in Fig. P.4. The martensitic and austenitic PH stainless steels are directly hardened by thermal treatment. The semiaustenitic stainless steels are supplied as an unstable austenitic, which is the workable condition, and must be transformed to martensite before aging.

On average, the general corrosion resistance is below that of type 304 stainless. However, the corrosion resistance of type PH 15-7Mo alloy approaches that of type 316 stainless. The martensitic and semi-austenitic grades are resistant to chloride stress cracking. These materials are susceptible to hydrogen embrittlement.

The PH steels have a myriad of uses in small forged parts and even in larger support members in aircraft designs. They have been considered for landing gears. Many golf club heads are made from these steels by investment casting techniques, and the manufacturers advertise that clubs are being made from 17-4 stainless steels. Applications also include fuel tanks, landing gear covers, pump parts, shafting, bolts, saws, knives, and flexible-type expansion joints.

### PH 13-8Mo (S13800)

PH 13-8Mo is the registered trademark of Armco Inc. It is a martensitic precipitation/age-hardening stainless steel capable of high strength and hardness along with good levels

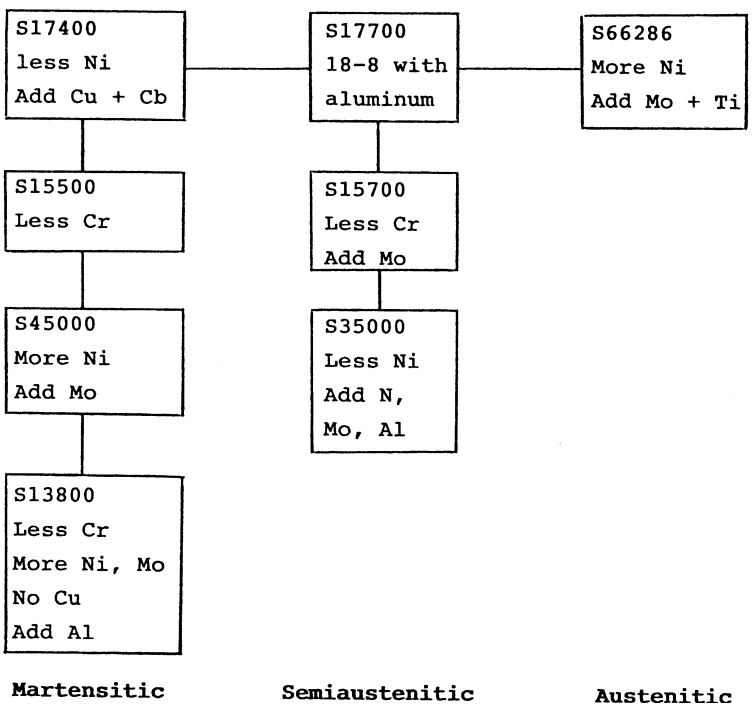



**Figure P.4** Precipitation-hardened stainless steel.

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**Table P.55** Chemical Composition of Alloy PH-13-8Mo (S13800)

| Chemical | Weight percent |
|---|---|
| Carbon | 0.05 |
| Manganese | 0.10 |
| Phosphorus | 0.010 |
| Sulfur | 0.008 |
| Silicon | 0.10 |
| Chromium | 12.5–13.25 |
| Nickel | 7.5–5.50 |
| Molybdenum | 2.00–2.50 |
| Aluminum | 0.90–1.35 |
| Nitrogen | 0.010 |
| Iron | Balance |

of resistance to both general corrosion and stress corrosion cracking. The chemical composition is shown in Table P.55.

## Alloy 15-5PH (S15500)

Alloy 15-5PH, a martensitic precipitation hardening stainless steel, is the trademark of Armco Inc. It provides a combination of high strength, good corrosion resistance, good mechanical properties at temperatures up to 600°F (316°C), and good toughness in both the longitudinal and transverse directions in both the base metal and welds. The chemical composition is shown in Table P.56.

As supplied from the mill in Condition A, 15-5PH stainless steel can be heat treated at a variety of temperatures to develop a wide range of properties. In Condition A, alloy 15-5PH exhibits useful mechanical properties. The tests at Kure Beach, NC show excellent stress corrosion resistance after 14 years of exposure. Condition A has been used successfully in numerous applications.

However, in critical applications, alloy 15-5PH should be used in the precipitation-hardened condition rather than Condition A. Heat treating to the hardened condition,

**Table P.56** Chemical Composition of Alloy 15-5PH (S15500)

| Chemical | Weight percent |
|---|---|
| Carbon | 0.07 max. |
| Manganese | 1.00 max. |
| Phosphorus | 0.04 max. |
| Sulfur | 0.03 max. |
| Silicon | 1.00 max. |
| Chromium | 14.0–15.50 |
| Nickel | 3.50–5.50 |
| Copper | 2.50–4.50 |
| Columbium + tantalum | 0.15–0.45 |
| Iron | Balance |

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especially at the higher end of the temperature range, stress relieves the structure and may provide more reliable resistance to stress corrosion cracking than Condition A.

The general level of corrosion resistance of alloy 15-5PH exceeds that of types 410 and 431 and is approximately equal to that of alloy 17-4PH. Very little rusting is experienced when exposed to 5% salt fog at 95°F (35°C) for a period of 500 h. When exposed to seacoast atmospheres rust gradually develops. This is similar to other precipitation-hardening stainless steels. The general level of corrosion resistance of alloy 15-5PH stainless steel is best in the fully hardened condition and decreases slightly as the aging temperature is increased.

## Alloy 17-4PH (S17400)

Alloy 17-4PH is a trademark of Armco Inc. It is a martensitic hardening stainless steel. The chemical composition of this alloy is shown in Table P.57.

As supplied from the mill in Condition A, 17-4PH stainless steel can be heat treated at a variety of temperatures to develop a wide range of properties. In critical applications, alloy 17-4PH should be used in the precipitation-hardened condition rather than in Condition A. Heat treating to the hardened condition, especially at the higher end of the temperature range, stress relieves the structure and may provide more reliable resistance to stress corrosion cracking than in Condition A.

Alloy 17-4PH has excellent corrosion resistance. It withstands attack better than any of the standard hardenable stainless steels and is comparable to type 304 in most media. It is equivalent to type 304 when exposed in rural or mild industrial atmospheres. When exposed in a seacoast atmosphere, it will gradually develop overall light rusting and pitting in all heat-treated conditions. As with other stainless steels, crevice attack will occur when exposed to stagnant seawater for any length of time. Table P.58 shows the compatibility of alloy 17-4PH with selected corrodents.

**Table P.57** Chemical Composition of Alloy 17-4PH (S17400)

| Chemical | Weight percent |
|---|---|
| Carbon | 0.07 max. |
| Manganese | 1.00 max. |
| Phosphorus | 0.04 max. |
| Sulfur | 0.03 max. |
| Silicon | 1.00 max. |
| Chromium | 15.00–17.50 |
| Nickel | 3.00–5.00 |
| Copper | 3.00–5.00 |
| Columbium + tantalum | 0.15–0.45 |
| Iron | Balance |

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**Table P.58** Compatibility of 17-4PH Stainless Steel with Selected Corrodents[a]

| Chemical | °F | °C | Chemical | °F | °C |
|---|---|---|---|---|---|
| Acetic acid 20% | 200 | 93 | Calcium chloride | 110 | 43 |
| Acetic acid, glacial | x | x | Calcium hypochlorite | x | x |
| Acetyl chloride | 110 | 43 | Calcium sulfate | 150 | 54 |
| Acetylene | 110 | 43 | Carbon dioxide, dry | 210 | 99 |
| Allyl alcohol | 90 | 32 | Carbon dioxide, wet | 210 | 99 |
| Aluminum fluoride | x | x | Carbon monoxide | 230 | 110 |
| Aluminum hydroxide | 80 | 27 | Carbon tetrachloride | 150 | 66 |
| Aluminum nitrate | 110 | 43 | Chloric acid 20% | x | x |
| Aluminum potassium sulfate | x | x | Chlorine liquid | x | x |
| Aluminum sulfate | x | x | Chlorosulfonic acid | x | x |
| Ammonia, anhydrous | 270 | 132 | Chromic acid 10% | x | x |
| Ammonium bifluoride | x | x | Chromic acid 30% | x | x |
| Ammonium carbonate | 110 | 43 | Chromic acid 40% | x | x |
| Ammonium chloride | x | x | Chromic acid 50% | x | x |
| Ammonium hydroxide 10% | 210 | 99 | Ethyl alcohol | 170 | 77 |
| Ammonium nitrate | 130 | 54 | Ethyl chloride, dry | 210 | 99 |
| Ammonium persulfate | 130 | 54 | Ferric nitrate | 150 | 66 |
| Amyl acetate | 90 | 32 | Ferrous chloride | x | x |
| Amyl alcohol | 90 | 32 | Fluorine gas, dry | 230 | 110 |
| Amyl chloride | 90 | 32 | Formic acid 10% | 180 | 82 |
| Aniline | 170 | 71 | Heptane | 130 | 54 |
| Aniline hydrochloride | x | x | Hydrobromic acid | x | x |
| Antimony trichloride | x | x | Hydrochloric acid | x | x |
| Argon | 210 | 99 | Hydrocyanic acid | x | x |
| Arsenic acid | 130 | 54 | Hydrogen sulfide, wet | x | x |
| Barium hydroxide | 110 | 43 | Iodine | x | x |
| Barium sulfate | 130 | 54 | Magnesium chloride | x | x |
| Beer | 110 | 43 | Magnesium hydroxide | 140 | 66 |
| Beet sugar liquors | 110 | 43 | Magnesium nitrate | 130 | 54 |
| Benzene | 130 | 54 | Magnesium sulfate | 130 | 54 |
| Benzene sulfonic acid | x | x | Methylene chloride | 130 | 54 |
| Benzoic acid | 150 | 66 | Phenol | 130 | 54 |
| Benzyl alcohol | 110 | 43 | Phosphoric acid 5% | 200 | 93 |
| Boric acid | 110 | 43 | Phosphoric acid 10% | 200 | 93 |
| Bromine gas, dry | x | x | Phosphoric acid 25–50% | 200 | 93 |
| Bromine gas, moist | x | x | Phosphoric acid 70% | x | x |
| Bromine liquid | x | x | Phthalic acid | 270 | 132 |
| Butyl cellosolve | 140 | 66 | | | |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. When compatible, the corrosion rate is less than 20 mpy.
*Source:* Ref. 8

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## Alloy 17-7PH (S17400)

This is a semiaustenitic stainless steel. In the annealed or solution-annealed condition it is austenitic (nonmagnetic), and in the aged or cold-worked condition it is martensitic (magnetic). The chemical composition is shown in Table P.59.

Alloy 17-7PH exhibits high strength in all conditions. Service over 1050°F (565°C) will cause overaging. Overaging may occur at lower temperatures depending on the tempering temperature selected.

In the aged condition, this alloy is resistant to chloride cracking. Its corrosion resistance in general is on a par with type 304 stainless steel.

## Alloy 350 (S35000)

This is a chromium–nickel–molybdenum stainless alloy hardenable by martensitic transformation and precipitation hardening. The chemical composition is shown in Table P.60.

Alloy 350 normally contains 5–10% delta ferrite, which aids weldability. When heated, it has high strength. However, to achieve optimum properties, a complex heat treatment is required including two subzero [–100°F (–73°C)] exposures. Unless cooled to subzero temperatures prior to aging, the alloy may be subject to intergranular attack.

In general, the corrosion resistance of alloy 350 is similar to that of type 304 stainless steel.

This alloy is used where high strength and corrosion resistance at room temperatures is essential.

**Table P.59** Chemical Composition of Alloy 17-7PH (S17700)

| Chemical | Weight percent |
|---|---|
| Carbon | 0.09 max. |
| Aluminum | 0.75–1.5 |
| Chromium | 16.0–18.0 |
| Nickel | 6.5–7.75 |
| Iron | Balance |

**Table P.60** Chemical Composition of Alloy 350 (S35000)

| Chemical | Weight percent |
|---|---|
| Carbon | 0.07–0.11 |
| Manganese | 0.50–1.25 |
| Phosphorus | 0.04 |
| Sulfur | 0.03 |
| Silicon | 0.50 |
| Chromium | 16.00–17.00 |
| Nickel | 4.00–5.00 |
| Molybdenum | 2.50–3.25 |
| Nitrogen | 0.07–0.13 |
| Iron | Balance |

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## Alloy 355 (S35500)

Alloy 355 is a chromium–nickel–molybdenum stainless alloy hardenable by martensitic transformation and precipitation hardening. The chemical composition is shown in Table P.61.

Depending on the heat treatment, the alloy may be austenitic with formability similar to other austenitic stainless steels. Other heat treatments yield a martensitic structure with high strength.

Alloy 355 exhibits better corrosion resistance than other quench-hardenable martensitic stainless steels. Services over 1000°F (538°C) will cause overaging. Overaging may occur at lower temperatures depending on the tempering temperature selected. Overaged material is subject to intergranular corrosion. A subzero treatment during heat treatment removes this susceptibility.

Alloy 355 finds application where high strength is required at intermediate temperatures.

## Custom 450 (S45000)

Custom 450 is the trademark of Carpenter Technology Corp. It is a martensitic age-hardenable stainless steel with very good corrosion resistance and moderate strength. Table P.62 contains its chemical composition.

**Table P.61** Chemical Composition of Alloy 355 (S35500)

| Chemical | Weight percent |
|---|---|
| Carbon | 0.10–0.15 |
| Manganese | 0.50–1.25 |
| Phosphorus | 0.04 |
| Sulfur | 0.03 |
| Silicon | 0.05 |
| Chromium | 15.00–16.00 |
| Nickel | 4.00–5.00 |
| Molybdenum | 2.50–3.25 |
| Nitrogen | 0.07–0.13 |
| Iron | Balance |

**Table P.62** Chemical Composition of Custom 450 (S45000)

| Chemical | Weight percent |
|---|---|
| Carbon | 0.05 |
| Manganese | 2.00 |
| Phosphorus | 0.03 |
| Sulfur | 0.03 |
| Silicon | 1.00 |
| Chromium | 14.00–16.00 |
| Nickel | 5.00–7.00 |
| Molybdenum | 0.50–1.00 |
| Copper | 1.25–1.75 |
| Columbium | 8 × %C min. |
| Iron | Balance |

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Unlike alloy 17-4, Custom 450 can be used in the solution-annealed condition. The corrosion resistance of Custom 450 stainless is similar to that of type 304 stainless steel. Custom 450 alloy is used in applications where type 304 is not strong enough or type 410 is insufficiently corrosion resistant.

## Custom 455 (S45500)

Custom 455 is a registered trademark of Carpenter Technology Corp. It is a martensitic age-hardenable stainless steel that is relatively soft and formable in the annealed condition. The chemical composition is shown in Table P.63.

Custom 455 exhibits high strength with corrosion resistance that is better than type 410 and approaching type 430. Service over 1050°F (565°C) will cause overaging. Overaging may occur at lower temperatures depending on the tempering temperature.

The alloy may be susceptible to hydrogen embrittlement under some conditions. Custom 455 alloy should be considered when ease of fabrication, high strength, and corrosion resistance are required. Custom 455 alloy is suitable to be used in contact with nitric acid and alkalies. It also resists chloride stress corrosion cracking. Materials such as sulfuric acid, phosphoric acid, hydrochloric acid, hydrofluoric acid, and seawater will attack Custom 455.

## Alloy A286 (S66286)

Alloy A286 is an austenitic precipitation-hardenable stainless steel. Its chemical composition will be found in Table P.64. The alloy is nonmagnetic. The mechanical properties of alloy A286 are retained at temperatures up to 1300°F (704°C).

Alloy A286 has excellent resistance to sulfuric and phosphoric acids and good resistance to nitric acid and organic acids. It is also satisfactory for use with salts, seawater, and alkalies.

**Table P.63** Chemical Composition of Custom 455 (S45500)

| Chemical | Weight percent |
|---|---|
| Carbon | 0.05 |
| Manganese | 0.50 |
| Phosphorus | 0.040 |
| Sulfur | 0.030 |
| Silicon | 0.50 |
| Chromium | 11.00–12.50 |
| Nickel | 7.50–9.50 |
| Titanium | 0.80–1.40 |
| Columbium + tantalum | 0.10–0.50 |
| Copper | 1.50–2.50 |
| Molybdenum | 0.50 |
| Iron | Balance |

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**Table P.64** Chemical Composition of Alloy A286 (S66286)

| Chemical | Weight percent |
|---|---|
| Carbon | 0.08 |
| Manganese | 2.00 |
| Silicon | 1.00 |
| Chromium | 13.50–16.00 |
| Nickel | 24.00–27.00 |
| Molybdenum | 1.00–2.30 |
| Titanium | 1.90–2.30 |
| Vanadium | 0.10–0.50 |
| Aluminum | 0.35 |
| Boron | 0.003–0.010 |
| Iron | Balance |

## Alloy 718 (NO7718)

Alloy 718 is a precipitation-hardened nickel-base alloy designed to display exceptionally high yield, tensile, and creep properties up to 1300°F (704°C). It can also be used at temperatures as low as –423°F (–253°C). Table P.65 shows the chemical composition.

Excellent oxidation resistance is shown up to 1800°F (952°C). Alloy 718 is resistant to sulfuric acid, organic acids, and alkalies. It is also resistant to chloride stress corrosion cracking. Hydrochloric, hydrofluoric, phosphoric, and nitric acids and seawater will attack the alloy.

This alloy has been used for jet engines and high-speed airframe parts such as wheels, buckets, and spacers and high-temperature bolts and fasteners.

## Alloy X-750 (NO7750)

This is a precipitation-hardening alloy that is highly resistant to chemical corrosion and oxidation. The chemical composition is shown in Table P.66. Alloy X750 exhibits excel-

**Table P.65** Chemical Composition of Alloy 718 (N07718)

| Chemical | Weight percent |
|---|---|
| Carbon | 0.10 |
| Manganese | 0.35 |
| Silicon | 0.35 |
| Phosphorus | 0.015 |
| Sulfur | 0.015 |
| Chromium | 17.00–21.00 |
| Nickel + cobalt | 50.00–55.00 |
| Molybdenum | 2.80–3.30 |
| Columbium + tantalum | 4.75–5.50 |
| Titanium | 0.65–1.15 |
| Aluminum | 0.35–0.85 |
| Boron | 0.001–0.006 |
| Copper | 0.015 |
| Iron | Balance |

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**Table P.66** Chemical Composition of Alloy X-750 (N07750)

| Chemical | Weight percent |
|---|---|
| Carbon | 0.08 |
| Nickel + columbium | 70.00 |
| Chromium | 14.00–17.00 |
| Manganese | 0.30 |
| Sulfur | 0.010 |
| Silicon | 0.50 |
| Copper | 0.05 |
| Columbium + tantalum | 0.70–1.20 |
| Titanium | 2.25–2.70 |
| Aluminum | 0.40–1.00 |
| Iron | 5.0–9.0 |

lent properties down to cryogenic temperatures and corrosion and oxidation resistance up to 1300°F (704°C). When exposed to temperatures above 1300°F (704°C), overaging results in a loss of strength. Alloy X-750 is resistant to sulfuric, hydrochloric, phosphoric, and organic acids, alkalies, salts, and seawater. It is also resistant to chloride stress corrosion cracking. Hydrofluoric and nitric acids will attack the alloy.

The alloy finds application where strength and corrosion resistance are important, for example, as high-temperature structured members for jet engine parts, heat-treating fixtures, and forming tools.

## Pyromet Alloy 31

Pyromet alloy 31 is a trademark of Carpenter Technology. It is a precipitation-hardenable superalloy that exhibits corrosion resistance and strength to 1500°F (816°C). It is resistant to sour brines and hot sulfidation attack.

Applications include hardware in coal gasification units. It has a chemical composition as shown in Table P.67.

## Pyromet Alloy CTX-1

Pyromet alloy CTX-1 is a trademark of Carpenter Technology. This is a high-strength, precipitation-hardening superalloy having a low coefficient of expansion with high strength at temperatures up to 1200°F (649°C). If exposed to atmospheric conditions above 1000°F (538°C), a protective coating must be applied to the alloy.

Applications include gas turbine engine components and hot-work dies. The chemical composition will be found in Table P.68.

## Pyromet Alloy CTX-3

This is a low-expansion, high-strength, precipitation-hardenable superalloy having significant improvement in notched stress rupture strength over Pyromet CTX-1. As with alloy CTX-1, a protective coating must be applied if the alloy is to be exposed at atmospheric conditions above 1000°F (538°C).

Table P.69 shows the chemical composition.

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**Table P.67** Chemical Composition of Pyromet Alloy 31

| Chemical | Weight percent |
|---|---|
| Carbon | 0.04 |
| Manganese | 0.20 |
| Silicon | 0.20 |
| Phosphorus | 0.015 |
| Sulfur | 0.015 |
| Chromium | 27.7 |
| Nickel | 55.5 |
| Molybdenum | 2.0 |
| Titanium | 2.5 |
| Aluminum | 1.5 |
| Columbium | 1.1 |
| Boron | 0.005 |
| Iron | Balance |

**Table P.68** Chemical Composition of Alloy CTX-1

| Chemical | Weight percent |
|---|---|
| Carbon | 0.05 |
| Manganese | 0.50 |
| Silicon | 0.50 |
| Phosphorus | 0.015 |
| Sulfur | 0.015 |
| Chromium | 0.50 |
| Molybdenum | 0.20 |
| Copper | 0.50 |
| Nickel | 38.00–40.00 |
| Columbium + tantalum | 2.50–3.50 |
| Titanium | 1.25–1.75 |
| Aluminum | 0.70–1.20 |
| Boron | 0.0075 |
| Cobalt | 14.00–16.00 |
| Iron | Balance |

**Table P.69** Chemical Composition of Alloy CTX-3

| Chemical | Weight percent |
|---|---|
| Carbon | 0.05 |
| Manganese | 0.50 |
| Silicon | 0.50 |
| Phosphorus | 0.015 |
| Sulfur | 0.015 |
| Chromium | 0.50 |
| Nickel | 37.00–39.00 |

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**Table P.69** Chemical Composition of Alloy CTX-3 (Continued)

| Chemical | Weight percent |
|---|---|
| Copper | 0.50 |
| Cobalt | 13.00–15.00 |
| Columbium + tantalum | 4.50–5.50 |
| Titanium | 1.25–1.75 |
| Aluminum | 0.25 |
| Boron | 0.012 |
| Iron | Balance |

## Pyromet Alloy CTX-909

Alloy CTX-909 is a high-strength, precipitation-hardenable superalloy that offers significant improvements over alloys CTX-1 and CTX-3 due to its combination of tensile properties and stress system strength to 1200°F (649°C) in the recrystallized condition combined with the use of common age-hardening treatments.

As with other CTX alloys, a protective coating is required if the alloy is exposed to atmospheric conditions above 1000°F (538°C). The chemical composition is shown in Table P.70.

**Table P.70** Chemical Composition of Pyromet Alloy CTX-909

| Chemical | Weight percent |
|---|---|
| Carbon | 0.06 |
| Manganese | 0.50 |
| Silicon | 0.40 nom. |
| Phosphorus | 0.015 |
| Sulfur | 0.015 |
| Chromium | 0.50 |
| Nickel | 38.00 nom. |
| Cobalt | 14.00 nom. |
| Titanium | 1.60 nom. |
| Columbium + tantalum | 4.90 nom. |
| Aluminum | 0.15 |
| Copper | 0.50 |
| Boron | 0.012 |
| Iron | Balance |

**Table P.71** Chemical Composition of Pyromet Alloy V-57

| Chemical | Weight percent |
|---|---|
| Carbon | 0.08 |
| Manganese | 0.35 |
| Silicon | 0.50 |
| Phosphorus | 0.015 |

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**Table P.71** Chemical Composition of Pyromet Alloy V-57 (Continued)

| Chemical | Weight percent |
|---|---|
| Sulfur | 0.015 |
| Chromium | 13.50–16.00 |
| Nickel | 22.50–28.50 |
| Molybdenum | 1.00–1.50 |
| Titanium | 2.70–3.20 |
| Vanadium | 0.50 |
| Aluminum | 00 |
| Boron | 0.005–0.012 |
| Iron | Balance |

### Pyromet Alloy V-57

This is an iron-base, austenitic, precipitation-hardening alloy for parts requiring high strength and good corrosion resistance at operating temperatures to 1400°F (760°C). It is produced by Carpenter Technology. Chemically, it has the composition shown in Table P.71.

### Thermospan Alloy

Thermospan alloy is a trademark of Carpenter Technology. It is a precipitation-hardenable superalloy that has an excellent combination of tensile properties and stress rupture strength in the recrystallized condition with the use of common solution and age-hardening treatments.

As a result of the chromium addition, significant improvements in environmental resistance over that of the CTX alloys are realized. The chemical composition of thermospan alloy is shown in Table P.72.

See Ref. 2.

## PYREX

This is the trade name of Corning Glass's borosilicate glass. See "Borosilicate Glass."

**Table P.72** Chemical Composition of Thermospan Alloy

| Chemical | Weight percent |
|---|---|
| Carbon | 0.05 |
| Manganese | 0.50 |
| Silicon | 0.30 |
| Phosphorus | 0.015 |
| Sulfur | 0.015 |
| Chromium | 5.50 |
| Nickel | 25.0 |
| Cobalt | 29.0 |
| Titanium | 0.80 |
| Columbium | 4.80 |
| Aluminum | 0.50 |
| Copper | 0.50 |
| Boron | 0.01 |
| Iron | Balance |

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## PYROLYSIS

Pyrolysis is a chemical decomposition caused by heat or severe oxidation. The molecule of all plastic materials is an organic molecule that is subject to pyrolysis. This can occur by fire or it can occur, for example, by contact with very strong sulfuric acid (e.g., 93%), which completely destroys the molecule, and severe oxidation takes place. The resin turns black and loses all physical strength, so that the structure is destroyed. Service life is measured in a matter of hours. The thermoset resins are particularly subject to pyrolysis from concentrated sulfuric or nitric acids. Polyesters can withstand up to 78% sulfuric acid for short periods and 70% sulfuric acid almost indefinitely at room temperature. Above room temperature, oxidation becomes so severe that the molecule is destroyed. Some of the thermoplasts such as polyethylene, polypropylene, and polyvinyl chloride are exceptions and can tolerate higher concentrations.

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# Q

## QUENCH

To quench is to rapidly cool a metal or alloy from an elevated temperature by means of immersion in water, salt solution, or oil, or by forced air cooling, to prevent it from reaching a stable condition and in so doing impart special properties to the metal or alloy.

## QUENCH ANNEALING

Quench annealing is a high-temperature solution heat treatment followed by a water quenching. This procedure dissolves chromium carbide, thereby forming a more homogeneous alloy. It is a procedure used to minimize intergranular corrosion of austenitic stainless steels. It is also called solution quenching.

## QUENCHING AND TEMPERING (HARDENING AND TEMPERING)

The quenching of steel into water or oil, converting it to martensite and increasing internal stress, which is relieved by heating (tempering) up to 212–392°F (100–200°C) to diffuse carbon and precipitate small carbides to improve the material's strength and ductility.



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# R

## RADIATION CORROSION

Metals that are exposed to intense radiation in the form of neutrons or other energetic particles undergo lattice changes resembling those resulting from severe cold work. Lattice vacancies, interstitial atoms, and dislocations are produced, all of which increase the diffusion rate of specific impurities or alloyed components.

See Ref. 1.

## REBAR CORROSION

Rebar corrosion is the corrosion of the steel reinforcing bars in concrete. Reinforcement for concrete, both regular and prestressed, must be protected to prevent corrosion. The amounts of cover required for protection under various conditions are shown in the table.

| Condition | Cover, in. |
|---|---|
| Concrete surface poured against the ground | 3 |
| Concrete surface to come into contact with the ground after casting: | |
| reinforcement larger than No. 5 | 2 |
| reinforcement smaller than No. 5 | 1½ |
| Beams and girders not exposed to weather: | |
| main steel | 1½ |
| stirrups and ties | 1 |
| Joists, slabs, and walls not exposed to weather | 3/4 |
| Columns, spirals, and ties | 1½ |

The cover must be at least equal to the bar diameter except for joists and slabs. For columns the cover must be 1½ times the maximum size of the coarse aggregate.

The above recommendations for cover are minimums. When corrosive conditions are to be encountered, the cover should be increased. In all cases the concrete in the cover should be made as impermeable as possible.

## RED BRASS

See "Copper and Copper Alloys."



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## REDUCING ACIDS

Reducing or nonoxidizing acids are those inorganic and organic acids that evolve gaseous hydrogen during the corrosion of active metals. They are corrosive to metals above hydrogen in the electromotive series when in the presence of oxygen or oxidizing agents, whose reduction takes the place of hydrogen evolution.

The behavior of passive metals cannot always be predicted because behavior is dependent upon the acid concentration, temperature, dissolved oxygen, and specific contaminants.

### Inorganic Acids

The inorganic acids include hydrochloric acid, hydrofluoric acid, phosphoric acid, and dilute and intermediate concentrations of sulfuric acid.

#### *Hydrochloric Acid*

Hydrochloric acid is produced by dissolving hydrogen chloride gas in water. The concentrated acid is 36%. It is a highly corrosive acid whose corrosive behavior can be drastically modified as a result of contaminants. Muriatic acid is a 30% commercial acid contaminated with dissolved ferric iron salts. The presence of trace amounts of chlorinated solvents or aromatic solvents has a bearing on the resistance of plastics and elastomers to what would nominally be called hydrochloric acid.

#### *Hydrofluoric Acid*

Hydrogen fluoride gas dissolved in water produces hydrofluoric acid, a very toxic and dangerous acid. The laboratory grade is usually a 48% concentration.

#### *Phosphoric Acid*

Commercial-grade phosphoric acid contains fluorides and other impurities such as chlorides, sulfates, and metal ions, particularly if manufactured by the "wet" process of digestion of phosphate rock with sulfuric acid. Food-grade phosphoric acid is free of these contaminants. Consequently, the corrosion characteristics of the commercial grade of acid can be unpredictable. In any case it is quite corrosive.

#### *Sulfuric Acid*

Sulfuric acid reacts both as an oxidizing and as a reducing acid. Concentrated acid, above 70% concentration, reacts as an oxidizing acid (see "Oxidizing Acids"), while dilute and intermediate concentrations below 70% react as a reducing acid. The corrosive effect is also affected by temperature and contaminants as well as dilution.

### Organic Acids

There are two reducing organic acids that are of particular concern. They are formic and acetic acids.

#### *Formic Acid*

Formic acid is a strong organic acid similar in corrosiveness to the dilute mineral acids. Its greatest corrosive properties are exhibited when the acid is hot and anaerobic. When anhydrous it is a powerful dehydrating agent.

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### *Acetic Acid*

Of the organic acids, acetic acid is the most commercially important. The corrosion properties of chemically pure acid are very predictable. Crude or unrefined acetic acid may contain peracids or peroxides that affect the corrosive properties and at times are unpredictable.

### *Other Organic Acids*

The higher-molecular-weight acids are generally less corrosive than acetic acid. Material recommendations for acetic acid can usually be used for butyric, propionic, and other acids and will be conservative.

## Specific Materials

Following is a general analysis of the behavior of various materials of construction in the presence of the inorganic and organic reducing acids. More specific and expanded information can be gotten from Ref. 2, and from details on the specific material of construction.

### *Light Metals*

Aluminum and magnesium are severely attacked by hydrochloric acid.

Magnesium is resistant to hydrofluoric acid up to a 2% concentration due to an insoluble film of corrosion products. Aluminum and its alloys should not be exposed to hydrofluoric acid, even in dilute concentrations.

Aluminum and magnesium have no practical application in the handling of phosphoric acid.

Dilute sulfuric acid will attack aluminum and magnesium.

Aluminum is resistant to formic acid in concentrations above 30%. Below 30% aluminum is rapidly attacked at temperatures only slightly above ambient.

Concentrated (glacial) acetic acid is compatible with aluminum up to a temperature of 200°F (93°C). As the concentration decreases, the corrosivity increases, even in cold solutions.

### *Iron and Steel*

Iron and steel are not compatible with hydrochloric acid. They are rapidly attacked.

Although steels are resistant to concentrated hydrofluoric acid <64% up to approximately 90°F (32°C) because of their protective film of corrosion products, they should not be used, since hydrogen blistering may occur, and welds may be preferentially attacked. Hardened steels are subject to environmental cracking.

Cast irons and alloy irons are not compatible with hydrofluoric acid and should not be used. High-silicon iron is also not compatible.

Phosphoric acid above 70% concentration will form a protective film on steel. However, because of iron contamination, steel is not used to handle phosphoric acid.

High-silicon iron is resistant to all concentrations of phosphoric acid to the atmospheric boiling point provided no fluorides are present.

Cast iron and steel are attacked by sulfuric acid in concentrations less than 70%.

High-silicon cast iron is resistant to all concentrations of sulfuric acid up to 70% and 200°F (93°C).

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Formic acid will corrode iron and steel. High-silicon iron is resistant to all aqueous concentrations but is attacked by anhydrous acid.

Acetic acid will attack iron and steel in all concentrations, even cold. High-silicon iron is resistant to all concentrations of acetic acid to the atmospheric boiling point.

### *Stainless Steels*

All grades of stainless steel will be attacked by hydrochloric acid.

Hydrofluoric acid is not compatible with any stainless steel. Martensitic grades are subject to hydrogen cracking, and other grades are subject to pitting and/or stress corrosion cracking.

Above 5% concentration of phosphoric acid, type 304 and type 316 stainless steels are subject to intergranular corrosion. Type 316L can be used to handle uncontaminated phosphoric acid up to 85% to approximately 175°F (80°C). Type 317L and alloy 20Cb3 are better choices. Alloy 20Cb3 is resistant to all concentrations of phosphoric acid to 210°F (99°C). In the absence of contaminants alloy 825 is resistant to all concentrations of phosphoric acid to the atmospheric boiling point.

Martensitic and ferritic grades of stainless steel will be attacked by all concentrations of sulfuric acid to 70% with varying temperature limits based on concentration. Refer to Ref. 2.

Formic acid will cause pitting in type 316 stainless steel and intergranular corrosion in type 304. Alloy 20Cb3 is resistant to all concentrations of formic acid, including anhydrous acid to a temperature of 210°F (99°C).

Type 304 and Type 316 stainless steels are resistant to all concentrations of acetic acid. However type 316L can be used up to a temperature of 400°F (204°C). Type 304 stainless is limited to a maximum temperature of 160°F (70°C).

### *Copper Alloys*

In the presence of dissolved oxygen or oxidizing ions, copper and its alloys will be attacked. Since the cupric ion is an oxidant, few practical applications can be found. Dealloying is also a potential problem.

The amount of oxygen or oxidants contained in hydrofluoric acid will determine the degree of corrosion to copper and its alloys. Normally, copper and its alloys are not considered for this service.

Copper and copper alloys can be used in sulfuric acid concentrations to 70% provided there are absolutely no oxidizing species present, including dissolved oxygen.

Copper is resistant to formic acid up to 5% concentration in the absence of other oxidants.

Copper is not recommended for the handling of acetic acid, since even a slight attack will discolor the refined acid.

### *Lead*

Corrosion products formed on lead by hydrochloric acid are soluble and are easily washed away by flow, removing any protective film.

Hydrofluoric acid is compatible with lead up to a 60% concentration at 77°F (25°C), or with 25% acid up to 175°F (80°C). Attack will increase with acid strength and temperature.

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Lead is resistant to 80% pure phosphoric and/or 85% impure phosphoric acid up to 390°F (200°C). The resistance is due to the formation of films of insoluble lead phosphates. Erosion or impingement effects will cause corrosion.

Lead and its alloys are resistant to sulfuric acid up to 70% concentration below the atmospheric boiling point. However, the protective sulfide film may be removed by organic contaminants (organic acids, alkyl sufates).

Lead is attacked by formic acid and acetic acid.

### *Nickel Alloys*

Alloy B-2 resists boiling hydrochloric acid provided there are no traces of oxidizing agents such as ferric ions present. Alloy C-276 will resist dilute acid containing ferric chloride but only to an intermediate temperature of 140°F (60°C). Alloy 600 is compatible with acid up to 15% at 80°F (26°C).

Alloy 400 is compatible with all concentrations of hydrofluoric acid up to 250°F (120°C). However, it is susceptible to stress corrosion cracking in the vapors when air is present. Nickel 200 is resistant to anhydrous HF up to 300°F (150°C). In aqueous solutions it is limited to nonoxidizing conditions below 175°F (85°C). Alloy 400 is a much better choice. Alloy 600 is compatible with dilute hydrofluoric acid but has a great tendency to pit at higher concentrations.

Alloy 400 is resistant to all concentrations of phosphoric acid to approximately 200°F (90°C) provided there are no stronger oxidants present than dissolved oxygen and the cupric ion corrosion products do not accumulate.

Alloy B-2 is resistant to all concentrations of phosphoric acid to approximately 150°F (65°C) and to 50% acid to the atmospheric boiling point.

Alloy 200, alloy 400, and alloy B-2 are resistant to nonaerated sulfuric acid, free of oxidants in all concentrations to 70%.

Formic acid is compatible with alloy 200 and alloy 400. Alloy C-276 is resistant to formic acid that is contaminated at elevated temperatures.

### *Reactive Metals*

Titanium is not resistant to hydrochloric acid. Zirconium is compatible with all concentrations of hydrochloric acid to 225°F (107°C) provided the concentration of oxidizing species is less than 50 ppm. If the oxidizing species exceeds 50 ppm, pyrophoric corrosion products may be formed. Tantalum is resistant to all concentrations of hydrochloric acid to 345°F (175°C) but is subject to attack by hydrogen chloride vapors at 265°F (130°C).

Hydrofluoric acid, or even small traces of fluorides, will severely attack titanium, zirconium, and tantalum.

In the absence of fluorides, zirconium will resist phosphoric acid to approximately 60% concentration, and tantalum is resistant to any concentration up to 345°F (175°C) provided the fluoride contamination is less than 10 ppm. Titanium will be attacked by phosphoric acid unless the acid contains oxidizing contaminants.

Zirconium is resistant to all concentrations of sulfuric acid to 70% concentration at the atmospheric boiling point. Unless oxidizing contaminants are present, titanium will be attacked by dilute sulfuric acid. Tantalum is resistant to all concentrations of sulfuric acid to 70% and at the boiling point provided no fluorides are present.

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Formic acid will attack titanium unless strongly oxidizing contaminants are present. Zirconium is resistant to formic acid up to 90% concentration up to 210°F (99°C). Tantalum is resistant to all concentrations of formic acid, including anhydrous, up to a temperature of 300°F (149°C).

### *Nonmetallic Materials*

Ceramic and glass materials are extremely resistant to hydrochloric acid. Hydrochloric acid can be handled in rubber-lined equipment up to 175°F (80°C) provided organic solvent contaminants are not present. Contaminants such as chlorinated hydrocarbons or aromatic solvents (benzene, toluene, etc.) will be preferentially absorbed and concentrated to cause failure of the rubber or of its adhesive. Halogenated or hydrogenated polyesters are also compatible with all concentrations of hydrochloric acid to various temperatures depending upon the concentrations. Refer to Ref. 2.

Hydrofluoric acid will attack plastics with hydroxyl groups. Polyethylene, polystyrene, methacrylates, and vinyls are resistant up to 60% concentration at 120°F (50°C). Fluorinated plastics are compatible up to their operating temperature limits but are subject to permeation. Polyesters are rapidly attacked, as are glass and other siliceous ceramics. Synthetic soft rubbers such as butyl, neoprene, and Hypalon are compatible with 60% acid to 160°F (70°C).

Fluoride-free phosphoric acid can be handled by glass up to 60% concentration and 212°F (100°C).

Carbon is resistant to all concentrations of phosphoric acid to 700°F (350°C). Various plastic materials and elastomers are resistant to all concentrations of phosphoric acid to the temperature limitations shown in the table.

Resistance of Plastic and Elastomeric Materials to Phosphoric Acid

| | Temperature limit | |
|---|---|---|
| Material | °F | °C |
| CPVC | 180 | 82 |
| E-CTFE, PVDF | 240 | 116 |
| ETFE, furan | 260 | 127 |
| FEP | 400 | 204 |
| PFA, PEEK, PES, PP | 200 | 93 |
| Polyesters | 220 | 104 |
| PTFE | 500 | 260 |
| Hypalon | 200 | 93 |
| Viton, EPDM | 300 | 149 |
| Natural rubber | 100 | 38 |
| Butyl rubber | 140 | 60 |
| PE, PVC | 140 | 60 |

As long as there are no fluorides present, glass and other ceramics will resist all concentrations of sulfuric acid up to 70%. Dilute and intermediate concentrations of sulfuric acid can also be handled by carbon and graphite to the boiling point. Plastic

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and elastomeric materials can handle all concentrations of sulfuric acid to 70% to the temperature limitations shown in the table.

Resistance of Plastic and Elastomeric Materials to Sulfuric Acid up to 70%

| Material | Temperature limit °F | °C |
|---|---|---|
| CPVC | 180 | 82 |
| E-CTFE, furan, PFA, PVDF | 240 | 116 |
| ETFE, polysulfone, EPDM | 300 | 149 |
| FEP | 400 | 204 |
| Polyesters, PP, CIIR | 200 | 93 |
| PE, PVC | 140 | 60 |
| PPFE | 500 | 260 |
| Hypalon | 240 | 116 |
| Viton | 340 | 171 |
| Neoprene | 200 | 93 |
| Natural rubber | 140 | 60 |

Glass, carbon, and ceramic ware are fully resistant to formic acid, including anhydrous. Because of the solvent nature of formic acid, plastics can be subject to attack, depending upon temperature. Temperature limitations of plastics and elastomeric materials are shown in the table.

Resistance of Plastic and Elastomeric Materials to Formic Acid

| Material | Temperature limit °F | °C |
|---|---|---|
| CPVC, PE | 140 | 60 |
| E-CTFE, PVDF | 200 | 93 |
| ETFE, furan | 260 | 127 |
| FEP, PTFE | 400 | 204 |
| PFA, PP | 200 | 93 |
| PVC | 100 | 38 |
| Butyl rubber, CIIR | 140 | 60 |
| Hypalon | 200 | 93 |
| EPDM | 300 | 149 |
| Viton | 180 | 82 |
| Neoprene | 160 | 70 |

Glass, carbon, and graphite are fully resistant to acetic acid. Because of the solvent effects of organic acids, the applications of plastics and elastomeric materials are limited. However, the fully fluorinated grades of plastics are completely resistant. Temperature limitations of plastics and elastomeric materials are shown in the table

See Ref. 2.

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Resistance of Plastic and Elastomeric Materials to Acetic Acid

| Material | Temperature limit °F | °C |
|---|---|---|
| E-CTFE, PES | 200 | 93 |
| ETFE | 220 | 104 |
| FEP | 400 | 204 |
| Furan | 260 | 127 |
| PFA | 240 | 116 |
| PEEK | 140 | 60 |
| PP, PVDF | 180 | 82 |
| PVC | 120 | 49 |
| PTFE | 460 | 238 |
| CIIR | 160 | 71 |
| EPDM | 300 | 148 |
| Butyl rubber, Buna-N | 80 | 26 |

## REDUCING ATMOSPHERE CORROSION

Reducing atmosphere corrosion occurs in coal- and oil-fired boilers resulting from direct reaction of the water wall tubes with a substoichiometric gaseous environment containing sulfur, or with deposited, partially burned char containing iron pyrites. The reducing conditions affect corrosion in two ways. They tend to lower the melting temperature of any deposited slag, which increases its ability to dissolve the normal protective oxide scale on the tubes, and the stable gaseous sulfur compounds, including hydrogen sulfide, which react to form iron sulfide. The iron sulfide scale formed provides less protection than the normal iron oxide scale, thereby allowing corrosion to take place.

## RIDDICK'S CORROSION INDEX

Riddick's corrosion index is used to determine the corrosivity of soft waters. Characteristics of the water such as calcium carbonate solubility, chloride ion concentration, dissolved oxygen, silica concentration, and noncarbonate hardness are taken into account in making the determination.

## RIMMED STEEL

See "Killed Carbon Steel."

## RUST

Rust is the corrosion product of iron or iron-based alloys consisting largely of hydrous ferric oxides. It is an electrochemical process that takes place only in the presence of acids or other electrolytes in the water. The hydrous ferric oxide is orange to reddish brown in color. It consists of nonmagnetic $\alpha\,Fe_2O_3$ (hematite) or the magnetic root $\sqrt{Fe_2O_3}$. Nonferrous metals, therefore, corrode but do not rust.

## REFERENCES

1. UK Chatterjee, SK Bose, SK Roy. Environmental Degradation of Metals. New York: Marcel Dekker, 2001.
2. PA Schweitzer. Corrosion Resistance Tables. 4th ed. New York: Marcel Dekker, 1993.

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# S

## SACRIFICIAL ANODE

See also "Cathodic Protection."

Use of a sacrificial anode is a means of cathodic protection. By selecting an anode constructed of a metal more active in the galvanic series than the metal to be protected, a galvanic cell may be established with the current flowing such that the metal to be protected becomes the cathode and is protected from corrosion while the anode is corroded (sacrificed). These sacrificial anodes are usually composed of magnesium or magnesium-based alloys. Occasionally, zinc and aluminum have been used.

Most sacrificial anodes in use in the United States are of magnesium construction. Approximately 10 million pounds of magnesium are used annually for this purpose. These anodes are used to protect buried pipelines and metal structures. Magnesium rods have also been placed in steel hot-water tanks to increase the life of these tanks.

See Ref. 1.

## SARAN

See "Polyvinylidene Chloride."

## SCAB CORROSION

Scab corrosion is the condition where the paint film remains intact but corrosion has taken place under the paint film as a result of external damage and the paint film is nonadherent to the metal substrate.

## SEASON CRACKING

This is a form of stress corrosion cracking that is usually applied to the stress corrosion cracking of brass. The term originates from early in the twentieth century when cartridge shells made of 70% copper and 30% zinc were found to crack over a period of time. It was later realized that ammonia from decaying organic matter in combination with residual stresses in the brass was responsible for the crack of these shells. This phenomenon was called "season cracking" because the presence of high humidity during warm, moist climates (or seasons) promoted the stress corrosion cracking.



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Stress corrosion cracking of brass commonly occurs when brass is subjected to an applied or residual tensional stress while in contact with a trace of ammonia or amine in the presence of moisture and oxygen.

See "Copper and Copper Alloys."

## SELECTIVE CORROSION

See "Dezincification." Also called selective leaching.

## SELECTIVE LEACHING

Removal of one element from a solid alloy by a corrosion process. See "Dezincification."

## SEMIKILLED STEEL

See "Killed Carbon Steel."

## SENSITIZATION

Sensitization is the term applied to the precipitation of chromium carbides in the grain boundaries of both austenitic 300 series alloys and the straight chromium grades such as types 405 and 410 stainless steel, as a result of exposure to temperatures in the range of 800 to 1600°F (425 to 870°C). This results in intergranular corrosion or cracking.

As the chromium carbides develop, the adjacent metal becomes depleted in dissolved chromium, creating a zone adjacent to the grain boundary of locally corrosion-susceptible iron-nickel alloy. The local composition of the straight chromium grades may approach that of carbon steel. This chromium-depleted zone has less corrosion resistance than the adjacent unaffected alloy and can react galvanically with the unaffected zone, accelerating corrosion rates.

There is not complete agreement over the lower threshold temperature that causes sensitization. It has been reported that cold-worked austenitic stainless steels sensitize at temperatures as low as 700°F (370°C). Solution-annealed austenitic stainless steels require extremely long exposure times to sensitize at temperatures below 850°F (455°C). In general, sensitization takes place most rapidly when the temperature is in the range of 1500°F (815°C).

Sensitization can cause two types of corrosion problems: weld rusting and intergranular corrosion. Refer to "Intergranular Corrosion."

## S-GLASS

S-glass is used as a reinforcing material for thermosetting resins. See "Thermoset Reinforcing Materials."

## SHEET LININGS

Designers of tanks and process vessels are faced with the problem of choosing the most reliable material of construction at reasonable cost. When handling corrosive materials, a

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choice must often be made between the use of an expensive metallic material of construction or the use of a low-cost material from which to fabricate the shell and then install a corrosion-resistant lining. Carbon steel has been and still is the material predominantly selected, although there has been a tendency over the past few years to use a fiberglass-reinforced plastic shell. This latter choice has the advantage of providing atmospheric corrosion protection of the shell exterior.

For many years vessels have been successfully lined with various rubber formulations, both natural and synthetic. Many such vessels have given over 20 years of reliable service.

With the development of newer synthetic elastomeric and plastic materials, the variety of lining materials available has greatly increased.

As with any material, the corrosion resistance, allowable operating values, and cost varies with each. Care must be taken when selecting the lining material that it is compatible with the corrodent being handled at the operating temperatures and pressures required.

## Shell Design

In order for a lining to perform satisfactorily, the vessel shell must meet certain design configurations. Although these details may vary slightly depending upon the specific lining material to be used, there are certain basic principles that apply in all cases.

1. The vessel must be of butt-welded construction.
2. All internal welds must be ground flush.
3. All weld spatter must be removed.
4. All sharp corners must be ground to a minimum of $\frac{1}{8}$ in. radius.
5. All outlets must be of the flanged or pad type. Certain lining materials require that nozzles be no less than 2 in. (55 mm) in diameter.
6. No protrusions are permitted inside of the vessel. Once the lining has been installed, there should be no welding permitted on the exterior of the vessel.

After the fabrication has been completed, the interior surface of the vessel must be prepared to accept the lining. This is a critical step. Unless the surface is properly prepared, proper bonding of the lining to the shell will not be achieved. The basic requirement is that the surface be absolutely clean. To ensure proper bonding, all surfaces to be lined should be abrasive blasted to white metal in accordance with SSPC specification Tp5-63 or NACE specification NACE-1. A white-metal surface condition is defined as being one from which all rust, scale, paint, and the like has been removed and the surface has a uniform gray-white appearance. Streaks or stains of rust or other contaminants are not allowed. A near-white blast-cleaned finish equal to SSPC SP-10 is allowed on occasion. This is a more economical finish. In any case it is essential that the finish be as the lining contractor has specified. Some lining contractors will fabricate the vessel as well as preparing the surface. When the total responsibility is placed on the lining contractor, the problem is simplified, and usually a better-quality product will be the result.

When a vessel shell is fabricated from a reinforced thermosetting plastic (RTP), several advantages are realized. The RTPs themselves generally have a wider range of corrosion resistance but relatively low allowable operating temperatures. When a fluoropolymer type lining is applied to an RTP shell, the temperature to which the backup RTP is exposed has been reduced, in addition to preventing the RTP from becoming exposed to the chemicals in the process system. An upper temperature limit for using RTP dual laminates is 350°F (177°C).

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The dual laminate construction lessens the problem of permeation through liners. If there is permeation, it is believed to pass through the RTP structure at a rate equal to or greater than through the fluoropolymer itself, resulting in no potential for collection of permeate at the thermoplastic-to-thermoset interface. If delamination does not occur, permeation is not a problem.

## Considerations in Liner Selection

Before a lining material is selected, careful consideration should be given to several broad categories, specifically materials being handled, operating conditions, and conditions external to the vessel.

The following questions must be answered about the materials being handled.

1. What are the primary chemicals being handled and at what concentrations?
2. Are there any secondary chemicals, and if so at what concentrations?
3. Are there any trace impurities or chemicals?
4. Are there any solids present, and if so what is their particle size and concentration?
5. If a vessel, will there be agitation, and to what degree? If a pipeline, what are the flow rates, maximum and minimum?
6. What are the fluid purity requirements?

The answers will narrow the selection to those materials that are compatible. This next set of questions will narrow the selection still further by eliminating those materials that do not have the required physical and/or mechanical properties.

1. What is the normal operating temperature and temperature range?
2. What peak temperatures can be reached during shutdown, startup, process upset, etc.?
3. Will any mixing areas exist where exothermic or heat of mixing temperatures can develop?
4. What is the normal operating pressure?
5. What vacuum conditions and range are possible during operation, startup, shutdown, or upset conditions?
6. Will there be temperature cycling?
7. What cleaning methods will be used?

Finally, consideration should be given to the conditions external to the vessel or pipe.

1. What are the ambient temperature conditions?
2. What is the maximum surface temperature during operation?
3. What are the insulation requirements?
4. What is the nature of the external environment? This can dictate finish requirements and/or affect the selection of the shell material.
5. What are the external heating requirements?
6. Is grounding necessary?

With the answers to these questions an intelligent selection of liner and shell can be made.

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## Design Considerations

In addition to selecting a lining material that is resistant to the corrodent being handled, there are three other factors that must be considered in the design, namely permeation, absorption, and environmental stress cracking. Permeation and absorption can cause

1. Bond failure and blistering, resulting from the accumulation of fluids at the bond when the substrate is less permeable than the liner, or from corrosion/reaction products if the substrate is attacked by the permeant.
2. Failure of the substrate from corrosive attack.
3. Loss of contents through the substrate and liner as a result of the eventual failure of the substrate. In unbonded linings it is important that the space between the liner and substrate be vented to the atmosphere, not only to allow minute quantities of permeant vapor to escape but also to prevent entrapped air from collapsing the liner.

## Permeation

Also see "Permeation."

All materials are somewhat permeable to chemical molecules, but plastic materials tend to be an order of magnitude greater in their permeability rates than metals. Polymers can be permeated by gases, vapors, or liquids. Permeation is strictly a physical phenomenon: there is no chemical attack on the polymer. It is a molecular migration either through microvoids in the polymer (if the structure is more or less porous) or between polymer molecules.

Permeation is a function of two variables, one relating to diffusion between molecular chains and the other to the solubility of the permeant in the polymer. The driving forces of diffusion are the concentration gradients in liquids and the partial pressure gradient for gases. Solubility is a function of the affinity of the permeant for the polymer.

Material passing through cracks and voids is not related to permeation. These are two distinct happenings. They are not related in any way.

Permeation is affected by the factors

1. Temperature and pressure
2. Permeant concentration
3. Thickness of the polymer

An increase in temperature will increase the permeation rate, since the solubility of the permeant in the polymer will increase, and as the temperature rises, the polymer chain movement is stimulated, permitting more permeants to diffuse among the chain more easily. For many gases the permeant rates increase linearly with the partial pressure gradient, and the same effect is experienced with concentration gradients of liquids. If the permeant. is highly soluble in the polymer, the permeability increase may not be linear.

The thickness of the polymer affects the permeation. An increase in thickness will generally decrease permeation by the square of the thickness. However, there are disadvantages to this approach. First, as the lining thickness is increased, thermal stresses on the bond are increased, resulting in bond failure. Temperature changes and large differences in coefficients of thermal expansion are the most common causes of bond failure. The thickness and modulus of elasticity of the lining material are two of the factors that influence these stresses. In addition, as the thickness of the sheet lining material increases,

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it becomes more difficult to form, and heat may have to be applied. Also, the thicker sheets are more difficult to weld. Third is cost. As the thickness of the material increases, not only does the material cost more but also the labor cost increases because of the greater difficulty of working with the material. If polymers such as FEP, PTFE, or PVDF are being used, the cost may become prohibitive.

The density of the polymer, in addition to the thickness, will also have an effect on the permeation rate. The higher the specific gravity of the sheet, the fewer will be the voids present through which permeation can take place. A comparison of the specific gravity between two different polymers will not give an indication as to the relative permeation rates. However, a comparison between two liners of the same polymer will provide the difference in the relative permeation rates. The liner having the greater density will have the lower permeation rate.

Other factors affecting permeation consisting of chemical and physicoehemical properties are

1. Ease of condensation of the permeant. Chemicals that condense readily will permeate at a higher rate.
2. The higher the intermolecular chain forces (e.g., Van der Waals hydrogen bonding) of the polymer, the lower the permeation rate.
3. The higher the level of crystallinity in the polymer, the lower the permeation rate.
4. The greater the degree of cross-linking within the polymer, the lower the permeation rate.
5. Chemical similarity between the polymer and the permeant. When the permeant and polymer have similar functional groups, the permeant rate will increase.
6. The smaller the molecule of the permeant, the greater the permeation rate.

The magnitude of any of the effects will be a function of the combination of the polymer and the permeant in actual service.

## Absorption

Also see "Absorption."

Polymers have the potential to absorb varying amounts of corrodents they come into contact with, particularly organic liquids. This can result in swelling, cracking, and penetration to the substrate. Swelling can cause softening of the polymer, introduce high stresses, and cause failure of the bond. If the polymer has a high absorption rate, permeation will probably take place. An approximation of the expected permeation and/or absorption of a polymer can be based on the absorption of water. These data are usually available. Table A.1 provides the water absorption rates for the more common polymers.

The failure due to absorption can best be understood by considering the "steam cycle" test described in the ASTM standards for lined pipe. A section of lined pipe is subjected to thermal and pressure fluctuations. This is repeated for 100 cycles. The steam creates a temperature and pressure gradient through the liner, causing absorption of a small quantity of steam, which condenses to water within the inner wall. Upon pressure release, or on reintroduction of steam, the entrapped water can expand to vapor, causing an original micropore. The repeated pressure and thermal cycling enlarges the micropores, ultimately producing visible water-filled blisters within the liner.

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In an actual process, the polymer may absorb process fluids, and repeated temperature or pressure cycling can cause blisters. Eventually corrodent may find its way to the substrate.

Related effects can occur when process chemicals are absorbed, which may later react, decompose, or solidify within the structure of the plastic. Prolonged retention of the chemicals may lead to their decomposition within the polymer. Although it is unusual, it is possible for absorbed monomers to polymerize.

Several steps can be taken to reduce absorption. Thermal insulation of the substrate will reduce the temperature gradient across the vessel, thereby preventing condensation and subsequent expansion of the absorbed fluids. This also reduces the rate and magnitude of temperature changes, keeping blisters to a minimum. The use of operating procedures or devices that limit the ratio of process pressure reductions or temperature increases will provide additional protection.

## Environmental Stress Cracking

Stress cracks develop when a tough polymer is stressed for an extended period of time under loads that are small relative to the polymer's yield point. Cracking will occur with little elongation of the material. The higher the molecular weight of the polymer, the less likelihood of environmental stress cracking, other things being equal. Molecular weight is a function of the length of individual chains that make up the polymer. Longer-chain polymers tend to crystallize less than polymers of lower molecular weight or shorter chains and also have greater load-bearing capacity.

Crystallinity is an important factor affecting stress corrosion cracking. The less the crystallization that takes place, the less the likelihood of stress cracking. Unfortunately, the lower the crystallinity, the greater the likelihood of permeation.

Resistance to stress cracking can be reduced by the absorption of substances that chemically resemble the polymer and will plasticize it. In addition, the mechanical strength will be reduced. Halogenated chemicals, particularly those consisting of small molecules containing fluorine or chlorine, are especially likely to be similar to the fluoropolymers and should be tested for their effect.

The presence of contaminants in a fluid may act as an accelerator. For example, polypropylene can safely handle sulfuric or hydrochloric acids, but iron or copper contamination in concentrated sulfuric or hydrochloric acids can result in the stress cracking of polypropylene.

## Elastomeric Linings

Elastomers, sometimes referred to as rubbers, have given many years of service in providing protection to steel vessels. Each of these materials can be compounded to improve certain of its properties. Because of this it is necessary that a complete specification for a lining using these materials include specific properties that are required for the application. These include resilience, hysteresis, static or dynamic shear and compression modulus, flex fatigue and cracking, creep resistance to oils and chemicals, permeability, and brittle point, all in the temperature range to be encountered in service. This will permit a competent manufacturer to propose lining material for the application.

Elastomeric linings are sheet applied and bonded to the steel substrate. The bonding material to be used is dependent upon the specific elastomer to be installed. Repair of these linings is relatively simple. Many older vessels with numerous repair patches are still operating satisfactorily.

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## Natural Rubber

The maximum temperature for continuous use of natural rubber is 175°F (80°C). The degree of curing to which natural rubber is subjected will determine whether it is classified as soft, semihard, or hard. Soft rubber is the form primarily used for lining material, although some hard linings are produced.

It provides excellent resistance to most inorganic salt solutions, alkalies, and nonoxidizing acids. Hydrochloric acid will react with soft rubber to form rubber hydrochloride, and therefore it is not recommended that natural (soft) rubber be used in contact with this acid. Strong oxidizing media such as nitric acid, concentrated sulfuric acid, permanganates, dichromates, chlorine dioxide, and sodium hypochlorite will severely attack rubber. Mineral and vegetable oils, gasoline, benzene, toluene, and chlorinated hydrocarbons also affect rubber. Cold water tends to preserve natural rubber. Natural rubber offers good resistance to radiation and alcohols. Refer to Table S.1 for the compatibility of multiple-ply (soft/hard/soft) natural rubber

See also "Natural Rubber."

**Table S.1** Compatibility of Multiple-Ply (Soft/Hard/Soft) Natural Rubber with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | x | x | Ammonium chloride, sat. | 160 | 71 |
| Acetamide | x | x | Ammonium fluoride 10% | x | x |
| Acetic acid 10% | x | x | Ammonium fluoride 25% | x | x |
| Acetic acid 50% | x | x | Ammonium hydroxide 25% | 100 | 38 |
| Acetic acid 80% | x | x | Ammonium hydroxide, sat. | 100 | 38 |
| Acetic acid, glacial | x | x | Ammonium nitrate | 160 | 71 |
| Acetic anhydride | x | x | Ammonium persulfate | | |
| Acetone | 140 | 60 | Ammonium phosphate | 160 | 71 |
| Acetyl chloride | | | Ammonium sulfate 10–40% | 160 | 71 |
| Acrylic acid | | | Ammonium sulfide | 160 | 71 |
| Acrylonitrile | | | Ammonium sulfite | | |
| Adipic acid | | | Amyl acetate | x | x |
| Allyl alcohol | | | Amyl alcohol | 100 | 38 |
| Allyl chloride | | | Amyl chloride | x | x |
| Alum | 160 | 71 | Aniline | x | x |
| Aluminum acetate | | | Antimony trichloride | | |
| Aluminum chloride, aqueous | 160 | 71 | Aqua regia 3:1 | x | x |
| Aluminum chloride, dry | 160 | 71 | Barium carbonate | 160 | 71 |
| Aluminum fluoride | x | x | Barium chloride | 160 | 71 |
| Aluminum hydroxide | | | Barium hydroxide | 160 | 71 |
| Aluminum nitrate | x | x | Barium sulfate | 160 | 71 |
| Aluminum oxychloride | | | Barium sulfide | 160 | 71 |
| Aluminum sulfate | 160 | 71 | Benzaldehyde | x | x |
| Ammonia gas | | | Benzene | x | x |
| Ammonium bifluoride | | | Benzene sulfonic acid 10% | x | x |
| Ammonium carbonate | 160 | 71 | Benzoic acid | 160 | 71 |
| Ammonium chloride 10% | 160 | 71 | Benzyl alcohol | x | x |
| Ammonium chloride 50% | 160 | 71 | Benzyl chloride | x | x |

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**Table S.1** Compatibility of Multiple-Ply (Soft/Hard/Soft) Natural Rubber with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Borax | 160 | 71 | Copper cyanide | 160 | 71 |
| Boric acid | 140 | 60 | Copper sulfate | 160 | 71 |
| Bromine gas, dry | | | Cresol | x | x |
| Bromine gas, moist | | | Cupric chloride 5% | x | x |
| Bromine liquid | | | Cupric chloride 50% | x | x |
| Butadiene | | | Cyclohexane | x | x |
| Butyl acetate | x | x | Cyclohexanol | | |
| Butyl alcohol | 160 | 71 | Dichloroacetic acid | | |
| *n*-Butylamine | | | Dichloroethane (ethylene dichloride) | x | x |
| Butyl phthalate | | | Ethylene glycol | 160 | 71 |
| Butyric acid | x | x | Ferric chloride | 160 | 71 |
| Calcium bisulfide | | | Ferric chloride 50% in water | 160 | 71 |
| Calcium bisulfite | 160 | 71 | Ferric nitrate 10–50% | x | x |
| Calcium carbonate | 160 | 71 | Ferrous chloride | 140 | 60 |
| Calcium chlorate | 140 | 60 | Ferrous nitrate | x | x |
| Calcium chloride | 140 | 60 | Fluorine gas, dry | x | x |
| Calcium hydroxide 10% | 160 | 71 | Fluorine gas, moist | | |
| Calcium hydroxide, sat. | 160 | 71 | Hydrobromic acid, dilute | 160 | 71 |
| Calcium hypochlorite | x | x | Hydrobromic acid 20% | 160 | 71 |
| Calcium nitrate | x | x | Hydrobromic acid 50% | 160 | 71 |
| Calcium oxide | 160 | 71 | Hydrochloric acid 20% | x | x |
| Calcium sulfate | 160 | 71 | Hydrochloric acid 38% | 160 | 71 |
| Caprylic acid | | | Hydrocyanic acid 10% | | |
| Carbon bisulfide | x | x | Hydrofluoric acid 30% | x | x |
| Carbon dioxide, dry | | | Hydrofluoric acid 70% | x | x |
| Carbon dioxide, wet | | | Hydrofluoric acid 100% | x | x |
| Carbon disulfide | x | x | Hypochlorous acid | | |
| Carbon monoxide | x | x | Iodine solution 10% | | |
| Carbon tetrachloride | x | x | Ketones, general | | |
| Carbonic acid | 160 | 71 | Lactic acid 25% | x | x |
| Cellosolve | x | x | Lactic acid, concentrated | x | x |
| Chloracetic acid | x | x | Magnesium chloride | 160 | 71 |
| Chloracetic acid, 50% water | x | x | Malic acid | 100 | 38 |
| Chlorine gas, dry | x | x | Manganese chloride | | |
| Chlorine gas, wet | x | x | Methyl chloride | x | x |
| Chlorine, liquid | x | x | Methyl ethyl ketone | x | x |
| Chlorobenzene | x | x | Methyl isobutyl ketone | x | x |
| Chloroform | x | x | Muriatic acid | 140 | 60 |
| Chlorosulfonic acid | x | x | Nitric acid 5% | x | x |
| Chromic acid 10% | x | x | Nitric acid 20% | x | x |
| Chromic acid 50% | x | x | Nitric acid 70% | x | x |
| Chromyl chloride | | | Nitric acid, anhydrous | x | x |
| Citric acid 15% | x | x | Nitrous acid, concentrated | x | x |
| Citric acid, concentrated | x | x | Oleum | | |
| Copper acetate | | | Perchloric acid 10% | | |
| Copper carbonate | x | x | Perchloric acid 70% | | |
| Copper chloride | x | x | Phenol | x | x |

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**Table S.1** Compatibility of Multiple-Ply (Soft/Hard/Soft) Natural Rubber with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Phosphoric acid 50–80% | 160 | 71 | Stannous chloride | 160 | 71 |
| Picric acid | | | Sulfuric acid 10% | 160 | 71 |
| Potassium bromide 30% | 160 | 71 | Sulfuric acid 50% | x | x |
| Salicylic acid | | | Sulfuric acid 70% | x | x |
| Silver bromide 10% | | | Sulfuric acid 90% | x | x |
| Sodium carbonate | 160 | 71 | Sulfuric acid 98% | x | x |
| Sodium chloride | 160 | 71 | Sulfuric acid 100% | x | x |
| Sodium hydroxide 10% | 160 | 71 | Sulfuric acid, fuming | x | x |
| Sodium hydroxide 50% | x | x | Sulfurous acid | x | x |
| Sodium hydroxide, concentrated | x | x | Thionyl chloride | | |
| Sodium hypochlorite 20% | x | x | Toluene | | |
| Sodium hypochlorite, concentrated | x | x | Trichloroacetic acid | | |
| Sodium sulfide to 50% | 160 | 71 | White liquor | | |
| Stannic chloride | 160 | 71 | Zinc chloride | 160 | 71 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable.

*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

## Isoprene

Natural rubber chemically is a natural *cis*-polyisoprene. Isoprene (IR) is a synthetic *cis*-polyisoprene. The corrosion resistance of IR is the same as that of natural rubber. The major difference is that isoprene has no odor and therefore can be used in the handling of certain food products.

## Neoprene

The maximum temperature under which neoprene (CR) can be used is 180–200°F (82–93°C). Excellent service is experienced in contact with aliphatic compounds (methyl and ethyl alcohols, ethylene glycols, etc.), aliphatic hydrocarbons, and most freon refrigerants. However, the outstanding property of neoprene is its resistance to attack from solvents, waxes, fats, oils, greases, and many other petroleum-based products. Dilute mineral acids, inorganic salt solutions, and alkalies can also be handled successfully.

Chlorinated and aromatic hydrocarbons, organic esters, aromatic hydroxy compounds, and certain ketones will attack neoprene, as will highly oxidizing acid and salt solutions such as nitric and concentrated sulfuric acids.

See also "Neoprene."

## Butyl Rubber

The maximum temperature to which butyl rubber (IIR) can be exposed on a continuous basis is 250–300°F (120–148°C). Butyl rubber is very nonpolar. It has exceptional resistance to dilute mineral acids, alkalies, phosphate ester oils, acetone, ethylene glycol, ethylene, and water. Resistance to concentrated acids, except nitric and sulfuric, is good. It will be attacked by petroleum oils, gasoline, and most solvents (except oxygenated solvents) but is resistant to swelling by vegetable and animal oils. Refer to "Butyl Rubber and Chlorobutyl Rubber" for more details.

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## Chlorsulfonated Polyethylene

The maximum temperature that Hypalon can be exposed to on a continuous basis is 250°F (121°C). Hypalon is highly resistant to attack by hydrocarbon oils and fuels, even at elevated temperatures. It is also resistant to such oxidizing chemicals as sodium hypochlorite, sodium peroxide, ferric chloride, and sulfuric, chromic, and hydrofluoric acids. Concentrated hydrochloric acid (37%) can be handled below 158°F (70°C). Below this temperature Hypalon can handle all concentrations without adverse effect. Nitric acid up to 60% concentration at room temperature can also be handled without adverse effect. Hypalon is also resistant to salt solutions, alcohols, and both weak and concentrated alkalies.

Aliphatic, aromatic, and chlorinated hydrocarbons, aldehydes, and ketones will attack Hypalon. Refer to Table C.17 for compatibility of Hypalon with selected corrodents.

## Urethane Rubber

The maximum temperature to which the urethane rubbers (AU) can be exposed on a continuous basis is 250°F (121°C). The urethane rubbers are resistant to most mineral and vegetable oils, greases, and fuels. They have limited service in weak acid solutions and cannot be used in concentrated acids. Neither are they resistant to steam or caustic, aromatic hydrocarbons, polar solvents, esters, or ethers. Ketones will attack urethane. Alcohols will soften and swell the urethane rubbers.

## Polyester Elastomer

The maximum temperature to which polyester elastomers (PE) can be exposed continuously is 302°F (150°C). The elastomers have excellent resistance to nonpolar materials such as oils and hydraulic fluids, even at elevated temperatures. At room temperature they are resistant to most polar fluids, such as acids, bases, amines, and glycols. Resistance is very poor at temperatures of 158°F (70°C) or above.

These elastomers are not resistant to polar fluids at elevated temperatures.

## Perfluoroelastomers

The maximum temperature to which PFEs may be subjected on a continuous basis is 400°F (205°C). These materials are sold under various trade names. Three typical brands are given in the table.

| Trade name | Manufacturer |
|---|---|
| Viton | DuPont |
| Technoflon | Ausimont |
| Fluorel | 3M |

The fluoroelastomers provide excellent resistance to oils, fuels, lubricants, most mineral acids, many aliphatic and aromatic hydrocarbons (carbon tetrachloride, benzene, toluene, xylene), gasoline, naphtha, chlorinated solvents, and pesticides.

These materials are not suitable for use with low-molecular-weight esters, ethers, ketones, certain amines, or hot anhydrous hydrofluoric or chlorosulfonic acids. Refer to Table E.3 for the compatibility of Viton with selected corrodents.

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## Thermoplastic Linings

Thermoplastic linings are used more extensively than any other type of lining. The most common thermoplasts used are

Polyvinyl chloride (PVC)
Chlorinated polyvinyl chloride (CPVC)
Polyvinylidene fluoride (PVDF)
Polypropylene (PP)
Polyethylene (PE)
Tetrafluoroethylene (PTFE)
Fluorinated ethylene propylene (FEP)
Perfluoralkoxy (PFA)
Ethylene-tetrafluoroethylenc (ETFE)
Ethylene-chlorotrifluorethylene (ECTFE)

These materials are capable of providing a wide range of corrosion resistance. Table S.2 lists the general area of corrosion resistance for each of the thermoplasts. This table is only a general guide. The resistance of a lining material to a specific corrodent should be checked.

These materials are used to line vessels as well as pipe and fittings. When vessels are lined, the linings, with the exception of plasticized PVC, are fabricated from sheet stock that must be cut, shaped, and joined. Joining is usually accomplished by hot gas welding. Several problems exist when a thermoplastic lining is bonded to a metal shell, due primarily to the large differences in the coefficient of thermal expansion and the difficulty of adhesion. If the vessel is to be used under ambient temperature, such as a storage vessel, the problem of thermal expansion differences is eliminated. However, the problem of adhesion is still present. Because of this, many linings are installed as loose linings in the vessel.

Techniques have been developed to overcome the problem of adhesion, making use of an intermediate bond. One approach is to heat the thermoplastic sheet, then impress into one surface a fiber cloth or nonwoven web. This provides half of the bond. Bonding to the metal surface is accomplished by the use of an epoxy adhesive that will bond to both the fiber and the metal.

**Table S.2** General Corrosion Resistance of Thermoplastic Lining Materials

| Material | Strong acids | Strong bases | Chlorinated solvents | Esters and ketones | Strong oxidants |
|---|---|---|---|---|---|
| PVC (type 1) | F | F | P | P | P |
| CPVC | F | F | F | P | P |
| PVDF | E | P | E | P | E |
| Polypropylene | G | E | P | F | P |
| Polyethylene | F | G | P | P | E |
| PTFE | E | E | E | E | E |
| FEP | E | E | E | E | E |
| ECTFE | E | E | E | E | E |

E = excellent; G = good; F = fair; P = poor.

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Welding techniques for joining the thermoplastic sheets are critical. Each weld must be continuous, leak tight, and mechanically strong. It is important that only qualified welders be used for this operation. Poor welding is a common cause of lining failure.

## Polyvinyl Chloride

The maximum allowable temperature for continuous operation of Type 1 PVC is 140°F (60°C). Plasticized PVC can be bonded directly to a metal substrate. Unplasticized PVC cannot be bonded directly. It is bonded to a plasticized material forming a dual laminate that is then bonded to a metal substrate.

Plasticized PVC does not have the same range of corrosion resistance as the unplasticized PVC (Type 1). Unplasticized PVC is resistant to attack by most acids and strong alkalies as well as gasoline, kerosene, and aliphatic alcohols and hydrocarbons. It is subject to attack by aromatics, chlorinated organic compounds, and lacquer solvents.

See also "Polyvinyl Chloride."

## Chlorinated Polyvinyl Chloride

CPVC can be operated continuously at a maximum temperature of 200°F (93°C). Chlorinated polyvinyl chloride is very similar in properties to PVC, except that it has a higher allowable operating temperature and a somewhat better resistance to chlorinated solvents. It is extremely difficult to hot weld the joints in a sheet lining. This factor should be considered when selecting this material.

CPVC is resistant to most acids, alkalies, salts, halogens, and many corrosive waters. In general, it should not be used to handle most polar organic materials including chlorinated or aromatic hydrocarbons, esters, and ketones.

See also "Chlorinated Polyvinyl Chloride."

## Polyvinylidene Fluoride

This material may be operated continuously at a maximum temperature of 275°F (135°C). PVDF is one of the most popular lining materials because of its range of corrosion resistance and high allowable operating temperature. Unless a dual laminate is used, linings of PVDF will be loose.

PVDF is resistant to most acids, bases, and organic solvents. It also has the ability to handle wet or dry chlorine, bromine, and other halogens.

It is not resistant to strong alkalies, fuming acids, polar solvents, amines, ketones, and esters. When used with strong alkalies, it stress cracks.

See also "Vinylidene Fluoride Elastomers."

## Polypropylene

The maximum allowable temperature under which PP can be operated continuously is 180°F (82°C). PP must be attached to a backing sheet in order to be secured as a lining. If a backing sheet is not used, the lining will be loose.

PP is resistant to sulfur-bearing compounds, caustics, solvents, acids, and other organic chemicals. It is not resistant to oxidizing-type acids, detergents, low-boiling hydrocarbons, alcohols, aromatics, and some chlorinated organic materials.

See also "Polypropylene."

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## Polyethylene

The maximum allowable temperature, at continuous contact, at which polyethylene (PE) can be used is 120°F (49°C). PE is the least expensive of all the plastic materials.

PE has a wide range of corrosion resistance ranging from potable water to corrosive wastes. It exhibits excellent resistance to strong oxidizing chemicals, alkalies, acids, and salt solutions.

See also "Polyethylene."

## Tetrafluorethylene

PTFE can be used continuously at 500°F (260°C). It cannot be bonded directly to metal substrates but can be bonded by using a laminated fiberglass sheet as a backing.

The material tends to creep under stress at elevated temperatures. When the vessel is designed, provisions should be made to retain the PTFE. PTFE liners are subject to permeation by some corrodents. Table P.5 provides the vapor permeation of PTFE by selected materials.

PTFE is chemically inert in the presence of most corrodents. There are very few chemicals that will attack it within normal use temperatures. These reactants are among the most violent oxidizers and reducing agents known. Elemental sodium in intimate contact with fluorocarbons removes fluorine from the polymer molecule. The other alkali metals (potassium, lithium, etc.) react in a similar manner.

Fluorine and related compounds (e.g., chlorine trifluoride) are absorbed into the PTFE resin with such intimate contact that the mixture becomes sensitive to a source of ignition such as impact.

The handling of 80% sodium hydroxide, aluminum chloride, ammonia, and certain amines at high temperatures may produce the same effect as elemental sodium. Also, slow oxidative attack can be produced by 70% nitric acid under pressure at 480°F (250°C).

See also "Permeation" and "Polytetrafluorethylene."

## Fluorinated Ethylene Propylene

FEP has a lower maximum operating temperature than PTFE. It exhibits changes in physical strength after prolonged exposure above 400°F (204°C), so the recommended maximum continuous operating temperature is 375°F (190°C).

Permeation of FEP liners can pose a problem. Table P.6 provides some permeation data relating to the more common chemicals. There is also some absorption of chemicals by FEP. This absorption can also lead to problems. Table A.2 is a listing of the absorption of selected liquids by FEP.

FEP basically has the same corrosion-resistant properties as PTFE but at a lower maximum temperature. It is resistant to practically all chemicals, the exception being extremely potent oxidizers such as chlorine trifluoride and related compounds. Some chemicals will attack FEP when present in high concentrations, at or near the service temperature limit.

See also "Fluorinated Ethylene Propylene."

## Perfluoralkoxy

PFA can be used continuously at 500°F (260°C). It is subject to permeation by certain gases and will absorb liquids. Table P.7 illustrates the permeability of PFA and Table A.3 lists the absorption of representative liquids by PFA.

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Perfluoralkoxy is inert to strong mineral acids, inorganic bases, inorganic oxidizers, aromatics, some aliphatic hydrocarbons, alcohols, aldehydes, ketones, esters, ethers, chlorocarbons, fluorocarbons, and mixtures of these compounds.

PFA will be attacked by certain halogenated complexes containing fluorine. These include chlorine trifluoride, bromine trifluoride, iodine pentafluoride, and fluorine. PFA can also be attacked by such metals as sodium or potassium, particularly in the molten state.

See also "Perfluoralkoxy."

## Ethylene-Tetrafluoroethylene

ETFE has a maximum continuous service temperature of 300°F (140°C). It is fairly inert to strong mineral acids, halogens, inorganic bases, and metal salt solutions. Under most conditions ETFE is resistant to alcohols, ketones, ethers, and chlorinated hydrocarbons.

Strong oxidizers (e.g., nitric acid), organic bases (e.g., amines), and sulfonic acid will attack ETFE.

See also "Ethylene-Tetrafluoroethylene."

## Ethylene-Chlorotrifluorethylene

The maximum service temperature of ECTFE is 340°F (170°C). ECTFE is very similar to PTFE as far as corrosion resistance is concerned, but it does not have the permeation problems associated with PTFE. It is resistant to strong mineral and oxidizing acids, alkalies, metal etchants, liquid oxygen, and essentially all organic solvents *except* hot amine (e.g., aniline, dimethylamine). ECTFE will be attacked by metallic sodium and potassium.

See also "Ethylene-Chlorotrifluoroethylene."

## Causes of Lining Failure

Linings, if properly selected, installed, and maintained, and if the vessel has been properly designed, fabricated, and prepared to accept the lining, will usually give many useful years of service. However, on occasion there have been lining failures, which can be attributed to one or more of the following causes.

### *Liner Selection*

This is the first step. Essential to this step is a careful analysis of the materials to be handled, their concentrations, and operating conditions as outlined in the beginning of this section. Consideration must also be given to the physical and mechanical properties of the liner to ensure that they meet the specified operating conditions. If there is any doubt, corrosion testing should be undertaken to guarantee the resistance of the liner material.

### *Inadequate Surface Preparation*

Surface preparation is extremely important. All specifications for surface preparation must be followed. If surface preparation is not done properly, poor bonding can result and/or mechanical damage to the liner is possible.

### *Thermal Stresses*

If sheet linings are not properly designed, thermal stresses produced by thermal cycling can eventually result in bond failure.

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### *Permeation*

Certain lining materials are subject to permeation when in contact with specific corrodents. When the possibility of permeation exists, an alternative lining material should be selected. Permeation can result in debonding resulting from corrosion products of fluids accumulating at the interface between the liner and the substrate. In addition, corrosion of the substrate can result, leading to leakage problems and eventual failure of the substrate.

### *Absorption*

As with permeation, absorption of the corrodent by the liner material can result in swelling of the liner, cracking, and eventual penetration to the substrate. This can lead to high stresses and debonding.

### *Welding Flaws*

It is essential that qualified personnel perform the welding and that only qualified and experienced contractors be used to install the linings. A welding flaw is a common cause of lining failure.

### *Debonding*

Debonding can also occur as a result of the use of the wrong bonding agent. Care should be taken that the proper bonding agent is employed for the specific lining being used.

### *Operation*

Lined vessels should be properly identified when installed, with the allowable operating characteristics of the liner posted to avoid damage to the liner during cleaning or repair operations. Most failures from this cause result while vessels are being cleaned or repaired. If live steam is used to clean the vessel, allowable operating temperatures may be exceeded. If the vessel is solvent cleaned, chemical attack may occur.

See Ref. 2.

## SHELTERED CORROSION

Corrosion taking place in locations where moisture condenses or accumulates and does not dry out for long periods of time is known as sheltered corrosion. Typical locations are the inside surfaces of automobile doors, storage tanks, etc. Also see "Atmospheric Corrosion."

## SHOT PEENING

Since cracks will not initiate or propagate in an area of compressive stress, stress corrosion cracking cannot occur. After all manufacturing operations on metals are completed, residual stresses remain in the finished part. These stresses can be either tensile or compressive. High residual tensile stresses will be present in the heat-affected zone adjacent to a welded joint, while compressive stresses may be present on the surface of induction-hardened components.

Shot peening is a cold-working process in which the surface of a part is bombarded with small spherical media called shot. Each piece of shot upon striking the metal part imparts a small indentation or dimple on the surface. For the dimple to form, the surface

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fibers of the material must be yielded in tension. The fibers below the surface try to restore the surface to its original shape, thereby producing, below the dimple, an area of cold worked material highly stressed in compression. By overlapping the dimples an even area of residual compressive stress is produced.

Materials typically used for shot peening are small spheres of cast steel, conditioned cut wire (both carbon and stainless steel), and ceramic and glass beads. Normally, cast steel is used, but in cases where iron contamination on the surface is a concern, stainless steel cut wire, glass, or ceramic beads are employed.

The effects of the compressive stress and the cold working induced by shot peening are responsible for the benefits derived. Compressive stresses are beneficial in increasing resistance to fatigue failure, corrosion fatigue, stress corrosion cracking, hydrogen-assisted cracking, fretting, galling, and erosion caused by cavitation. Benefits received due to cold working include work hardening, intergranular corrosion resistance, surface texturing, closing of porosity, and testing the bond of coatings.

Fretting can develop when the relative motion of microscopic amplitude occurs between two metal surfaces. Fine abrasive oxides form as a result of this rubbing. These oxides contribute to the scoring of the surfaces. Fretting gives rise to one or more forms of damage, such as fretting corrosion, fretting wear, or fretting fatigue. (See "Fretting Corrosion.") Shot peening has proven to be successful in retarding fretting by increasing the surface hardness and providing residual compressive stresses at the fretting surfaces.

Stress corrosion cracking is the failure of metal by cracking as a result of the combined action of corrosion and static tensile stress (either externally applied or internal, i.e., residual). Cracking may be either intergranular or transgranular depending on the metal and the corrodent. Refer to "Stress Corrosion Cracking." Most metals such as aluminum, copper, magnesium, nickel, steel, and stainless steel alloys are susceptible to stress corrosion cracking when a tensile stress at or above their threshold limits exists and they are exposed to specific corrosive environments.

The primary sources of stress contributing to SCC are applied as a result of pressure, poor fit-up, residual resulting from heat treatment, welding, machining, or forming. Shot peening produces compressive stresses that retard and in many cases prevent SCC.

Hydrogen-assisted cracking, or hydrogen embrittlement, is the result of atomic hydrogen penetrating and reacting with the metal, reducing the metal's ductility and ability to withstand cyclic loads. (See "Hydrogen Damage.") Shot peening retards the migration of hydrogen through the metal. It not only increases the time it takes hydrogen to migrate through the metal but also lowers the steady-state permeation rate of hydrogen by as much as 24%.

When austenitic stainless steels are subjected to heating in the range of 900 to 1500°F (482 to 815°C), such as in welding, there is a preferential precipitation of chromium carbides in the grain boundaries. This results in a depletion of chromium in the areas adjacent to these grain boundaries, reducing the corrosion resistance of such regions and making the alloy susceptible to intergranular corrosion. (See "Intergranular Corrosion.")

Shot peening prior to exposure to this sensitization temperature range breaks up grains and grain boundaries and provides many nucleation sites for chromium carbide precipitation. Since the chromium carbides precipitate randomly in the peened surface rather than preferentially along the grain boundaries, there is no continuous path for corrosion to follow, and intergranular corrosion does not occur.

See Refs. 3–10.

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## SILICON CARBIDE

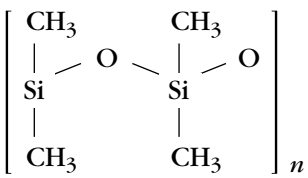
Silicon carbide fibers are used as a reinforcing material for thermosetting resins. See "Thermoset Reinforcing Materials."

## SILICON CARBIDE FIBERS

Silicon carbide fibers are produced by a chemical vapor deposition process in which a heated carbon monofilament approximately 33 μm in diameter reacts with a mixture of hydrogen and chlorinated alkyl silicones. These fibers have been used on a development basis for reinforcing aluminum and titanium and to some extent for ceramic and organic matrices.

## SILICONE

Silicon is in the same chemical group as carbon but is a more stable element. The silicones are a family of synthetic polymers that are partly organic and partly inorganic. They have a backbone of alternating silicon and oxygen atoms rather than a backbone of carbon-carbon atoms. The basic structure is



Typically the silicon atoms will have one or more organic side groups attached to them, generally phenol ($C_6H_5$–), methyl ($CH_3$–), or vinyl ($CH_2 = CH$–) units. These groups impart properties such as solvent resistance, lubricity, and reactivity with organic chemicals and polymers. Silicone polymers may be filled or unfilled depending upon the properties required and the application.

Silicone polymers possess several properties that distinguish them from their organic counterparts:

1. Chemical inertness
2. Weather resistance
3. Extreme water repellency
4. Uniform properties over a wide temperature range
5. Excellent electrical properties over a wide range of temperature and frequencies
6. Low surface tension
7. High degree of slip or lubricity
8. Excellent release properties
9. Inertness and compatibility, both physiologically and in electronic applications

Silicone resins and composites produced with silicone resins exhibit outstanding long-term thermal stability at temperatures approaching 572°F/300°C and excellent moisture resistance and electrical properties. These materials are also useful in the cryogenic temperature range. Table S.3 shows the effect of cryogenic temperatures on the physical properties of silicone glass fabric laminates. Refer to Table S.4 for the physical and mechanical properties of mineral- and/or glass-filled silicones.

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**Table S.3** Strength of Silicone Glass Fabric Laminate at Cryogenic Temperatures

| Transformation (°F/°C) | Tensile strength (psi × $10^3$) | Flexural strength (psi × $10^3$) | Compressive strength (psi × $10^3$) |
|---|---|---|---|
| 72/22 | 30 | 38 | 21 |
| –110/–79 | 47 | 46 | 39 |
| –320/–201 | 70 | 67 | 43 |
| –424/–253 | 76 | 65 | 46 |

**Table S.4** Physical and Mechanical Properties of Silicone Laminates

| Property | |
|---|---|
| Specific gravity | 1.8–2.03 |
| Water absorption (24 h at 73°F/23°C) (%) | 0.15 |
| Dielectric strength, short-term (V/mil) | 200–550 |
| Tensile strength at break (psi) | 500–1500 |
| Tensile modulus (psi × $10^3$) | |
| Elongation at break (%) | 80–800 |
| Compressive strength (psi) | 21,000 |
| Flexural strength (psi) | 38,000 |
| Compressive modulus (psi × $10^3$) | |
| Flexural modulus (psi × $10^3$) at | |
| 73°F/23°C | |
| 200°F/93°C | |
| 250°F/121°C | |
| Izod impact (ft-lb/in., of notch) | |
| Hardness, Shore | A10–80 |
| Coefficient of thermal expansion ($10^{-6}$ in./in./°F) | 20–50 |
| Thermal conductivity ($10^{-4}$ cal-cm/s-$cm^2$ °C or Btu/h/$ft^2$/°F/in.) | 7–18 |
| Deflection temperature at | |
| 264 psi (°F) | >500 |
| 66 psi (°F) | |
| Max. operating temperature (°F/°C) | >550/288 |
| Limiting oxygen index (%) | |
| Flame spread | |
| Underwriters lab rating (Sub. 94) | |

As discussed previously, the silicone atoms may have one or more organic side groups attached. The addition of these side groups has an effect on the corrosion resistance. Therefore, it is necessary to check with the supplier as to the properties of the silicone laminate being supplied. Table S.5 lists the compatibility of a silicone laminate (with methyl groups appended to the silicon atoms) with selected corrodents.

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**Table S.5** Compatibility of Methyl Appended Silicone Laminate with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetic acid 10% | 90 | 32 | Lactic acid, concd. | 80 | 27 |
| Acetic acid 50% | 90 | 32 | Magnesium chloride | 400 | 204 |
| Acetic acid 80% | 90 | 32 | Methyl alcohol | 410 | 210 |
| Acetic acid, glacial | 90 | 32 | Methyl ethyl ketone | x | x |
| Acetone | 100 | 43 | Methyl isobutyl ketone | x | x |
| Acrylic acid 75% | 80 | 27 | Nitric acid 5% | 80 | 23 |
| Acrylonitrile | x | x | Nitric acid 20% | x | x |
| Alum | 220 | 104 | Nitric acid 70% | x | x |
| Aluminum sulfate | 410 | 210 | Nitric acid, anhydrous | x | x |
| Ammonium chloride 10% | x | x | Oleum | x | x |
| Ammonium chloride 50% | 80 | 27 | Phenol | x | x |
| Ammonium chloride, sat. | 80 | 27 | Phosphoric acid 50–80% | x | x |
| Ammonium fluoride 25% | 80 | 27 | Propyl alcohol | 400 | 204 |
| Ammonium hydroxide 25% | x | x | Sodium carbonate | 300 | 149 |
| Ammonium nitrate | 210 | 99 | Sodium chloride 10% | 400 | 204 |
| Amyl acetate | 80 | 27 | Sodium hydroxide 10% | 90 | 27 |
| Amyl alcohol | x | x | Sodium hydroxide 50% | 90 | 27 |
| Amyl chloride | x | x | Sodium hydroxide, concd. | 90 | 27 |
| Aniline | x | x | Sodium hypochlorite 20% | x | x |
| Antimony trichloride | 80 | 27 | Sodium sulfate | 400 | 204 |
| Aqua regia 3:1 | x | x | Stannic chloride | 80 | 27 |
| Benzene | x | x | Sulfuric acid 10% | x | x |
| Benzyl chloride | x | x | Sulfuric acid 50% | x | x |
| Boric acid | 390 | 189 | Sulfuric acid 70% | x | x |
| Butyl alcohol | 80 | 27 | Sulfuric acid 90% | x | x |
| Calcium bisulfide | 400 | 204 | Sulfuric acid 98% | x | x |
| Calcium chloride | 300 | 149 | Sulfuric acid 100% | x | x |
| Calcium hydroxide 30% | 200 | 93 | Sulfuric acid, fuming | x | x |
| Calcium hydroxide, sat. | 400 | 204 | Sulfurous acid | x | x |
| Carbon bisulfide | x | x | Tartaric acid | 400 | 204 |
| Carbon disulfide | x | x | Tetrahydrofuran | x | x |
| Carbon monoxide | 400 | 204 | Toluene | x | x |
| Carbonic acid | 400 | 204 | Tributyl phosphate | x | x |
| Chlorobenzene | x | x | Turpentine | x | x |
| Chlorosulfonic acid | x | x | Vinegar | 400 | 204 |
| Ethylene glycol | 400 | 204 | Water, acid mine | 210 | 99 |
| Ferric chloride | 400 | 204 | Water, demineralized | 210 | 99 |
| Hydrobromic acid 50% | x | x | Water, distilled | 210 | 99 |
| Hydrochloric acid 20% | 90 | 32 | Water, salt | 210 | 99 |
| Hydrochloric acid 38% | x | x | Water, sea | 210 | 99 |
| Hydrofluoric acid 30% | x | x | Xylene | x | x |
| Lactic acid, all conc. | 80 | 27 | Zinc chloride | 400 | 204 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

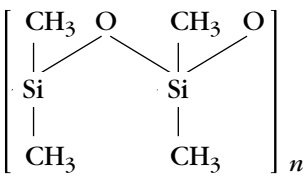
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However, in general, silicone laminates can be used in contact with dilute acids and alkalies, alcohols, and animal and vegetable oils. They are also resistant to aliphatic hydrocarbons, but aromatic solvents such as benzene, toluene, gasoline, and chlorinated solvents will cause excessive swelling. Although they have excellent resistance to water and weathering, they are not resistant to high pressure, high-temperature steam.

Silicone laminates find application as radar domes, structures in electronics, heaters, rocket components, slot wedges, ablator shields, coil forms, and terminal boards.

## SILICONE AND FLUOROSILICONE RUBBERS

The silicone rubbers (SI), also known as polysiloxanes, are a series of compounds whose polymer structure consists of silicone and oxygen atoms rather than the carbon structures of most other elastomers. The silicones are derivatives of silica, $SiO_2$ or O = Si = O. When the atoms are combined so that the double linkages are broken and methyl groups enter the linkages, silicone rubber is produced:




Silicone is in the same chemical group as carbon but is a more stable element, and therefore more stable compounds are produced from it. The basic structure can be modified with vinyl or fluoride groups, which improve such properties as tear resistance, oil resistance, and chemical resistance. This results in a family of silicones that covers a wide range of physical and environmental requirements.

### Physical and Mechanical Properties

The silicones are some of the most heat-resistant elastomers available and the most flexible at low temperatures. Their effective operating temperature range is from –60 to 450°F (–51 to 232°C). They exhibit excellent properties even at the lowest temperature.

The fluorosilicones have an effective operating temperature range of –100 to 375°F (–73 to 190°C).

Silicone rubbers possess outstanding electrical properties, superior to those of most elastomers. The decomposition product of carbon-based elastomers is conductive carbon black, which can sublime and thus leave nothing for insulation, whereas the decomposition product of the silicone rubbers is an insulating silicone dioxide. This property is taken advantage of in the insulation of electric motors. The polysiloxanes have poor abrasion resistance, tensile strength, and tear resistance, but they exhibit good compression set resistance and rebound properties in both cold and hot environments. Their resistance to flame is good.

The physical and mechanical properties of silicone rubbers are given in Table S.6.

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**Table S.6** Physical and Mechanical Properties of Silicone (SI) Rubbers[a]

| | |
|---|---|
| Specific gravity | 1.05–1.94 |
| Brittle point | –75°F (–6°C) |
| Water absorption, %/24 h | 0.02–0.6 |
| Dielectric strength, V/mil | 350–590 |
| Dissipation (power) factor | |
| at 60 Hz | 0.0007 |
| at 1 MHz | $8.5 \times 10^{-3}$–$2.6 \times 10^{-3}$ |
| Dielectric constant | |
| at 60 Hz | 2.91 |
| at 1 MHz | 2.8–3.94 |
| Volume resistivity, ohm-cm | $1 \times 10^{14}$–$1 \times 10^{16}$ |
| Water absorption, %/24 h | 0.02–0.1 |
| Tensile strength, psi | 1200–6000 |
| Elongation % at break | 800 |
| Hardness, Shore A | 20–90 |
| Abrasion resistance | Poor |
| Maximum temperature, continuous use | 450°F (232°C) |
| Tear resistance | Fair to good |
| Compression set, % | 10–15 |
| Impact resistance, notch $\frac{1}{8}$ -in, specimen, ft-lb/in. | 0.25–0.30 |
| Resistance to sunlight | Excellent |
| Effect of aging | Nil |
| Resistance to heat | Excellent |

[a]These are representative values since they may be altered by compounding.

The fluorosilicones (FSIs) have essentially the same physical and mechanical properties as the silicones but with some improvement in adhesion to metals and impermeability.

Table S.7 lists the physical and mechanical properties of the fluorosilicones.

**Table S.7** Physical and Mechanical Properties of FluorosiIicones[a]

| | |
|---|---|
| Specific gravity | 1.4 |
| Hardness, Shore A | 40–75 |
| Tensile strength, psi | 1000–5400 |
| Elongation, % at break | 100–500 |
| Compression set, % | 15 |
| Tear resistance | Poor to fair |
| Maximum temperature, continuous use | 375°F (190°C) |
| Abrasion resistance | Poor |
| Resistance to sunlight | Excellent |
| Effect of aging | Nil |
| Resistance to heat | Excellent |

[a]These are representative values since they may be altered by compounding.

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## Resistance to Sun, Weather, and Ozone

The silicone and fluorosilicone rubbers display excellent resistance to sun, weathering, and ozone. Their properties are virtually unaffected by long-term exposure.

## Chemical Resistance

Silicone rubbers can be used in contact with dilute acids and alkalies, alcohols, animal and vegetable oils, and lubricating oils. They are also resistant to aliphatic hydrocarbons, but aromatic solvents such as benzene, toluene, gasoline, and chlorinated solvents will cause excessive swelling. Although they have excellent resistance to water and weathering, they are not resistant to high-pressure, high-temperature steam.

The fluorosilicone rubbers have better chemical resistance than the silicone rubbers. They have excellent resistance to aliphatic hydrocarbons and good resistance to aromatic hydrocarbons, oil and gasoline, animal and vegetable oils, dilute acids and alkalies, and alcohols; and fair resistance to concentrated alkalies. Table S.8 provides the compatibility of the silicone rubbers with selected corrodents.

**Table S.8** Compatibility of Silicone Rubbers with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetamide | 80 | 27 | Benzene | x | x |
| Acetic acid 10% | 90 | 32 | Benzyl chloride | x | x |
| Acetic acid 20% | 90 | 32 | Boric acid | 390 | 189 |
| Acetic acid 50% | 90 | 32 | Butyl alcohol | 80 | 27 |
| Acetic acid 80% | 90 | 32 | Calcium acetate | x | x |
| Acetic acid vapors | 90 | 32 | Calcium bisulfite | 400 | 204 |
| Acetic acid, glacial | 90 | 32 | Calcium chloride, all concentrations | 300 | 149 |
| Acetone | 110 | 43 | Calcium hydroxide to 30% | 210 | 99 |
| Acetone, 50% water | 110 | 43 | Calcium hydroxide, sat. | 400 | 204 |
| Acetophenone | x | x | Carbon bisulfide | x | x |
| Acrylic acid 75% | 80 | 27 | Carbon monoxide | 400 | 204 |
| Acrylonitrile | x | x | Carbonic acid | 400 | 204 |
| Aluminum acetate | x | x | Chlorobenzene | x | x |
| Aluminum phosphate | 400 | 204 | Chlorosulfonic acid | x | x |
| Aluminum sulfate | 410 | 210 | Dioxane | x | x |
| Ammonia gas | x | x | Ethane | x | x |
| Ammonium chloride 10% | 80 | 27 | Ethers, general | x | x |
| Ammonium chloride 28% | 80 | 27 | Ethyl acetate | 170 | 77 |
| Ammonium chloride, sat. | 80 | 27 | Ethyl alcohol | 400 | 204 |
| Ammonium hydroxide 10% | 210 | 99 | Ethyl chloride | x | x |
| Ammonium hydroxide, sat. | 400 | 204 | Ethylene chloride | x | x |
| Ammonium nitrate | 80 | 27 | Ethylene diamine | 400 | 204 |
| Amyl acetate | x | x | Ethylene glycol | 400 | 204 |
| Amyl alcohol | x | x | Ferric chloride | 400 | 204 |
| Aniline | 80 | 27 | Fluosilicic acid | x | x |
| Aqua regia 3:1 | x | x | Formaldehyde, all concentrations | 200 | 93 |
| Barium sulfide | 400 | 204 | Fuel oil | x | x |

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**Table S.8** Compatibility of Silicone Rubbers with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Gasoline | x | x | Phenol | x | x |
| Glucose (corn syrup) | 400 | 204 | Phosphoric acid | x | x |
| Glycerine | 410 | 210 | Picric acid | x | x |
| Green liquor | 400 | 204 | Potassium chloride 30% | 400 | 204 |
| Hexane | x | x | Potassium cyanide 30% | 410 | 210 |
| Hydrobromic acid | x | x | Potassium dichromate | 410 | 210 |
| Hydrochloric acid dilute | 90 | 32 | Potassium hydroxide to 50% | 210 | 99 |
| Hydrochloric acid 20% | 90 | 32 | Potassium hydroxide 90% | 80 | 27 |
| Hydrochloric acid 35% | x | x | Potassium nitrate to 80% | 400 | 204 |
| Hydrofluoric acid | x | x | Potassium sulfate 10% | 400 | 204 |
| Hydrogen peroxide, all concentrations | 200 | 93 | Potassium sulfate, pure | 400 | 204 |
| Lactic acid, all concentrations | 80 | 27 | Propane | x | x |
| Lead acetate | x | x | Propyl acetate | x | x |
| Lime sulfur | 400 | 204 | Propyl alcohol | 400 | 204 |
| Linseed oil | x | x | Propyl nitrate | x | x |
| Magnesium chloride | 400 | 204 | Pyridine | x | x |
| Magnesium sulfate | 400 | 204 | Silver nitrate | 410 | 210 |
| Mercury | 80 | 27 | Sodium acetate | x | x |
| Methyl alcohol | 410 | 210 | Sodium bisulfite | 410 | 210 |
| Methyl cellosolve | x | x | Sodium borate | 400 | 204 |
| Methyl chloride | x | x | Sodium carbonate | 300 | 149 |
| Methyl ethyl ketone | x | x | Sodium chloride 10% | 400 | 204 |
| Methylene chloride | x | x | Sodium hydroxide, all concentrations | 90 | 32 |
| Mineral oil | 300 | 149 | Sodium peroxide | x | x |
| Naphtha | x | x | Sodium sulfate | 400 | 204 |
| Nickel acetate | x | x | Sodium thiosulfate | 400 | 204 |
| Nickel chloride | 400 | 204 | Stannic chloride | 80 | 27 |
| Nickel sulfate | 400 | 204 | Styrene | x | x |
| Nitric acid 5% | 80 | 27 | Sulfite liquors | x | x |
| Nitric acid 10% | 80 | 27 | Sulfuric acid | x | x |
| Nitric acid 20% | x | x | Sulfurous acid | x | x |
| Nitric acid, anhydrous | x | x | Tartaric acid | 400 | 204 |
| Nitrobenzene | x | x | Tetrahydrofuran | x | x |
| Nitrogen | 400 | 204 | Toluene | x | x |
| Nitromethane | x | x | Tributyl phosphate | x | x |
| Nitrous acid–sulfuric acid 50:50 | x | x | Turpentine | x | x |
| Oils, vegetable | 400 | 204 | Vinegar | 400 | 204 |
| Oleic acid | x | x | Water, acid mine | 210 | 99 |
| Oleum | x | x | Water, demineralized | 210 | 99 |
| Oxalic acid to 50% | 80 | 27 | Water, distilled | 210 | 99 |
| Ozone | 400 | 204 | Water, salt | 210 | 99 |
| Palmitic acid | x | x | Water, sea | 210 | 99 |
| Parrafin | x | x | Xylene | x | x |
| Peanut oil | 400 | 204 | Zinc chloride | 400 | 204 |
| Perchloric acid | x | x | | | |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x.
*Source:* Extracted from PA Schweitzer. *Corrosion Resistance Tables,* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

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## Applications

Because of their unique thermal stability and their insulating values, the silicone rubbers find many uses in the electrical industries, primarily in appliances, heaters, furnaces, aerospace devices, and automotive parts.

Their excellent weathering qualities and wide temperature range have also resulted in their employment as caulking compounds.

When silicone or fluorosilicone rubbers are infused with a high-density conductive filler, an electric path is created. These conductive elastomers are used as part of an EMI/RFI/EMP shielding process in forms such as O-rings and gaskets to provide

1. Shielding for containment to prevent the escape of EMI internally generated by the device
2. Shielding for exclusion to prevent the intrusion of EMI/RFI/EMP created by outside sources into the protected device
3. Exclusion or containment plus pressure or vacuum sealing to provide EMI/EMP attenuation and pressure containment and/or weatherproofing
4. Grounding and contacting to provide a dependable low-impedance connection to conduct electric energy to ground, often used where mechanical mating is imperfect or impractical

The following equipment is either capable of generating EMI or susceptible to EMI:

Aircraft and aerospace electronics
Digital instrumentation and process control systems
Analog instrumentation
Automotive electronics
Communication systems
Radio-frequency instrumentation and radar
Medical electronics
Security systems (military and commercial)
Home appliances
Business machines
Military and marine electronics

Table S.9 lists some typical properties of these infused elastomers.

**Table S.9** Typical Properties of Conductive Elastomers[a]

| Property | SI | FSI |
|---|---|---|
| Volume resistivity, ohm-cm | 0.002–0.01 | 0.002–0.01 |
| Shielding effectiveness, dB | | |
| at 200 kHz (H field) | 30–75 | 60–75 |
| at 100 kHz (E field) | 70–120 | 95–1 20 |
| at 500 kHz (E field) | 60–120 | 90–120 |
| at 2 GHz (plane wave) | 40–120 | 80–115 |
| at 10 GHz (plane wave) | 30–120 | 75–120 |
| Heat aging, ohm-cm | 0.006–0.012 | 0.006–0.015 |
| Electrical stability after break, ohm-cm | 0.003–0.015 | 0.003–0.015 |
| Vibration resistance, ohm-cm | | |
| during | 0.004–0.008 | 0.004–0.008 |
| after | 0.002–0.010 | 0.002–0.005 |

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**Table S.9** Typical Properties of Conductive Elastomers[a] (Continued)

| Property | SI | FSI |
|---|---|---|
| EMP survivability, kA/in. perimeter | 0.9 | 0.9 |
| Specific gravity | 1.9–4.5 | 2.1–4.1 |
| Hardness, Shore A | 50–85 | 70–85 |
| Tensile strength, psi | 175–600 | 200–500 |
| Elongation, % at break | 20–300 | 70–300 |
| Tear strength, psi | 20–75 | 40–50 |
| Compression set, % | 22–40 | 24–29 |
| Operating temperature | | |
| min, °F/°C | –85/–65 | –85/–65 |
| max, °F/°C | 392/200 | 392/200 |

[a]These are typical values since they may be altered by compounding. SI = silicone; FSI = fluorosilicone.

See Refs. 2 and 11.

## SILOXIRANE

Siloxirane is the registered trademark for Tankinetics homopolymerized polymer with an ether cross-linking (carbon–oxygen–carbon) having a very dense, highly cross-linked molecular structure. The end products are extremely resistant to material abrasion, have a wide range of chemical resistance, and have an operating temperature range of –80 to 500°F (–62 to 260°C). The specific maximum operating temperature will be dependent upon the material being handled.

Following is a list of some of the chemicals with which Siloxirane is compatible.

| | |
|---|---|
| Acetamide | Dimethyl formamide |
| Acetic acid, glacial | Ethanol |
| Acetic anhydride | Ethyl acetate |
| Acetone | Ferric chloride |
| Aluminum chloride | Formaldehyde |
| Ammonium chloride | Furan |
| Ammonium hydroxide | Furfural alcohol |
| Aqua regia | Gasohol |
| Benzene | Gasoline |
| Benzene sulfonic acid | Green liquor |
| Black liquor (paper) | Hydraulic oil |
| Bromine water | Hydrazine |
| Calcium hypochlorite | Hydrochloric acid 0–37% |
| Carbon tetrachloride | Hydrochloric acid 1% |
| Chloric acid | Hydrofluoric acid 40% |
| Chlorine water | Hydrofluoric acid 52% |
| Chloroacetic acid | Iodine |
| Chlorobenzene | Jet fuel |
| Chromic acid 10% | Kerosene |
| Chromic acid 50% | Ketones |
| Dibutylphthalate | Latex |
| Dichlorobenzene | Methanol |

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| | |
|---|---|
| Methyl ethyl ketone | Sulfite liquor (paper) |
| Methyl isobutyl ketone | Sulfur trioxide |
| Methylene chloride | Sulfuric acid 1–70% |
| Molten sulfur | Sulfuric acid 70–90% |
| Monochloroacetic acid | Sulfuric acid 90–98% |
| Nickel plating | Sulfuric acid, fuming oleum |
| Nitrous oxide | Tallow |
| Phosphoric acid | Thionyl chloride |
| Phosphoric acid 85% | Toluene |
| Sodium chloride | Trichloroethylene |
| Sodium dichromate | Tricresylphosphate |
| Sodium hydroxide | Water, deionized |
| Sodium hypochlorite 17% | Water, salt |
| Sodium hypochlorite, aged | White liquor (paper) |

## SOIL CORROSION

When soil is dry it is not corrosive. It becomes corrosive as a result of its water content and related water-soluble salts that permit it to act as an electrolyte. Moisture received by the soil from the atmosphere contains specific contaminants and picks up specific water-soluble materials from the soil. Such materials include salts of aluminum, calcium, magnesium, and sodium, sulfates, chlorides, carbonates, phosphates, and silicates. This subjects construction materials to a wide variety of corrosive conditions.

In addition to the problem of localized cells, buried pipelines are also subject to macrocell action. Because of the differences in soil chemistry, soil compaction, thermal effects, and bacterial action, long sections of pipeline may become anodic to other long sections. Stray DC currents will cause electrolysis. Corrosion of buried structures can also be caused by telluric currents, which are a result of fluctuations in the earth's magnetic field as well as stray currents from AC power lines.

The corrosivity of soil is influenced by three factors: resistivity, chemistry, and physical characteristics.

### Resistivity

Resistivity is the property of a material, as opposed to resistance, which is the resultant property of a physical entity. For example, copper has a certain resistivity, but a piece of copper wire has resistance.

Many physical and chemical aspects of the soil give it its resistivity. It is determined by passing a known current $I$ through a known volume of soil (volume = depth × width × length) and measuring the difference in voltage $E$ due to current flow. From Ohm's Law we have

$$R = \frac{E}{I}$$

and resistivity is

$$P = R \times \frac{W \times d}{L}$$

where $W$ is width, $d$ is depth, and $L$ is length.

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Resistivity is expressed in ohm-centimeters (Ω cm) when $R$ is expressed in ohms (Ω), area ($W \times d$) in square centimeters, and length ($L$) in centimeters. For example, sea water has a resistivity of 25 to 75 Ω cm, while a specific volume of seawater has so many ohms resistance. The lower the value of the resistivity, the more highly corrosive a material is.

Soil is considered highly corrosive if its resistivity is 2000 Ω cm or less. It is considered mildly corrosive when its resistivity is between 2000 and 10,000 Ω cm, while at 10,000 to 20,000 Ω cm it is considered only slightly corrosive. If the resistivity of the soil is below 25,000 Ω cm, cathodic protection is recommended.

### Soil Chemistry

Different types of soils can contain a wide variety of chemical species. These not only influence the electrolytic nature of the soil but will also have specific ion effects (for example, chlorides for pitting or stress corrosion cracking or sulfides for stress corrosion cracking). Varying amounts of water may be available from the water table or atmospheric ingress.

### Composition and Condition

Sand, clay, loam, and rock are four major categories of soil. With the exception of nonporous rock, any of these categories can have varying degrees of moisture and varying chemical contaminants. Dry desert sand is totally different from wet salty sand.

Ordinary earth will have different degrees of compaction. Freshly excavated and filled trenches will be more apt to absorb moisture and oxygen than undisturbed soil.

### Overall Corrosivity

Resistivity alone is not the only criterion for judging a soil's corrosivity. Besides resistivity, the other factors that must be taken into account are pH, chloride content, redox potential, and type of soil. Overall rating of soil as to its corrosivity can be made by use of the different arithmetical point values from the following table.

| Factor | Points | Factor | Points |
|---|---|---|---|
| 1. pH | | 4. Soil type | |
| 0–2 | 5 | clay (blue gray) | 10 |
| 2–4 | 3 | clay/stone | 5 |
| 4–8.5 | 0 | clay | 3 |
| 8.5+ | 3 | silt | 2 |
| | | clean sand | 0 |
| 2. Chlorides, ppm | | 5. Soil resistivity | |
| 1000+ | 10 | <1000 | 10 |
| 500–1000 | 6 | 1000–1500 | 8 |
| 200–500 | 4 | 1500–2500 | 6 |
| 50–200 | 2 | 2500–5000 | 4 |
| 0–50 | 0 | 5000–10,000 | 2 |
| | | 10,000+ | 0 |
| 3. Redox, mV (vs. copper; copper sulfate) | | | |
| negative | 5 | | |
| 0–50 | 4 | | |
| 50–100 | 3.5 | | |
| 100+ | 0 | | |

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Based on the above factors, the overall rating of the corrosivity of the soil is as follows:

| Point total | Rating |
|---|---|
| 15+ | Severe |
| 10–15 | Appreciable |
| 5–10 | Moderate |
| 0–5 | Mild |

## Reaction of Specific Materials

Depending upon the specific chemistry of the soil, different materials will react in different ways. However, some generalizations can be made and specific problems highlighted.

### *Concrete*

Portland cement–type concrete is suitable for soil contact if a type appropriate to the sulfate concentration and chlorides and other chemical variants is used. Most important are the pH and sulfate effects.

### *Steels*

Steel should not be exposed to soil unless some type of corrosion control is employed, such as a barrier coating, cathodic protection, or environmental control (mixing of extraneous materials in the soil such as lime, sand, or water repellents to reduce the corrosivity). The most effective approach is to use a combination of a coating and cathodic protection.

### *Cast Iron*

Cast iron is more resistant than steel because of the adherent nature of the rust formed under normal conditions. In soils of low pH or those saturated with soft aggressive waters it can be subject to graphitic corrosion. Corrosion can also be aggravated by bacterial action. Underground cast iron pipe is usually protected by a barrier coating. Because of the difficulty of establishing continuity across the mechanical joints of cast iron pipe, cathodic protection is not often used.

### *Zinc*

Specific soil chemistry will determine the suitability of zinc. In general, galvanized steel is not recommended for underground service since the zinc coating is very thin and anodically active to every metallic structure in the area. However, galvanized steel structured legs for power lines and such can be used provided they are protected by a coating.

### *Aluminum*

If protected from galvanic demands and specific ion effects (chlorides), aluminum can provide satisfactory underground service. Because of the possibility of generating high alkali concentrations when using cathodic protection, care must be taken, since such alkali concentrations can corrode aluminum.

### *Stainless Steels*

High chloride concentrations and/or oxygen concentration cells will pit all stainless steels. Austenitic stainless steel underground piping should be coated and cathodically protected, since corrosive conditions can arise, and localized attack can lead to rapid penetration.

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### *Lead*

Lead is generally resistant but can be corroded by stray electrical currents and specific chemical contaminants.

### *Copper Alloys*

Sulfate-bearing bacteria in soils can cause corrosion by sulfides. If ammonia is present from the rotting of nitrogenous compounds, corrosion or stress corrosion cracking can take place. However, copper is usually satisfactory. Copper pipe was used by the Egyptian pharaoh Cheops to transport water to the royal bath. Several years ago a remnant of this pipe was unearthed still in usable condition, a testimony to copper's durability and resistance to corrosion.

### *Plastics*

Plastic is an ideal material for underground service, provided temperature and pressure otherwise permit. Major concerns are mechanical damage from rock fill and other foreign objects, due to ground subsidence or surface traffic imposing a loading force against the pipe or vessel wall.

## SOLEF

See "Polyvinylidene Fluoride."

## SOLUTION QUENCHING

See "Quench Annealing."

## SPHERADIZING

See "Annealing."

## STAINLESS STEELS

Probably the most widely known and most widely used metallic material for corrosion resistance is stainless steel. For many years this was the only material available.

Stainless steel is not a single material, as its name might imply, but rather a broad group of alloys, each of which exhibits its own physical and corrosion-resistant properties. Stainless steels are alloys of iron to which a minimum of 11% chromium has been added to provide a passive film to resist "rusting" when the material is exposed to weather. This film is self-forming and self-healing in environments where the stainless steel is resistant. As more chromium is added to the alloy, improved corrosion resistance results. Consequently, there are stainless steels with chromium contents of 15%, 17%, 20%, and even higher. Chromium provides resistance to oxidizing environments such as nitric acid and also provides resistance to pitting and crevice attack.

Other alloying ingredients are added to further improve the corrosion resistance and mechanical strength. Molybdenum is extremely effective in improving pitting and crevice corrosion resistance.

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By the addition of copper, improved resistance to general corrosion in sulfuric acid is obtained. This will also strengthen some precipitation-hardenable grades. In sufficient amounts, though, copper will reduce the pitting resistance of some alloys.

The addition of nickel will provide improved resistance to reducing environments and stress corrosion cracking. Nitrogen can also be added to improve corrosion resistance to pitting and crevice attack, and to improve strength.

Columbium and titanium are added to stabilize carbon. They form carbides and reduce the amount of carbon available to form chromium carbides, which can be deleterious to corrosion resistance.

As a result of these alloying possibilities, more than 70 stainless steels are available. These can be divided into four major categories depending upon their microstructure. The classifications are

Austenitic
Ferritic
Martensitic
Duplex

Refer to these headings for specific information about each type.

See Refs. 12–14.

## STRESS CORROSION CRACKING (SCC)

Certain alloys (or alloy systems) in specific environments may be subject to stress corrosion cracking (SCC). Stress corrosion cracking occurs at points of stress. Usually the metal or alloy is visually free of corrosion over most of its surface, yet fine cracks penentrate through the surface at the points of stress. Depending upon the alloy system and corrodent combination, the cracking can be intergranular or transgranular. The rate of propagation can vary greatly and is affected by stress levels, temperature, and concentration of the corrodent. This type of attack takes place in certain media. All metals are potentially subject to SCC. The conditions necessary for stress corrosion cracking are

1. Suitable environment
2. Tensile stress
3. Sensitive metal
4. Appropriate temperature and pH values

An ammonia-containing environment can induce SCC in copper-containing alloys, while with low-alloy austenitic stainless steels a chloride-containing environment is necessary. It is not necessary to have a high concentration of corrodent to cause SCC. A solution containing only a few parts per million of the critical ion is all that is necessary. Temperature and pH are also factors. There is usually a threshold temperature below which SCC will not take place and a maximum or minimum pH value before cracking will start.

Normally, SCC will not occur if the part is in compression. Failure is triggered by a tensile stress that must approach the yield stress of the metal. The stresses may be induced by faulty installation or they may be residual stresses from welding, straightening, bending, or accidental denting of the component. Pits, which act as stress concentration sites, will often initiate SCC.

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The alloy content of stainless steels, particularly nickel, determines the sensitivity of the metal to SCC. Ferritic stainless steels that are nickel free, and the high nickel alloys are not subject to stress corrosion cracking. An alloy with a nickel content greater than 30% is immune to SCC. The most common grades of stainless steel (304, 304L, 316, 316L, 321, 347, 303, and 301) have nickel contents in the range of 7–10% and are the most susceptible to stress corrosion cracking.

Examples of stress corrosion cracking include the cracking of austenitic stainless steels in the presence of chlorides, caustic embrittlement cracking of steel in caustic solutions, cracking of cold-formed brass in ammonia environments, and cracking of Monel in hydrofluorosilicic acid. Table S.10 is a partial listing of alloy systems subject to SCC.

**Table S.10** Alloy-Environment Combinations Causing Stress Corrosion Cracking

| Alloy | Environment |
|---|---|
| Aluminum alloys | Air with water vapor |
| | Potable waters |
| | Seawater |
| | NaCl solutions |
| | $NaCl–H_2O_2$ solutions |
| Carbon steels | Caustic NaOH solutions |
| | Calcium, ammonium, and sodium nitrate solutions |
| | HCN solutions |
| | Acidified $H_2S$ solutions |
| | Anhydrous liquid ammonia |
| | Carbonate/bicarbonate |
| | $CO/CO_2$ solutions |
| | Seawater |
| Copper alloys | Ammoniacal solutions |
| | Amines |
| | Nitrites |
| Nickel alloys | Caustic alkaline solutions |
| | High-temperature chloride solutions |
| | High-purity steam |
| | Hydrofluoric acid |
| | Acidic fluoride solutions |
| Stainless steels | |
| Austenitic | Hot acid chloride solutions |
| | $NaCl–H_2O_2$ solutions |
| | $NaOH–H_2S$ solutions |
| | Seawater |
| | Concentrated caustic solutions |
| | Neutral halides, $Br^-$, $I^-$, $F^-$ |

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**Table S.10** Alloy-Environment Combinations Causing Stress Corrosion Cracking (Continued)

| Alloy | Environment |
|---|---|
| Austenitic (sensitized) | Polythionic acids |
| | Sulfurous acid |
| | Pressurized hot water containing 2 ppm dissolved oxygen |
| Ferritic | $H_2S$, $NH_4Cl$, $NH_4NO_3$ |
| | Hypochlorite solutions |
| Martensitic | Caustic NaOH solutions |
| Titanium alloys | Red fuming nitric acid |
| | Hot salts, molten salts |
| | $N_2O_4$ |
| | Methanol/halide |

In severe combinations, such as type 304 stainless steel in a boiling magnesium chloride solution, extensive cracking can be generated in a matter of hours.

Fortunately, in most industrial applications the progress of SCC is much slower. However, because of the nature of the cracking, it is difficult to detect until extensive corrosion has developed, which can lead to unexpected failure.

Tensile stresses can assist in other corrosion processes, such as the simple mechanical fatigue process. Corrosion fatigue is difficult to differentiate from simple mechanical fatigue, but is recognized as a factor when the environment is believed to have accelerated the normal fatigue process. Such systems can also have the effect of lowering the endurance limit such that fatigue will occur at a stress level below which it would normally be expected.

It is important that any stresses that may have been induced during the fabrication be removed by an appropriate stress relief operation. The design should also avoid stagnant areas that could lead to pitting and the initiation of stress concentration sites.

See Ref. 15.

## STRESS RELIEF

Fabrication processes, such as rolling or forging, uneven heating or cooling, or welding are all capable of inducing residual stresses in a metal. The magnitude of these stresses is usually on the order of the yield strength of the metal, but in some cases it approaches the tensile strength of the metal.

Carbon and low-alloy steels are heated to a temperature in the range of 1000 to 1350°F (595 to 730°C) to be stress relieved. They are held at this temperature for a period of time, then air cooled. The minimum holding time is specified by the appropriate engineering code. The holding temperature must be less than the lower transformation temperature of the steel, which is the lowest temperature at which austenite forms. For plain carbon steels this temperature is 1333°F (720°C).

As metals and alloys are heated, their yield strengths decrease. Residual stresses in excess of the reduced yield strength are eliminated. Upon cooling, the maximum residual stress possible is the yield strength at the holding temperature. For carbon steels, this heat treatment process reduces residual stresses by approximately two-thirds.

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Austenitic stainless steels are not usually stress relieved or postweld heat treated. When such treatments are given to austenitic stainless steels, they are held at a temperature of 1600 to 1650°F (870 to 900°C) followed by rapid cooling. The rapid cooling is necessary to prevent sensitization. If austenitic stainless steels are exposed to heat treating operation at less than 1600°F (870°C), they can be sensitized. For this reason, local stress relief of unstabilized austenitic stainless steel is usually impractical, since the runout areas immediately adjacent to the region being heat treated will be sensitized.

## SUPERAUSTENITIC STAINLESS STEELS

The classification of superaustenitic stainless steels came about during the 1970s and 1980s. Carpenter Steel's introduction of alloy 20 in 1951 as a cast material was the foundation for this class of materials. In 1965 Carpenter introduced the wrought product 20Cb3. This alloy became popular as an intermediate step between 316 stainless steel and the more highly alloyed nickel-base materials. It was a cost-effective way to combat chloride stress cracking.

Because of the high nickel content of 20Cb3, it received a nickel-base alloy UNS designation as UNS N08020. However, since the main constituent is iron, it is truly a stainless steel.

The term superaustenitic is derived from the fact that the composition plots high above the austenite–ferrite boundary on the Schaeffler diagram. Unlike the 300 series stainless alloys, there is no chance of developing ferrite in this material. Many of the superaustenitic alloys have been assigned nickel-base identification numbers, but they are truly stainless steels.

The initial alloys that were developed exhibited good general corrosion resistance to strong acids, but their pitting resistance was only slightly better than that of type 316L. In order to improve the pitting resistance and crevice corrosion resistance, the molybdenum content was increased. One of the first to be introduced was 904L (UNS N08904), which increased the molybdenum content to 4% and reduced the nickel content to 25%. The reduction in nickel content was a cost-saving factor, with a minimal loss in general corrosion resistance and maintenance of sufficient resistance to chloride stress corrosion cracking.

Improvements continued with the alloying addition of nitrogen to offset the tendency for the formation of the sigma phase and an increase of the molybdenum content to 6%. This concept was introduced with two alloys, 254SMO (S31254) and Al-6XN (N08367).

### Alloy 20Cb3

This alloy has the following composition:

| Chemical | Weight percent |
|---|---|
| Chromium | 20.0 |
| Nickel | 33.5 |
| Silicon | 1.00 max. |
| Manganese | 0.75 max. |
| Carbon | 0.07 max. |
| Niobium/tantalum | 8 × % carbon min. |
| Iron | Balance |

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The alloy is stabilized with niobium and tantalum.

Alloy 20Cb3 was originally developed to provide improved corrosion resistance to sulfuric acid. However, it has found wide application throughout the chemical process industry.

This alloy is weldable, machinable, and cold formable and has minimal carbide precipitation due to welding. It is particularly useful in the handling of sulfuric acid. It is resistant to stress corrosion cracking in sulfuric acid at a variety of temperatures and concentrations. The resistance of 20Cb3 to chloride stress corrosion cracking is also increased over type 304 and type 316 stainless steels. The alloy also exhibits excellent resistance to sulfide stress cracking and consequently finds many applications in the oil industry.

In high concentrations of chlorides, alloy 20Cb3 is vulnerable to pitting and crevice attack. For improved resistance to these types of corrosion the 2% molybdenum must be increased to 4% or 6% as has been done in alloy 20Mo4 and 20Mo6. Table S.11 lists the compatibility of alloy 20Cb3 with selected corrodents.

**Table S.11** Compatibility of Type 20Cb3 Stainless Steel with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetaldehyde | 200 | 93 | Ammonium fluoride, 25% | 90 | 32 |
| Acetamide | 60 | 16 | Ammonium hydroxide, 25% | 90 | 32 |
| Acetic acid, 10% | 220 | 104 | Ammonium hydroxide, sat. | 210 | 99 |
| Acetic acid, 50% | 300 | 149 | Ammonium nitrate[b] | 210 | 99 |
| Acetic acid, 80% | 300 | 149 | Ammonium persulfate | 210 | 99 |
| Acetic acid, glacial | 300 | 149 | Ammonium phosphate | 210 | 99 |
| Acetic anhydride | 180 | 82 | Ammonium sulfate, 10–40% | 210 | 99 |
| Acetone | 220 | 104 | Ammonium sulfide | 210 | 99 |
| Acetyl chloride | 210 | 99 | Ammonium sulfite | 210 | 99 |
| Acrylonitrile | 210 | 99 | Amyl acetate | 310 | 154 |
| Adipic acid | 210 | 99 | Amyl alcohol | 160 | 71 |
| Allyl alcohol | 300 | 149 | Amyl chloride | 130 | 54 |
| Allyl chloride | 200 | 93 | Aniline | 500 | 260 |
| Alum | 200 | 93 | Antimony trichloride | 200 | 93 |
| Aluminum acetate | 60 | 16 | Aqua regia, 3:1 | x | x |
| Aluminum chloride, aqueous | 120 | 43 | Barium carbonate | 90 | 32 |
| Aluminum chloride, dry | 120 | 43 | Barium chloride, 40% | 210 | 99 |
| Aluminum fluoride | x | x | Barium hydroxide, 50% | 230 | 110 |
| Aluminum hydroxide | 80 | 27 | Barium sulfate | 210 | 99 |
| Aluminum nitrate | 80 | 27 | Barium sulfide | 210 | 99 |
| Aluminum sulfate | 210 | 99 | Benzaldehyde | 210 | 99 |
| Ammonia gas | 90 | 32 | Benzene | 230 | 110 |
| Ammonium bifluoride | 90 | 32 | Benzene sulfonic acid, 10% | 210 | 99 |
| Ammonium carbonate | 310 | 154 | Benzoic acid | 400 | 204 |
| Ammonium chloride, 10% | 230 | 110 | Benzyl alcohol | 210 | 99 |
| Ammonium chloride, 50% | 170 | 77 | Benzyl chloride | 230 | 110 |
| Ammonium chloride, sat.[b] | 210 | 99 | Borax | 100 | 38 |
| Ammonium fluoride, 10% | 90 | 32 | Boric acid | 130 | 54 |

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**Table S.11** Compatibility of Type 20Cb3 Stainless Steel with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Bromine gas, dry | 80 | 27 | Ferric chloride | x | x |
| Bromine gas, moist | x | x | Ferric chloride, 50% in water | x | x |
| Butadiene | 180 | 82 | Ferric nitrate, 10–50% | 210 | 99 |
| Butyl acetate | 300 | 149 | Ferrous chloride | x | x |
| Butyl alcohol | 90 | 32 | Fluorine gas, dry | 570 | 299 |
| Butyl phthalate | 210 | 99 | Fluorine gas, moist | x | x |
| Butyric acid | 300 | 149 | Hydrobromic acid, dilute | x | x |
| Calcium bisulfide | 300 | 149 | Hydrobromic acid, 20% | x | x |
| Calcium carbonate | 210 | 99 | Hydrobromic acid, 50% | x | x |
| Calcium chlorate | 90 | 32 | Hydrochloric acid, 20% | x | x |
| Calcium chloride | 210 | 99 | Hydrochloric acid, 38% | x | x |
| Calcium hydroxide, 10% | 210 | 99 | Hydrocyanic acid, 10% | 210 | 99 |
| Calcium hydroxide, sat. | 210 | 99 | Hydrofluoric acid, 30% | 190 | 88 |
| Calcium hypochlorite | 90 | 32 | Hydrofluoric acid, 70% | x | x |
| Calcium oxide | 80 | 27 | Hydrofluoric acid, 100% | 80 | 27 |
| Calcium sulfate | 210 | 99 | Iodine solution, 10% | x | x |
| Caprylic acid | 400 | 204 | Ketones, general | 100 | 38 |
| Carbon bisulfide | 210 | 99 | Lactic acid, 25%[b] | 210 | 49 |
| Carbon dioxide, dry | 570 | 299 | Lactic acid, conc., air free | 300 | 149 |
| Carbon dioxide, wet | 400 | 204 | Magnesium chloride | 200 | 93 |
| Carbon disulfide | 210 | 99 | Malic acid, 50% | 160 | 71 |
| Carbon monoxide | 570 | 299 | Manganese chloride, 40% | 210 | 99 |
| Carbon tetrachloride | 210 | 99 | Methyl chloride | 210 | 99 |
| Carbonic acid | 570 | 299 | Methyl ethyl ketone | 200 | 93 |
| Cellosolve | 210 | 99 | Methyl isobutyl ketone | 210 | 99 |
| Chloracetic acid | 80 | 27 | Muriatic acid | x | x |
| Chlorine gas, dry | 400 | 204 | Nitric acid, 5% | 200 | 93 |
| Chlorine gas, wet | x | x | Nitric acid, 20% | 210 | 99 |
| Chlorobenzene, dry | 100 | 38 | Nitric acid, 70% | 210 | 99 |
| Chloroform | 210 | 99 | Nitric acid, anhydrous | 80 | 27 |
| Chlorosulfonic acid | 130 | 54 | Nitrous acid, conc. | 90 | 32 |
| Chromic acid, 10% | 130 | 54 | Oleum | 110 | 43 |
| Chromic acid, 50% | 140 | 60 | Perchloric acid, 10% | 100 | 38 |
| Chromyl chloride | 210 | 99 | Perchloric acid, 70% | 110 | 43 |
| Citric acid, 15% | 210 | 99 | Phenol | 570 | 299 |
| Citric acid, conc. | 210 | 99 | Phosphoric acid, 50–80% | 210 | 99 |
| Copper acetate | 100 | 38 | Picric acid | 300 | 149 |
| Copper carbonate | 90 | 32 | Potassium bromide, 30% | 210 | 99 |
| Copper chloride | x | x | Salicylic acid | 210 | 99 |
| Copper cyanide | 210 | 99 | Silver bromide, 10% | 90 | 32 |
| Copper sulfate | 210 | 99 | Sodium carbonate | 570 | 299 |
| Cupric chloride, 5% | 60 | 16 | Sodium chloride, to 30%[b] | 210 | 99 |
| Cupric chloride, 50% | x | x | Sodium hydroxide, 10% | 300 | 149 |
| Cyclohexane | 200 | 93 | Sodium hydroxide, 50%[c] | 300 | 149 |
| Cyclohexanol | 80 | 27 | Sodium hydroxide, conc. | 200 | 93 |
| Dichloroethane (ethylene dichloride) | 210 | 99 | Sodium hypochlorite, 30% | 90 | 32 |
| Ethylene glycol | 210 | 99 | Sodium sulfide, to 50% | 200 | 93 |

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**Table S.11** Compatibility of Type 20Cb3 Stainless Steel with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | Maximum temp. °C | Chemical | Maximum temp. °F | Maximum temp. °C |
|---|---|---|---|---|---|
| Stannic chloride | x | x | Sulfuric acid, 100% | 300 | 149 |
| Stannous chloride, 10% | 90 | 32 | Sulfuric acid, fuming | 210 | 99 |
| Sulfuric acid, 10% | 200 | 93 | Sulfurous acid | 360 | 182 |
| Sulfuric acid, 50% | 110 | 43 | Toluene | 210 | 99 |
| Sulfuric acid, 70% | 120 | 49 | White liquor | 100 | 38 |
| Sulfuric acid, 90% | 100 | 38 | Zinc chloride | 210 | 99 |
| Sulfuric acid, 98% | 300 | 149 | | | |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. When compatible the corrosion rate is <20 mpy.
[b]Material subject to intergranular corrosion.
[c]Material subject to stress cracking.
*Source:* Ref. 2.

## Alloy 20Mo-4 (N08024)

This alloy is similar to alloy 20Cb3 but with 4% molybdenum content instead of the 2% providing improved pitting and crevice corrosion resistance over alloy 20Cb3. The chemical composition is as follows:

| Chemical | Weight percent |
|---|---|
| Nickel | 35–40 |
| Chromium | 22.5–25.0 |
| Molybdenum | 3.5–5.0 |
| Copper | 0.5–1.5 |
| Niobium | 0.15–0.35 |
| Carbon | 0.03 max. |
| Iron | Balance |

Alloy 20Mo-4 has outstanding corrosion resistance to chloride pitting and crevice corrosion with good resistance to sulfuric acid and various other acid environments. Applications include heat exchangers, chemical process equipment, and wet-process phosphoric acid environments.

## Alloy 20Mo-6 (N08026)

Of the three grades of alloy 20 this offers the highest level of pitting and crevice corrosion resistance. Alloy 20Mo-6 is resistant to corrosion in hot chloride environments and is also resistant to oxidizing media. This alloy is designed for applications where better pitting and crevice corrosion resistance is required than 20Cb3 offers.

Alloy 20Mo-6 is melted with low carbon to provide a high level of resistance to intergranular corrosion. It also possesses excellent resistance to chloride stress corrosion cracking. When in contact with sulfuric acid, excellent resistance is shown at 176°F

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(80°C) with the exception of concentrations in the range of 75–97 wt%. In boiling sulfuric acid 20Mo-6 stainless has good resistance to general corrosion only in relatively dilute solutions. At approximately 10% concentration of boiling sulfuric acid, the corrosion rate becomes excessive.

The alloy is highly resistant to phosphoric acid, both wet-process plant acid and reagent-grade concentrated phosphoric acid.

Alloy 20Mo-6 has the following composition:

| Chemical | Weight percent |
|---|---|
| Chromium | 22.00–26.00 |
| Nickel | 33.00–37.20 |
| Molybdenum | 5.00–6.70 |
| Silicon | 0.03–0.50 |
| Manganese | 1.00 |
| Phosphorus | 0.03 |
| Carbon | 0.03 |
| Iron | Balance |

## 25-6Mo (N08925)

Alloy 25-6Mo is produced by Inco International. It is also known as 1925 hMo. Typical and specified compositions of this alloy are as follows:

| | Weight percent | |
|---|---|---|
| Chemical | Alloy 25-6Mo | UNS N08926 |
| Carbon | 0.02 max. | 0.02 max. |
| Chromium | 19.0–21.0 | 20.0–21.0 |
| Nickel | 24.0–26.0 | 24.5–25.5 |
| Molybdenum | 6.0–7.0 | 6.0–6.8 |
| Nitrogen | 0.15–0.25 | 0.18–0.20 |
| Copper | 0.5–1.5 | 0.8–1.0 |
| Manganese | 2.0 max. | 2.0 max. |
| Phosphorus | 0.03 max. | 0.03 max. |
| Sulfur | 0.010 max. | 0.010 max. |
| Silicon | 0.050 max. | 0.050 max. |
| Iron | Balance | Balance |

This alloy is especially suited for applications in high-chloride environments such as brackish water, seawater, caustic chlorides, and pulp mill bleach systems.

In brackish and wastewater systems, microbially influenced corrosion can occur, especially in systems where equipment has been idle for extended periods. A 6% molybdenum alloy offers protection from manganese-bearing, sulfur-bearing, and generally reducing types of bacteria. Because of its resistance to microbially influenced corrosion, alloy 25-6Mo is being used in wastewater piping systems of power plants.

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In saturated sodium chloride environments and for pH values of 6–8, alloy 25-6Mo maintains a corrosion rate of less than 1 mpy and shows no pitting even at temperatures up to boiling.

## Alloy 904L (N08904)

This is a fully austenitic low-carbon chromium stainless steel with additives of molybdenum and copper. It has a chemical composition as follows:

| Chemical | Weight percent |
|---|---|
| Carbon | 0 .02 |
| Chromium | 21.0 |
| Nickel | 25.5 |
| Molybdenum | 4.7 |
| Copper | 1.5 |
| Iron | Balance |

Its high nickel and chromium contents make alloy 904L resistant to corrosion in a wide variety of both oxidizing and reducing environments. Molybdenum and copper are included in the alloy for increased resistance to pitting and crevice corrosion and to general corrosion in reducing acids. Other advantages of the alloy's composition are sufficient nickel for resistance to chloride ion stress corrosion cracking and low carbon content for resistance to intergranular corrosion.

The alloy's outstanding attributes are resistance to nonoxidizing acids along with resistance to pitting, crevice corrosion, and stress corrosion cracking in such media as stack gas condensate and brackish water.

Alloy 904L is especially suited for handling sulfuric acid. Hot solutions at moderate concentrations represent the most corrosive conditions. It also has excellent resistance to phosphoric acid.

At high temperatures 904L may be subject to stress corrosion cracking.

Alloy 904L finds applications in piping systems, pollution control equipment, heat exchangers, and bleaching systems.

## Alloy 800 (N08800)

The composition of alloy 800 is as follows:

| Chemical | Weight percent |
|---|---|
| Nickel | 30.0–35.0 |
| Chromium | 19.0–23.0 |
| Aluminum | 0.15–0.6 |
| Titanium | 0.15–0.6 |
| Carbon | 0.10 max. |
| Iron | Balance |

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This alloy is used primarily for its oxidation resistance and strength at elevated temperatures. It is particularly useful for high-temperature applications be cause the alloy does not form the embrittling sigma phase after long exposures at 1200–1600°F (649–871°C). High creep and rupture strengths are other factors contributing to its performance in many other applications. It resists sulfidation, internal oxidation, scaling, and carburization.

At moderate temperatures the general corrosion resistance of alloy 800 is similar to that of the other austenitic nickel–iron–chromium alloys. However, as the temperature increases, alloy 800 continues to exhibit good corrosion resistance, while other austenitic alloys are unsatisfactory for the service.

Alloy 800 has excellent resistance to nitric acid at concentrations up to about 70%. It resists a variety of oxidizing salts, but not halide salts. It also has good resistance to organic acids, such as formic, acetic, and propionic. Alloy 800 is particularly suited for the handling of hot corrosive gases such as hydrogen sulfide.

In aqueous service alloy 800 has general resistance that falls between type 304 and type 316 stainless steels. Thus the alloy is not widely used for aqueous service. While not immune, alloy 800 has a stress corrosion cracking resistance better than that of the 300 series of stainless steels and may be substituted on that basis. Table S.12 provides the compatibility of alloy 800 with selected corrodents.

**Table S.12** Compatibility of Alloy 800 and Alloy 825 with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetic acid 10%[b] | 200 | 93 | Benzene | 190 | 88 |
| Acetic acid 50%[b] | 220 | 104 | Benzoic acid 5% | 90 | 32 |
| Acetic acid 80%[b] | 210 | 99 | Borax | 190 | 88 |
| Acetic acid, glacial[b] | 220 | 104 | Boric acid 5% | 210 | 99 |
| Acetic anhydride | 230 | 110 | Bromine gas, dry[b] | 90 | 32 |
| Acetone | 210 | 99 | Butyl acetate[b] | 90 | 32 |
| Acetyl chloride | 210 | 99 | Butyric acid 5% | 90 | 32 |
| Aluminum acetate | 60 | 16 | Calcium carbonate | 90 | 32 |
| Aluminum chloride, aqueous | 60 | 16 | Calcium chlorate | 80 | 27 |
| Aluminum fluoride 5% | 80 | 27 | Calcium chloride[b,c] | 60 | 16 |
| Aluminum hydroxide | 80 | 27 | Calcium hydroxide 10% | 200 | 93 |
| Aluminum sulfate | 210 | 99 | Calcium hypochlorite | x | x |
| Ammonium carbonate | 190 | 88 | Calcium sulfate | 90 | 32 |
| Ammonium chloride 10%[b] | 230 | 110 | Carbon monoxide | 570 | 299 |
| Ammonium chloride, sat. | 200 | 93 | Carbon tetrachloride | 90 | 32 |
| Ammonium hydroxide, sat. | 110 | 43 | Carbonic acid | 90 | 32 |
| Ammonium nitrate | 90 | 32 | Chloracetic acid | x | x |
| Ammonium persulfate | 90 | 32 | Chlorine gas, dry[b] | 90 | 32 |
| Ammonium sulfate 10–40% | 210 | 99 | Chlorine gas, wet | x | x |
| Ammonium sulfite | 210 | 99 | Chlorobenzene | 90 | 32 |
| Amyl acetate[b] | 200 | 93 | Chloroform | 90 | 32 |
| Amyl chloride | 90 | 32 | Chlorosulfonic acid | x | x |
| Aniline | 90 | 32 | Chromic acid 10%[b] | 210 | 99 |
| Antimony trichloride | 90 | 32 | Chromic acid 50% | x | x |
| Barium carbonate | 90 | 32 | Citric acid 15% | 210 | 99 |
| Barium sulfate | 90 | 32 | Citric acid, concentrated[b] | 210 | 99 |

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**Table S.12** Compatibility of Alloy 800 and Alloy 825 with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Copper acetate | 90 | 32 | Nitric acid 5% | 90 | 32 |
| Copper carbonate | 90 | 32 | Nitric acid 20% | 60 | 16 |
| Copper chloride 5%[b] | 80 | 27 | Nitric acid, anhydrous | 210 | 99 |
| Copper cyanide | 210 | 99 | Phenol | 90 | 32 |
| Copper sulfate | 210 | 99 | Picric acid | 90 | 32 |
| Cupric chloride 5% | x | x | Potassium bromide 5% | 90 | 32 |
| Ferric chloride | x | x | Salicylic acid | 90 | 32 |
| Ferric chloride 50% in water | x | x | Silver bromide 10%[b] | 90 | 32 |
| Ferric nitrate 10–50% | 90 | 32 | Sodium carbonate | 90 | 32 |
| Ferrous chloride[b,c] | 90 | 32 | Sodium chloride[c] | 200 | 93 |
| Fluorine gas, dry | x | x | Sodium hydroxide I0% | 90 | 32 |
| Fluorine gas, moist | x | x | Sodium hydroxide, concentrated | 90 | 32 |
| Hydrobromic acid 20% | x | x | Sodium sulfide to 50% | 90 | 32 |
| Hydrobromic acid 50% | x | x | Stannic chloride | x | x |
| Hydrochloric acid 20%[b] | 90 | 32 | Stannous chloride 5% | 90 | 32 |
| Hydrochloric acid 38% | x | x | Sulfuric acid 10%[b] | 230 | 110 |
| Hydrocyanic acid 10% | 60 | 16 | Sulfuric acid 50%[b] | 210 | 99 |
| Hydrofluoric acid 30% | x | x | Sulfuric acid 70%[b] | 150 | 66 |
| Hydrofluoric acid 70% | x | x | Sulfuric acid 90%[b] | 180 | 82 |
| Hydrofluoric acid 100% | x | x | Sulfuric acid 98%[b] | 220 | 104 |
| Magnesium chloride 10–50% | 170 | 77 | Sulfuric acid 100%[b] | 230 | 110 |
| Malic acid | 170 | 77 | Sulfuric acid, fuming | x | x |
| Manganese chloride 10–50% | 210 | 99 | Sulfurous acid[b] | 370 | 188 |
| Muriatic acid[b] | 90 | 32 | Zinc chloride 5% | 140 | 60 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. When compatible, corrosion rate is < 20 mpy.
[b]Applicable to alloy 825 only.
[c]Material subject to pitting.
*Source:* Ref. 2.

Applications include heat exchangers, process piping, steam generators, and heating element cladding.

Alloy 800H is a controlled version of alloy 800. The carbon content is maintained between 0.05% and 0.1% to provide the alloy with better elevated temperature creep and stress rupture properties. It is solution annealed to ensure the improved creep and stress-to-rupture properties.

Applications include superheater and reheater tubing, headers, and furnace tubing, as well as applications in the refining and heat treatment industries.

Alloy 800AT is similar to alloy 800 but has higher levels of aluminum and titanium. It is used for thermal processing applications, chemical and petrochemical piping, pigtails, and outlet manifolds.

## Alloy 825 (N08825)

Alloy 825 is very similar to alloy 800, but the composition has been modified to improve its aqueous corrosion resistance. Its chemical composition is as follows:

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| Chemical | Weight percent |
|---|---|
| Nickel | 38–46 |
| Chromium | 19.5–23.5 |
| Molybdenum | 2.3–3.5 |
| Copper | 1.5–3.0 |
| Titanium | 0.6–1.2 |
| Aluminum | 0.2 max |
| Iron | Balance |

The higher nickel content of alloy 825 compared with alloy 800 makes it resistant to chloride stress corrosion cracking. The addition of molybdenum and copper gives resistance to pitting and to corrosion in reducing acid environments, such as sulfuric or phosphoric acid solutions. Alloy 825 is resistant to pure sulfuric acid solutions up to 40% weight at boiling temperatures, and at all concentrations at a maximum temperature of 150°F (60°C). In dilute solutions the presence of oxidizing salts, such as cupric or ferric, actually reduces the corrosion rate. It has limited use in hydrochloric or hydrofluoric acids.

The chromium content of alloy 825 gives it resistance to various oxidizing environments such as nitrates, nitric acid solutions, and oxidizing salts. The alloy is not fully resistant to stress corrosion cracking when tested in magnesium chloride, but it has good resistance in neutral chloride environments.

If localized corrosion is a problem with the 300 series stainless steels, alloy 825 may be substituted. Alloy 825 also provides excellent resistance to corrosion by seawater. The compatibility of alloy 825 with selected corrodents is shown in Table S.12.

Applications include the nuclear industry, chemical processing, and pollution control systems.

### Type 330 (N08330)

This is a nickel–chromium iron alloy with the addition of silicon. Its chemical composition is as follows:

| Chemical | Weight percent |
|---|---|
| Carbon | 0.08 max. |
| Manganese | 2.00 max. |
| Silicon | 1.5–3.0 |
| Chromium | 17.00–20.00 |
| Nickel | 34.00–37.00 |
| Tantalum | 0.10 |
| Niobium | 0.20 |
| Iron | Balance |

Type 330 stainless steel has good strength at elevated temperatures, good thermal stability, and excellent resistance to carburizing and oxidizing atmospheres. It is weldable

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and machinable. This alloy has been used in low-stress applications to temperatures as high as 2250°F (1230°C) and has moderate resistance to creep to 1600°F (870°C).

Type 330 stainless resists the absorption of carbon and nitrogen, making it an excellent choice for furnace components. Overall it exhibits good corrosion resistance.

## Al-6XN (N08367)

Alloy Al-6XN is the registered trademark of Allegheny Ludlum Industries Inc. The typical and specified chemical compositions are as follows:

| Chemical | Typical Al-6N alloy | UNS N08367 specification |
|---|---|---|
| Carbon | 0.02 | 0.03 max. |
| Manganese | 0.0 | 2.00 max. |
| Phosphorus | 0.020 | 0.040 max. |
| Sulfur | 0.001 | 0.030 max. |
| Silicon | 0.40 | 1.00 max. |
| Chromium | 20.5 | 20.00–22.00 |
| Molybdenum | 6.2 | 6.00–7.00 |
| Nitrogen | 0.22 | 0.18–0.25 |
| Copper | 0.2 | 0.75 max. |
| Iron | Balance | Balance |

Alloy A1-6XN was originally designed to resist seawater. However, it has proven also to be resistant to a wide range of corrosive environments.

The high strength and corrosion resistance of this alloy makes it a better choice than the more expensive nickel-base alloys in applications where excellent formability, weldability, strength, and corrosion resistance are essential.

It is also a cost-effective alternative to less expensive alloys, such as type 316, that do not have the strength or corrosion resistance required to minimize life cycle costs in certain applications.

The high nickel and molybdenum contents provide improved resistance to chloride stress corrosion cracking. Copper has been kept to a residual level for improved performance in seawater. The high alloy composition resists crevice corrosion and pitting in oxidizing chloride solutions.

The low carbon content of the alloy defines it as an L grade, providing resistance to intergranular corrosion in the as-welded condition.

The corrosion-resistant properties of alloy Al-6XN show exceptional resistance to pitting, crevice attack, and stress cracking in high chlorides and general resistance in various acid, alkaline, and salt solutions found in chemical processing and other industrial environments. Excellent resistance is shown to oxidizing chlorides, reducing solutions, and seawater corrosion. Sulfuric, nitric, phosphoric, acetic, and formic acids can be handled at various concentrations and a variety of temperatures. The material is also approved for contact with foods. Refer to Table S.13 for the compatibility of alloy Al-6XN with selected corrodents.

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**Table S.13** Compatibility of Al-6XN Stainless Steel with Selected Corrodents[a]

| Chemical | Maximum temperature (°F/°C) |
|---|---|
| Acetic acid 20% | 210/99 |
| Acetic acid 80% | 217/103 |
| Formic acid 45% | 220/104 |
| Formic acid 50% | 220/104 |
| Nitric acid 10% | 194/90 |
| Nitric acid 65% | 241/116 |
| Oxalic acid 10% | 210/99 |
| Phosphoric acid 20% | 210/99 |
| Phosphoric acid 85% | 158/76 |
| Sulfamic acid 10% | 210/99 |
| Sulfuric acid 10% | x/x |
| Sulfuric acid 60% | 122/50 |
| Sulfuric acid 95% | 86/30 |
| Sodium bisulfate 10% | 210/99 |
| Sodium hydroxide 50% | 210/99 |

[a]Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. When compatible, the corrosion rate is <20 mpy.

Alloy Al-6XN finds applications as chemical process vessels and pipeline condensers, heat exchangers, power plant flue gas scrubbers, distillation columns, service water piping in nuclear plants, and food processing equipment.

## 254SMo (S31254)

This alloy is designed for maximum resistance to pitting and crevice corrosion. It has the following composition:

| Chemical | Weight percent |
|---|---|
| Carbon | 0.02 |
| Chromium | 19.5–20.5 |
| Nickel | 17.5–18.5 |
| Molybdenum | 6.0–6.5 |
| Nitrogen | 0.18–0.22 |
| Copper | 0.50–1.00 |
| Iron | Balance |

A PREN value above 33 is considered necessary for pitting and crevice resistance to ambient seawater. Alloy 254SMo has a PREN value of 45.8. With its high levels of chromium, molybdenum, and nitrogen, S31254 is especially suited for environments such as brackish water, seawater, pulp mill bleach plants, and other high-chloride process streams.

## Alloy 31 (N08031)

This alloy has the following composition:

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| Chemical | Weight percent |
|---|---|
| Carbon | 0.02 max. |
| Nickel | 31 |
| Chromium | 27 |
| Molybdenum | 6.5 |
| Copper | 1.8 |
| Nitrogen | 0.20 |
| Iron | Balance |

With a PREN value of 54.45, this alloy exhibits excellent resistance to pitting and crevice corrosion in neutral and acid solutions. The high chromium content of 27% imparts superior resistance to corrosive attack by oxidizing media.

### 654SMo (S32654)

This alloy contains 7+% of molybdenum, which provides it with corrosion resistance associated with nickel-based alloys. The composition is as follows:

| Chemical | Weight percent |
|---|---|
| Carbon | 0.02 |
| Chromium | 24.0 |
| Nickel | 22.0 |
| Molybdenum | 7.3 |
| Nitrogen | 0.5 |
| Copper | 0.5 |
| Manganese | 3.0 |
| Iron | Balance |

Alloy 654 has better resistance to localized corrosion than other superaustenitic alloys. Indications are that alloy 654 is as corrosion resistant as alloy C-276, based on tests in filtered seawater, bleach plants, and other aggressive chloride environments. It is intended to compete with titanium in the handling of high-chloride media.

## STYRENE-BUTADIENE-STYRENE (SBS) RUBBER

Styrene-butadiene-styrene (SBS) rubbers are either pure or oil-modified block copolymers. They are most suitable as performance modifiers in blends with thermoplastics or as a base rubber for adhesive, sealant, or coating formulations. SBS compounds are formulations containing block copolymer rubber and other suitable ingredients. These compounds have a wide range of properties and provide the benefits of rubberiness and easy processing on standard thermoplastic processing equipment.

### Physical and Mechanical Properties

Since the physical and mechanical properties vary greatly depending upon the formulation, this discussion of these properties is based on the fact that proper formulation will provide a material having the desired combination of properties.

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The degree of hardness will determine the flexibility of the final product. With a Shore A hardness range from 37 to 74, SBS rubbers offer excellent impact resistance and low-temperature flexibility. Their maximum service temperature is 150°F (65°C). They also exhibit good abrasion resistance and good resistance to water absorption and heat aging. Their resistance to compression set and tear is likewise good, as is their tensile strength.

The electrical properties of SBS rubber are only fair, and resistance to flame is poor.

The physical and mechanical properties of SBS rubber are given in Table S.14.

### Resistance to Sun, Weather, and Ozone

The SBS rubbers are not resistant to ozone, particularly when they are in a stressed condition. Neither are they resistant to prolonged exposure to sun or weather.

### Chemical Resistance

The chemical resistance of SBS rubbers is similar to that of natural rubber. They have excellent resistance to water, acids, and bases. Prolonged exposure to hydrocarbon solvents and oils will cause deterioration; however, short exposures can be tolerated.

### Applications

The specific formulation will determine the applicability of various products. Applications include a wide variety of general-purpose rubber items and use in the footwear industry. These rubbers are used primarily in blends with other thermoplastic materials and as performance modifiers.

See Refs. 2, 11, and 17.

## STYRENE-ETHYLENE-BUTYLENE-STYRENE (SEBS) RUBBER

Styrene-ethylene-butylene-styrene (SEBS) rubbers are either pure or oil-modified block copolymer rubbers. These rubbers are used as performance modifiers in blends with thermoplastics or as the base rubber for adhesive, sealant, or coating formulations. Formulations

**Table S.14** Physical and Mechanical Properties of Styrene-Butadiene-Styrene (SBS) Rubber[a]

| | |
|---|---|
| Specific gravity | 0.92–1.09 |
| Tear resistance | Good |
| Tensile strength, psi | 625–4600 |
| Elongation, % at break | 500–1400 |
| Hardness, Shore A | 37–74 |
| Abrasion resistance | Good |
| Maximum temperature, continuous use | 150°F (65°C) |
| Impact resistance | Good |
| Compression set at 74°F (23°C), % | 10–15 |
| Machining qualities | Can be ground |
| Resistance to sunlight | Poor |
| Effect of aging | Little |
| Resistance to heat | Fair |

[a]These are representative values since they may be altered by compounding.

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of SEBS compounds provide a wide range of properties with the benefits of rubberiness and easy processing on standard thermoplastic processing equipment.

## Physical and Mechanical Properties

The SEBS rubbers offer excellent impact resistance and low-temperature flexibility, are highly resistant to oxidation and ozone, and do not require vulcanization. Their degree of flexibility is a function of hardness, with their Shore A hardness ranging from 37 to 95. These rubbers are serviceable from –120 to 220°F (–75 to 105°C). They have excellent resistance to very low-temperature impact and bending. Their thermal life and aging properties are excellent, as is their abrasion resistance.

The electrical properties of SEBS rubbers are extremely good. Although the SEBS rubbers have poor flame resistance, compounding can improve their flame retardancy. This compounding reduces the operating temperature slightly.

The physical and mechanical properties of SEBS rubbers are given in Table S.15.

## Resistance to Sun, Weather, and Ozone

The SEBS rubbers and compounds exhibit excellent resistance to ozone. For prolonged outdoor exposure the addition of an ultraviolet absorber or carbon black pigment or both is recommended.

**Table S.15** Physical and Mechanical Properties of Styrene-Ethylene-Butylene-Styrene (SEBS) Rubbers[a]

| | |
|---|---|
| Specific gravity | 0.885–1.17 |
| Brittle point | –58 to –148°F (–50 to –100°C) |
| Tear strength, psi | 275–470 |
| Moisture absorption, mg/in.$^2$ | 1.2–3.3 |
| Dielectric strength, at 77°F (25°C) | |
| at 60 Hz | 2.1–2.8 |
| at 1 kHz | 2.1–2.8 |
| at 1 MHz | 2.1–2.35 |
| Dissipation factor at 77°F (25°C) | |
| at 60 Hz | 0.0001–0.002 |
| at 1 kHz | 0.0001–0.003 |
| at 1 MHz | 0.0001–0.01 |
| Dielectric strength, V/mil | 625–925 |
| Volume resistivity, ohm/cm | $9 \times 10^5$–$9.1 \times 10^{16}$ |
| Surface resistivity, ohm | $2 \times 10^{16}$–$9.5 \times 10^{16}$ |
| Insulation resistance constant at 60°F (15.6°C) and 500 V DC | $6.8 \times 10^4$–$2.5 \times 10^6$ |
| Insulation resistance at 60°F (15.6°C), megohms/1000 ft | $2.1 \times 10^4$–$1 \times 10^6$ |
| Tensile strength, psi | 1600–2700 |
| Elongation, % at break | 500–675 |
| Hardness, Shore A | 65–95 |
| Abrasion resistance | Good |
| Maximum temperature, continuous use | 220°F (105°C) |
| Impact resistance | Good |
| Resistance to sunlight | Good |
| Effect of aging | Small |
| Resistance to heat | Good |

[a]These are representative values since they may be altered by compounding.

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### Chemical Resistance

The chemical resistance of the SEBS rubbers is similar to that of natural rubber. They have excellent resistance to water, acids, and bases. Soaking in hydrocarbon solvents and oils will deteriorate the rubber, but short exposures can be tolerated.

### Applications

The SEBS rubbers find applications for a wide variety of general-purpose rubber items as well as in automotive, sporting goods, and other products. Many applications are found in the electrical industry for such items as flexible cords, welding and booster cables, flame-resistant appliance wiring materials, and automotive primary wire insulation.

See Refs. 2, 11, and 17.

## SULFATE-REDUCING BACTERIA

These bacteria are widespread in seawater, fresh water, soil, and muddy sediments. When they are present and there is an abundance of sulfate, and the surface of the substrate has a pH of between 5.5 and 8.5, they may cause anaerobic corrosion of iron and steel. The usual by-product of this metabolic process is hydrogen sulfide, which tends to retard cathodic reactions, particularly hydrogen evolution, and to accelerate anodic dissolution, thereby increasing corrosion. The corrosion product is iron sulfide, which precipitates when ferrous and sulfide ions are in contact.

## SULFIDATION

Also see "High-Temperature Corrosion." Sulfidation is oxidation by sulfur forming a sulfide film on the metal surface similar to an oxide film but less protective than a corresponding oxide film.

## SULFIDIC CORROSION

Sulfidic corrosion is most often found in petroleum refining. It is caused by a variety of sulfur compounds originating in the crude oils, including hydrogen sulfide, aliphatic sulfides, mercaptans, disulfides, polysulfides, and thiophenes. Corrosion takes place at process temperatures between 500 and 1000°F (260 and 540°C). The corrosion products are metal sulfides.

## SULFIDE STRESS CRACKING

Sulfide stress cracking is a form of hydrogen-assisted cracking and refers to the cracking of metals when hydrogen sulfide environments generate the hydrogen. The term is used primarily in the petroleum industry. See "Hydrogen Damage."

## SUPER PRO 230

See "Polyvinylidene Fluoride."

## SUPERFERRITIC STAINLESS STEELS

Ferritic stainless alloys are noted for their ability to resist chloride stress corrosion cracking, which is one of their most useful features in terms of corrosion resistance. Consequently,

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development efforts were undertaken during the 1970s to produce ferritic stainlesses that would possess a high level of general and localized pitting resistance as well.

The first significant alloy developed commercially to meet these requirements contained 26% chromium and 1% molybdenum. In order to obtain the desired corrosion resistance and acceptable fabrication characteristics, the material had to have very low interstitial element content. To achieve these levels the material was electron beam refined under a vacuum. It was known as E-Brite alloy. Carbon plus nitrogen levels were maintained below 0.02%.

The E-Brite alloy was termed superferritic because of its high level of corrosion resistance for a ferritic material and partly because it is located far into the ferritic zone on the Schaeffler diagram. For a period of years the usage of this alloy grew. Finally its benefits for the construction of pressure vessels were overshadowed by the difficult nature of fabrication and a concern over its toughness. Due to a very low level of interstitial elements the alloy has a tendency to absorb these elements during welding processes. Increases in oxygen plus nitrogen levels much over 100 ppm resulted in poor toughness. Even without these effects the alloy could exhibit a ductile-to-brittle transition temperature around room temperature. Other superferritic alloys were developed. The chemical compositions of selected superferritic alloys are shown in Table S.16.

## Type XM-27 (S44627

This alloy is also manufactured under the trade name of E-Brite by Allegheny Ludlum Industries Inc. It is a high-chromium specialty alloy. Refer to Table S-16 for the chemical composition.

In general, E-Brite has good general corrosion resistance in most oxidizing acids, organic acids, and caustics. It is resistant to pitting and crevice corrosion and free from chloride stress corrosion cracking. Refer to Table S.17 for the compatibility of alloy S44627 with selected corrodents.

**Table S.16** Chemical Composition of Selected Superferritic Stainless Steels[a]

| Alloy | C | Cr | Ni | Mo | N | Other |
|---|---|---|---|---|---|---|
| S44627 | 0.002 | 26.0 | — | 1.0 | 0.010 | |
| S44660 | 0.02 | 26.0 | 2.5 | 3.0 | 0.025 | Ti + Cb 0.5 |
| S44800 | 0.005 | 29.0 | 2.2 | 4.0 | 0.01 | |

[a]Values are in wt%.

**Table S.17** Compatibility of E-Brite Alloy S44627 with Selected Corrodents[a]

| | Maximum temp. | | | Maximum temp. | |
|---|---|---|---|---|---|
| Chemical | °F | °C | Chemical | °F | °C |
| Acetic acid, 10% | 200 | 93 | Acetic anhydride* | 300 | 149 |
| Acetic acid, 20% | 200 | 93 | Ammonium chloride, 10%* | 200 | 93 |
| Acetic acid, 50% | 200 | 93 | Aqua regia, 3:1 | x | x |
| Acetic acid, 80% | 130 | 54 | Beer | 160 | 71 |
| Acetic acid, glacial | 140 | 60 | Beet sugar liquors | 120 | 49 |

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**Table S.17** Compatibility of E-Brite Alloy S44627 with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Benzaldehyde* | 210 | 99 | Nitric acid, 40%* | 200 | 93 |
| Bromine water, 1% | 80 | 27 | Nitric acid, 50%* | 200 | 93 |
| Calcium hydroxide, 50%* | 210 | 99 | Nitric acid, 70%* | 200 | 93 |
| Chromic acid, 10% | 130 | 54 | Oxalic acid, 10% | x | x |
| Chromic acid, 30% | 90 | 32 | Phosphoric acid, 25–50%* | 210 | 99 |
| Chromic acid, 40% | 80 | 27 | Sodium chlorite | 90 | 32 |
| Chromic acid, 50% | x | x | Sodium hydroxide, 10% | 200 | 93 |
| Citric acid, 10% | 200 | 93 | Sodium hydroxide, 15% | 200 | 93 |
| Citric acid, 25% | 210 | 99 | Sodium hydroxide, 30% | 200 | 93 |
| Copper chloride, 5% | 100 | 38 | Sodium hydroxide, 50% | 180 | 82 |
| Ethylene chloride* | 210 | 99 | Sodium hypochlorite, 30%* | 90 | 32 |
| Ferric chloride | 80 | 27 | Stearic acid | 210 | 99 |
| Fluosilicic acid | x | x | Sulfamic acid | 100 | 38 |
| Formic acid, 80% | 210 | 99 | Sulfur dioxide, wet | 550 | 293 |
| Hydrochloric acid | x | x | Sulfuric acid, 10% | x | x |
| Lactic acid, 80% | 200 | 93 | Sulfuric acid, 30–90% | x | x |
| Methylene chloride | x | x | Sulfuric acid, 95% | 150 | 66 |
| Nitric acid, 5%* | 310 | 154 | Sulfuric acid, 98% | 280 | 138 |
| Nitric acid, 10%* | 310 | 154 | Sulfurous acid, 5%* | 210 | 99 |
| Nitric acid, 20%* | 320 | 160 | Tartaric acid, 50% | 210 | 99 |
| Nitric acid, 30%* | 320 | 160 | Toluene | 210 | 99 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. When compatible, corrosion rate is <2 mpy except for those marked with an *, whose corrosion rate is <20 mpy.
*Source:* Ref. 2.

This alloy also resists intergranular corrosion and is approved for use in contact with foods.

Applications include heat exchanger tubing, overhead condensers, reboilers, feed heaters (petroleum refining), pulp and paper liquid heaters, organic acid heaters and condensers, and nitric acid cooler condensers.

## Alloy S44660 (Sea-Cure)

Sea-Cure is the trademark of Trent Tube. It is a chromium–nickel–molybdenum super ferritic alloy. The chemical composition is shown in Table S.16.

Because of its chromium–nickel–molybdenum content it possesses excellent resistance to chloride-induced pitting, crevice corrosion, and stress corrosion cracking. It has better resistance than austenitic stainless steel to general corrosion in diverse conditions. Good to excellent resistance is shown to organic acids, alkalies, salts, and seawater, with good resistance shown to sulfuric, phosphoric, and nitric acids.

Sea-Cure is used in electric power plant condensers and feedwater heaters, and heat exchangers in chemical, petrochemical, and refining applications.

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## Alloy S44735 (29-40)

The chemical composition of alloy 29-40 is as follows:

| Chemical | Weight percent |
|---|---|
| Carbon | 0.03 max. |
| Manganese | 0.30 max. |
| Silicon | 1.00 max. |
| Chromium | 28.0–30.0 |
| Nickel | 1.0 |
| Phosphorus | 0.03 |
| Molybdenum | 3.60–4.20 |
| Titanium + niobium | 6.0–0.45 niobium, min. |
| Iron | Balance |

This alloy has improved general corrosion resistance and improved resistance to chloride pitting and stress corrosion cracking in some environments. The absence of nickel reduces the cost.

Applications are found in the utility industry, chemical processing equipment, household condensing furnaces, and vent pipes.

## Alloy S44800 (29-4-Z)

The chemical composition of alloy 29-4-Z is shown in Table S.16. This alloy has improved resistance to chloride pitting and stress corrosion cracking and improved general corrosion resistance in some environments.

Applications are found in chemical processing equipment and the utility industry for use in corrosive environments.

## Alloy S44700 (29-4)

This is a chromium–nickel–molybdenum alloy with the composition shown below:

| Chemical | Weight percent |
|---|---|
| Carbon | 0.010 max. |
| Manganese | 0.30 max. |
| Chromium | 28.0–30.0 |
| Nickel | 0.15 |
| Molybdenum | 3.50–4.20 |
| Silicon | 0.02 max. |
| Copper | 0.15 |
| Nitrogen | 0.02 |
| Iron | Balance |

Alloy 29-4 has excellent resistance to chloride pitting and stress corrosion cracking. Applications are found in the chemical processing and utility industries.

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# T

## TANTALUM

Tantalum is not a new material. Its first commercial use at the turn of the century was as filaments in light bulbs. Later, when it became apparent that tantalum was practically inert to attack by most acids, applications in the laboratory and in the chemical and medical industries were developed. The rise of the electronics industry accelerated the development of many new applications.

Much of this growth can be attributed to a broader range of tantalum powders and mill products available from the producers, which have a high melting point, the ability to form a dielectric oxide film, and chemical inertness. With these applications, new reduction, melting, and fabrication techniques have led to higher purities, higher reliabilities, and improved yields to finished products.

### Source of Tantalum

The earth's crust is made up of 92 naturally occurring elements, but these elements are not all present in equal amounts. Eight elements—oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium—make up 96.5% of the crust. The remaining 88 elements make up only 3.5%, with tantalum amounting to only 0.0002%.

If the tantalum were equally distributed in the rocks of the earth, it would be uneconomical to recover, and there would be no tantalum industry today. However, the tantalum is concentrated in a few unusual rocks in sufficient quantity to permit economical mining and refining. The most important tantalum minerals, tantalite microlites and wodginite, are found in rock formations known as pegmatites.

Pegmatites are coarse-grained rocks formed when molten rock material was cooled slowly. They range in size from 1 in. to many feet in diameter. Also found in the pegmatites are many rare elements such as tantalum, niobium, tin, lithium, and beryllium.

The only operating mine in North America is located at Bernic Lake in Manitoba, Canada. The other important mine in the Americas is found in Brazil. In the humid tropics, the rocks weather and rot to great depths. Many times, the rocks in which the tantalum minerals were formed have completely weathered and have been carried away by running water. The heavy tantalum minerals tend to be concentrated in deposits called placers. These can be panned or washed with machinery, much as gold was recovered during the gold rush. One important placer-type deposit is found in Greenbushes in western Australia.

Because tin and tantalum are often found together, tantalum is a by-product of the tin industry. Because most of the tantalum deposits are small, hard to find, and very expensive to mine, the result is a high-priced ore and a correspondingly high-priced metal.



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## Tantalum Manufacture

### *Ingot Consolidation*

The first production route for tantalum was by powder metallurgy. Tantalum powder, produced by one of several reduction techniques, is pressed into suitably sized bars and then sintered in vacuum at temperatures in excess of 3800°F (2100°C). When completed, the pressed and sintered bars are ready for processing into mill shapes. Forging, rolling, swaging, and drawing of tantalum is performed at room temperature on standard metal working equipment with relatively few modifications.

The powder metallurgy route, although still in use and adequate for many applications, has two major limitations: (1) The size of the bar capable of being pressed and sintered to a uniform density limits the size of the finished shape available, and (2) the amount of residual interstitial impurities, such as oxygen, carbon, and nitrogen, remaining after sintering adversely affects weldability.

The use of vacuum melting, either by consumable arc or electron-beam process, overcomes these limitations. Either melting technique is capable of producing ingots that are big enough and high enough in purity to meet most requirements of product size and specifications adequately, provided that starting materials are selected with care.

### *Quality Description*

The greatest volume of tantalum is supplied as powder for the manufacture of solid electrolytic tantalum capacitors.

Because it is necessary to distinguish between capacitor-grade powder and melting-grade powder, manufacturers of electronic components tend to use the term capacitor-grade when ordering forms such as wire, foil, and sheet to identify end use and desired characteristics.

The term capacitor-grade means that the material should have the ability to form an anodic oxide film of certain characteristics. Capacitor-grade in itself does not mean an inherently higher purity, cleaner surface, or different type of tantalum. It does mean that the material should be tested using carefully standardized procedures for electrical properties. If certain objective standards, such as formation voltage and leakage current, are not available against which to test the material, the use of the phrase capacitor-grade is not definitive.

Metallurgical-grade could be simply defined as non–capacitor-grade.

## Properties of Tantalum

### *Alloys Available*

Pure tantalum has a body-centered, cubic crystal lattice. There is no allotropic transformation to the melting point, which means that unalloyed tantalum cannot be hardened by heat treatment. Additions of oxygen, carbon, or nitrogen above normal levels, either purposefully or accidentally, are considered as alloying ingredients no matter what the concentration.

Tantalum–niobium alloys containing more than about 5–10% niobium are much less corrosion resistant than tantalum itself.

Tantalum–tungsten alloys containing more than 18% tungsten are inert to 20% hydrofluoric acid at room temperature. Few data are available on the 90Ta-10W alloy. It

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is known to be somewhat more oxidation resistant (e.g., to air at higher temperatures) than tantalum. The indication is that it has about the same corrosion resistance to acids as tantalum itself.

### *Mechanical Properties*

The room-temperature mechanical properties of tantalum are dependent on chemical purity, amount of reduction in cross-sectional area, and temperature of final annealing. Annealing time apparently is not critical. Close control over the many factors that affect mechanical properties is mandatory to ensure reproducible mechanical behavior. Typical mechanical properties for tantalum are shown in Table T.1.

Tantalum can be strengthened only by cold work, with a resulting loss in ductility. Because certain residual impurities have pronounced effects on ductility levels and metallurgical behavior, the purpose of most consolidation techniques is to make the material as pure as possible. Cold-working methods are used almost without exception to preclude the possibility of embrittlement by exposure to oxygen, carbon, nitrogen, and hydrogen at even moderate temperatures. Temperatures in excess of 800°F (425°C) should he avoided. Physical properties are shown in Table T.2.

**Table T.1** Mechanical and Physical Properties of Tantalum

| | |
|---|---|
| Modulus of elasticity psi $\times 10^6$ | 27 |
| Tensile strength psi $\times 10^3$ | |
| Grade VM | 30 |
| Grade PM | 40 |
| Yield strength 0.2% offset psi $\times 10^3$ | |
| Grade VM | 20 |
| Grade PM | 30 |
| Elongation in 2 in., % | 30+ |
| Hardness, Rockwell | |
| Grade VM | B-55 |
| Grade PM | B-65 |
| Density, lb/in.$^3$ | 0.6 |
| Specific gravity | 16.6 |
| Specific heat, Btu/lb °F | 0.036 |
| Thermal conductivity at 68 °F, Btu/h/ft$^2$/°F/in. | 377 |
| Coefficient of thermal expansion in./in./°F $\times 10^{-6}$ | 3.6 |

**Table T.2** Physical Properties of Tantalum

| | |
|---|---|
| Atomic weight | 180.9 |
| Density | 16.6 g/cm$^3$ (0.601 lb/in.$^3$) |
| Melting point | 2996°C (5432°F) |
| Vapor pressure at 1727°C | $9.525 \times 10^{-11}$ mmHg |

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**Table T.2** Physical Properties of Tantalum (Continued)

| | |
|---|---|
| Linear coefficient of expansion | 1135K: $5.76 \times 10^{-6}$/°C |
| | 1641K; $9.53 \times 10^{-6}$/°C |
| | 2030K; $12.9 \times 10^{-6}$/°C |
| | 2495K; $16.7 \times 10^{-6}$/°C |
| Thermal conductivity | 20°C: 0.130 cal/cm-s°C |
| | 100°C; 0.131 cal/cm-s°C |
| | 1430°C: 0.174 cal/cm-s°C |
| | 1630°C; 0.186 cal/cm-s°C |
| | 1830°C; 0.198 cal/cm-s°C |
| Specific heat | 100°C; 0.03364 cal/g |
| Electrical conductivity | 13.9% IACS |
| Electrical resistivity | –73°C; 9.0 μΩ/cm |
| | 75°C; 12.4 μΩ/cm |
| | 127°C: 18.0 μΩ/cm |
| | 1000°C; 54.0 μΩ/cm |
| | 1500°C: 71.0 μΩ/cm |
| | 2000°C; 87.0 μΩ/cm |

## TANTALUM-BASED ALLOYS

There are certain advantages to the use of tantalum-based alloys:

1. Alloying with a less expensive material reduces the cost of the material while still retaining essentially all of the corrosion-resistant properties.
2. The use of light material will reduce the overall weight.
3. Depending upon the alloying ingredient, the physical strength of tantalum may be improved.

### Tantalum–Tungsten Alloys

The tantalum–tungsten alloys are probably the most common. The addition of 2–3% tungsten will raise the strength of the tantalum by 30–50%. By also adding 0.15% niobium, a marked increase in the corrosion resistance to concentrated sulfuric acid at 392°F (200°C) is noted. In the lower temperature ranges, 347°F (175°C) or less, the resistance of the alloy is equal to that of pure tantalum.

When the tungsten concentration is increased to 18% or higher, the alloys exhibit essentially no corrosion rate in 20% hydrofluoric acid. This is a definite advantage over pure tantalum.

### Tantalum–Titanium Alloys

The tantalum–titanium alloys are receiving a great deal of study because this series of alloys shows considerable promise of providing a less expensive, lower-weight alloy having a corrosion resistance almost comparable with that of tantalum. Tantalum-titanium alloys show excellent resistance in nitric acid at 374°F (190°C) and at the boiling point.

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## Tantalum–Molybdenum Alloys

When these alloys are exposed to concentrated sulfuric acid and concentrated hydrochloric acid, they are extremely resistant, and the properties of tantalum are retained as long as the tantalum concentration is higher than 50%.

## Corrosion Resistance

Tantalum forms a thin, impervious, passive layer of tantalum oxide on exposure to oxidizing or slightly anodic conditions, even at a temperature as low as 77°F (25°C). Chemicals or conditions that attack tantalum, such as hydrofluoric acid, are those that penetrate or dissolve this oxide film, in the case of fluoride ion by forming the complex $TaF_5^{2-}$. Once the oxide layer is lost, the metal loses its corrosion resistance dramatically.

When in contact with most other metals, tantalum becomes cathodic. In galvanic couples in which tantalum becomes the cathode, nascent hydrogen forms and is absorbed by the tantalum, causing hydrogen embrittlement. Caution must be taken to electrically isolate tantalum from other metals or otherwise protect it from becoming cathodic.

Tantalum is inert to practically all organic and inorganic compounds at temperatures under 302°F (150°C). The only exceptions to this are hydrofluoric acid (HF) and fuming sulfuric acid. At temperatures under 302°F (150°C) it is inert to all concentrations of hydrochloric acid, to all concentrations of nitric acid (including fuming), to 98% sulfuric acid, to 85% phosphoric acid, and to aqua regia (refer to Table T.3).

**Table T.3** Materials to Which Tantalum Is Completely Inert, up to At Least 150°C (302°F)

| | |
|---|---|
| Acetic acid | Calcium hydroxide |
| Acetic anhydride | Calcium hypochlorite |
| Acetone | Carbon tetrachloride |
| Acids. mineral (except HF) | Carbonic acid |
| Acid salts | Carbon dioxide |
| Air | Chloric acid |
| Alcohols | Chlorinated hydrocarbons |
| Aluminum chloride | Chlorine oxides |
| Aluminum sulfate | Chlorine water and brine |
| Amines | Chlorine, wet or dry |
| Ammonium chloride | Chloroacetic acid |
| Ammonium hydroxide | Chrome-plating solutions |
| Ammonium phosphate | Chromic acid |
| Ammonium sulfate | Citric acid |
| Amyl acetate | Cleaning solutions |
| Amyl chloride | Copper salts |
| Aqua regia | Ethyl sulfate |
| Barium hydroxide | Ethylene dibromide |
| Body fluids | Fatty acids |
| Bromine, wet or dry | Ferric chloride |
| Butyric acid | Ferrous sulfate |
| Calcium bisulfate | Foodstuffs |
| Calcium chloride | Formaldehyde |

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**Table T.3** Materials to Which Tantalum Is Completely Inert, up to At Least 150°C (302°F) (Continued)

| | |
|---|---|
| Formic acid | Perchloric acid |
| Fruit products | Petroleum products |
| Hydriodic acid | Phenols |
| Hydrobromic acid | Phosphoric acid, < 4 ppm F |
| Hydrochloric acid | Phosphorus |
| Hydrogen | Phosphorus chlorides |
| Hydrogen chloride | Phosphorus oxychloride |
| Hydrogen iodide | Phthalic anhydride |
| Hydrogen peroxide | Potassium chloride |
| Hydrogen sulfide | Potassium dichromate |
| Hypochlorous acid | Potassium iodide, iodine |
| Iodine | Potassium nitrate |
| Lactic acid | Refrigerants |
| Magnesium chloride | Silver nitrate |
| Magnesium sulfate | Sodium bisulfate, aqueous |
| Mercury salts | Sodium bromide |
| Methyl sulfuric acid | Sodium chlorate |
| Milk | Sodium chloride |
| Mineral oils | Sodium hypochlorite |
| Motor fuels | Sodium nitrate |
| Nitric acid, industrial fuming | Sodium sulfate |
| Nitric oxides | Sodium sulfite |
| Nitrogen | Sugar |
| Nitrosyl chloride | Sulfamic acid |
| Nitrous oxides | Sulfur |
| Organic chlorides | Sulfur dioxide |
| Oxalic acid | Sulfuric acid, under 98% |
| Oxygen | Water |

Corrosion is first noticed at about 375°F (190°C) for 70% nitric acid, at about 345°F (175°C) for 98% sulfuric acid, and at about 355°F (180°C) for 85% phosphoric acid (refer to Fig.T.1).

Hydrofluoric acid, anhydrous HF, or any acid medium containing fluoride ion will rapidly attack the metal. One exception to fluoride attack appears to be in chromium plating baths. Hot oxalic acid is the only organic acid known to attack tantalum. The corrosion rates of tantalum in various acid media are given in Table T.4.

Referring to Fig. T.1, it will be seen that tantalum shows excellent resistance to reagent-grade phosphoric acid at all concentrations below 85% and temperatures under 374°F (190°C). However, if the acid contains more than a few parts per million of fluoride, as is frequently the case with commercial acid, corrosion of tantalum may take place. Corrosion tests should be run to verify the suitability under these conditions.

Figure T.2 indicates the corrosion resistance of tantalum to hydrochloric acid over the concentration range of 0–37% and temperature to 374°F (190°C).

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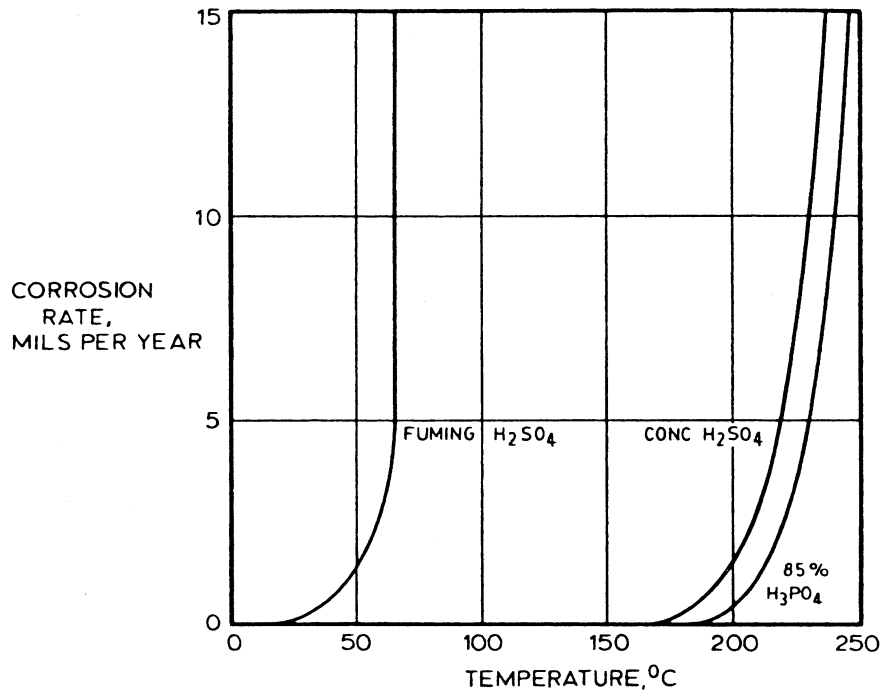



**Figure T.1** Corrosion rates of tantalum in fuming sulfuric acid, concentrated sulfuric acid, and 85% sulfuric acid. (from Ref. 5).

**Table T.4** Corrosion Rates of Tantalum in Selected Media

| Medium | Temperature (°C) | Temperature (°F) | Corrosion rate (mpy) |
|---|---|---|---|
| Acetic acid | 100 | 212 | Nil |
| $AlCl_3$ (10% soln.) | 100 | 212 | Nil |
| $NH_4CI$ (10% soln.) | 100 | 212 | Nil |
| HCI 20% | 21 | 70 | Nil |
| | 100 | 212 | Nil |
| Conc. | 21 | 70 | Nil |
| $HNO_3$ 20% | 100 | 212 | Nil |
| 70% | 100 | 212 | Nil |
| 65% | 170 | 338 | 1 |
| $H_3PO_4$ 85% | 25 | 76 | Nil |
| | 100 | 212 | Nil |
| $H_2SO_4$ | | | |
| 10% | 25 | 76 | Nil |
| 40% | 25 | 76 | Nil |
| 98% | 25 | 76 | Nil |
| 98% | 50 | 122 | Nil |
| 98% | 100 | 212 | Nil |

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**Table T.4** Corrosion Rates of Tantalum in Selected Media (Continued)

| Medium | Temperature (°C) | Temperature (°F) | Corrosion rate (mpy) |
|---|---|---|---|
| 98% | 200 | 392 | 3 |
| 98% | 250 | 482 | Rapid |
| $H_2SO_4$, fuming (15% $SO_3$) | 23 | 73 | 0.5 |
| | 70 | 158 | Rapid |
| Aqua regia | 25 | 78 | Nil |
| Chlorine, wet | 75 | 167 | Nil |
| $H_2O$ | | | |
| $Cl_2$ sat. | 25 | 76 | Nil |
| Seawater | 25 | 76 | Nil |
| Oxalic acid | 21 | 70 | Nil |
| | 96 | 205 | 0.1 |
| NaOH 5% | 21 | 70 | Nil |
| | 100 | 212 | 0.7 |
| 10% | 100 | 212 | 1 |
| 40% | 80 | 176 | Rapid |
| HF 40% | 25 | 76 | Rapid |

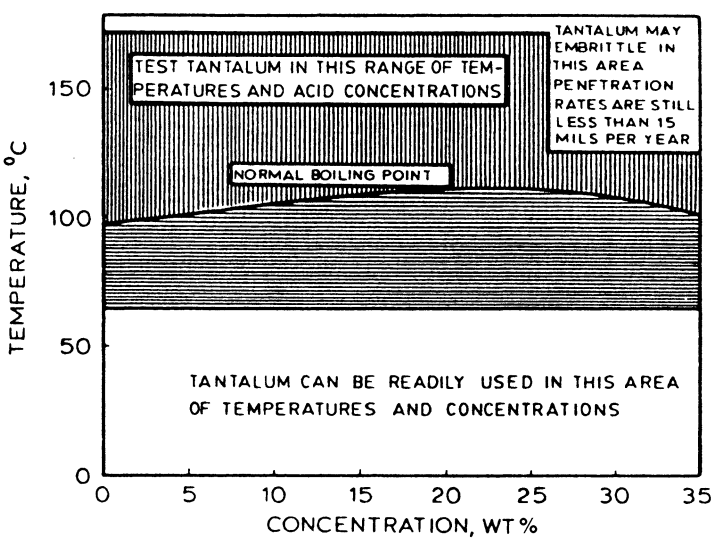



**Figure T.2** Corrosion resistance of tantalum in hydrochloric acid at various concentrations (from Ref. 5).

Figure T.3 indicates the corrosion resistance of tantalum to nitric acid in all concentrations and at all temperatures to boiling. The presence of chlorides in the acid does not reduce its corrosion resistance.

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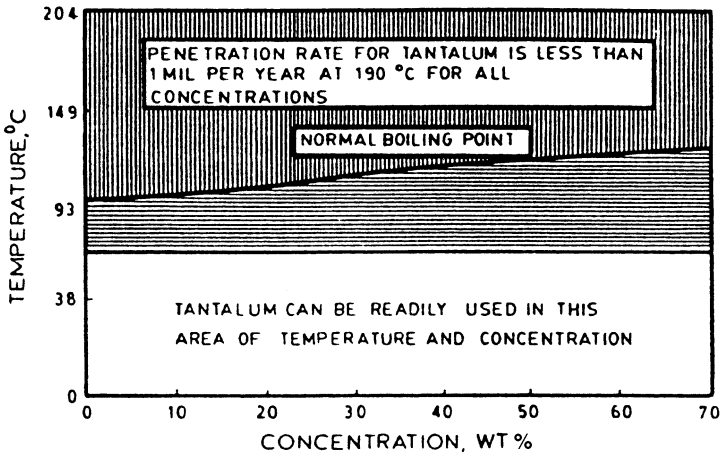



**Figure T.3** Corrosion resistance of tantalum in nitric acid at various concentrations and temperatures.

Fused sodium and potassium hydroxides and pyrosulfates dissolve tantalum. It is attacked by concentrated alkaline solutions at room temperature; it is fairly resistant to dilute solutions. Tantalum's resistance to oxidation by various gases is very good at low temperatures, but it reacts rapidly at high temperatures. Only HF and $SO_3$ attack the metal under 212°F (100°C); most gases begin to react with it at 570 to 750°F (300 to 400°C). As the temperature and concentration of such gases as oxygen, nitrogen, chlorine, hydrogen chloride, and ammonia are increased, oxidation becomes more rapid; the usual temperature for rapid failure is 930–1200°F (500–700°C). The conditions under which tantalum is attacked are noted in Table T.5. Refer to Table T.18 for the compatibility of tantalum with selected corrodents.

**Table T.5** Temperatures at which Various Media Attack Tantalum

| Medium | State | Remarks |
|---|---|---|
| Air | Gas | At temperatures over 300°C (572°F) |
| Alkaline solutions | Aqueous | At pH > 9, moderate temperature. some corrosion |
| Ammonia | Gas | Pits at high temperature and pressures |
| Bromine | Gas | At temperatures over 300°C (572°F) |
| Chlorine, wet | Gas | At temperatures over 250°C (482°F) |
| Fluorides, acid media | Aqueous | All temperatures and concentrations |
| Fluorine | Gas | At all temperatures |
| HBr 25% | Aqueous | Begins to corrode at temperatures over 190°C (374°F) |
| Hydrocarbons | Gas | React at temperatures around 1500°C (2732°F) |
| HCl 25% | Aqueous | Begins to corrode at temperatures over 190°C (374°F) |
| HF | Aqueous | Corrodes at all temperatures and pressures |
| Hydrogen | Gas | Causes embrittlement, especially at temperatures over 400°C (752°F) |
| HBr | Gas | At temperatures over 400°C (752°F) |
| HCl | Gas | At temperatures over 350°C (662°F) |
| HF | Gas | At all temperatures |

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**Table T.5** Temperatures at which Various Media Attack Tantalum (Continued)

| Medium | State | Remarks |
|---|---|---|
| Iodine | Gas | At temperatures over 300°C (572°F) |
| Nitrogen | Gas | At temperatures over 300°C (572°F) |
| Oxalic acid, sat. soln. | Aqueous | At temperatures of about 100°C (212°F) |
| Oxygen | Gas | At temperatures over 350°C (662°F) |
| $H_3PO_4$ 85% | Aqueous | Corrodes at temperatures over 180°C (356°F), at higher temperatures for lower concentrations |
| Potassium carbonate | Aqueous | Corrodes at moderate temperatures depending on concentration |
| Sodium carbonate | Aqueous | Corrodes at moderate temperatures depending on concentration |
| NaOH 10% | Aqueous | Corrodes at about 100°C (212°F) |
| NaOH | Molten | Dissolves metal rapidly (over 320°C) (608°F) |
| Sodium pyrosulfate | Molten | Dissolves metal rapidly (over 400°C) (752°F) |
| $H_2SO_4$ 98% | Aqueous | Begins to corrode at temperatures over 175°C (347°F); lower concentrations begin to corrode at higher temperatures |
| $H_2SO_4$ (oleum) (over 98% H2SO4) | Fuming | Corrodes at all temperatures |
| Sulfuric trioxide | Gas | At all temperatures |
| Water | Aqueous | Corrodes at pH > 9, reacts at high temperatures |

### Suggested Applications

Because of its relatively high price, tantalum can be recommended only for use in extremely corrosive media, in areas where no corrosion of the part can be tolerated, or where very high-purity materials are being processed. Although some plastics, and even glass, fulfill these requirements to a large extent, tantalum is a structurally sound material of construction, can take considerable mechanical abuse, and has a much higher heat transfer coefficient. Tantalum should be used as a material of construction in locations and for equipment where hot concentrated hydrochloric, sulfuric, or phosphoric acids will be present. Tantalum is used by the medical profession for instruments and for metal implants in the body. In the manufacture of high-purity chemicals and pharmaceuticals, tantalum ensures that no impurities are introduced from the container or reactor.

See Refs. 1–5.

## TARNISH

Tarnish is a surface discoloration of a metal caused by a thin film of corrosion product. This is quite common on silver surfaces.

## TECHNOFLON

See "Fluoroelastomers."

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## TEFLON

See "Polytetrafluoroethylene."

## TEFZEL

See "Ethylene-Tetrafluoroethylene."

## TEMPERING

Tempering is usually performed after a quenching operation. Quenching produces a hard and strong but brittle phase called martensite. Tempering is performed to promote some carbon diffusion from the martensite, thereby greatly improving the toughness and ductility of the quenched steel.

Tempering is usually done at 1000 to 1300°F (595 to 705°C). Thick sections of many ferritic steels cannot be cooled quickly enough in air to obtain a normalized structure. In order to hasten the cooling rate, the material is quenched. The objective is to produce the same type of microstructure that would be obtained from normalizing a thinner section of the same material. Quenching of very thick sections does not generate the cooling rates necessary to develop martensite. In these cases, tempering is used primarily for stress relief rather than for softening of the martensite.

At times, tempering is done in conjunction with other heat treatments such as normalizing. The purpose is usually to promote carbon diffusion with the intention of softening and/or toughening the steel. Stress relief may be a secondary or even a primary objective.

## TEREPHTHALIC POLYESTERS

This family of thermoset resins is based on terephthalic acid, which is a para-isomer of phthalic acids. The properties of cured terephthalic-based polyesters are similar to those of isophthalic polyesters with the terephthalics having higher heat distortion temperatures and being somewhat softer at equal saturation levels.

Corrosion resistance of the polyethylene terephthalates (PETs) is fairly similar to that of the isophthalics. Testing has indicated that the benzene resistance of comparably formulated resins is lower for PET versus isophthalic polyesters. This trend is also followed where retention of flexural modulus is elevated for various terephthalic resins versus the standard corrosion-grade isophthalic resin. The PET's loss of properties in gasoline is greater than the isophthalics at the same level of saturation; however, as the unsaturation increases, the gasoline resistance reverses, with the PET performing better. The trend was seen only at unsaturated acid levels of greater than 50 mol%. This was achieved with a reversal of performance in 10% sodium hydroxide, where the PET with lower unsaturation was better than the isophthalic level. This follows a general trend for thermosets, that as cross-link density increases, solvent resistance increases.

Refer to Table T.6 for the compatibility of terephthalate Polyester with selected corrodents.

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**Table T.6** Compatibility of Polyester Terephthalate (PET) with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetic acid 10% | 300 | 149 | Cyclohexane | 80 | 27 |
| Acetic acid 50% | 300 | 149 | Dichloroethane | x | x |
| Acetic anhydride | x | x | Ferric chloride | 250 | 121 |
| Acetone | x | x | Ferric nitrate 10–50% | 170 | 77 |
| Acetyl chloride | x | x | Ferrous chloride | 250 | 121 |
| Acrylonitrile | 80 | 26 | Hydrobromic acid 20% | 250 | 121 |
| Aluminum chloride, | | | Hydrobromic acid 50% | 250 | 121 |
| aqueous | 170 | 77 | Hydrochloric acid 20% | 250 | 121 |
| Aluminum sulfate | 300 | 149 | Hydrochloric acid 30% | x | x |
| Ammonium chloride, sat. | 170 | 77 | Hydrochloric acid 38% | 90 | 32 |
| Ammonium nitrate | 140 | 70 | Hydrocyanic acid 10% | 80 | 27 |
| Ammonium persulfate | 180 | 82 | Hydrofluoric acid 70% | x | x |
| Amyl acetate | 80 | 26 | Hydrofluoric acid 100% | x | x |
| Amyl alcohol | 250 | 121 | Lactic acid 25% | 250 | 121 |
| Aniline | x | x | Lactic acid, concd. | 250 | 121 |
| Antimony trichloride | 250 | 121 | Magnesium chloride | 250 | 121 |
| Aqua regia 3:1 | 80 | 26 | Methyl ethyl ketone | 250 | 121 |
| Barium carbonate | 250 | 121 | Methyl isobutyl ketone | x | x |
| Barium chloride | 250 | 121 | Muriatic acid | 90 | 32 |
| Benzaldehyde | x | x | Nitric acid 5% | 150 | 66 |
| Benzene | x | x | Perchloric acid 10% | x | x |
| Benzoic acid | 250 | 121 | Perchloric acid 70% | x | x |
| Benzyl alcohol | 80 | 27 | Phenol | x | x |
| Benzyl chloride | 250 | 121 | Phosphoric acid 50–80% | 250 | 121 |
| Boric acid | 200 | 93 | Sodium carbonate 10% | 250 | 121 |
| Bromine liquid | 80 | 27 | Sodium chloride | 250 | 121 |
| Butyl acetate | 250 | 121 | Sodium hydroxide 10% | 150 | 66 |
| Butyric acid | 250 | 121 | Sodium hydroxide 50% | x | x |
| Calcium chloride | 250 | 121 | Sodium hydroxide, concd | x | x |
| Calcium hypochlorite | 250 | 121 | Sodium hypochlorite 20% | 80 | 27 |
| Carbon tetrachloride | 250 | 121 | Sulfuric acid 10% | 160 | 71 |
| Chloroacetic acid 50% | x | x | Sulfuric acid 50% | 140 | 60 |
| Chlorine gas, dry | 80 | 27 | Sulfuric acid 70% | x | x |
| Chlorine gas, wet | 80 | 27 | Sulfuric acid 90% | x | x |
| Chloroform | 250 | 121 | Sulfuric acid 98% | x | x |
| Chromic acid 50% | 250 | 121 | Sulfuric acid 100% | x | x |
| Citric acid 15% | 250 | 121 | Sulfuric acid, fuming | x | x |
| Citric acid, concd. | 150 | 66 | Toluene | 250 | 121 |
| Copper chloride | 170 | 77 | Trichloroacetic acid | 250 | 121 |
| Copper sulfate | 170 | 77 | Zinc chloride | 250 | 121 |
| Cresol | x | x | | | |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available, Incompatibility is shown by an x. A blank space indicates that data are unavailable.

*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

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## THERMOPLASTIC ALLOYS

The alloying of several thermoplastic systems often produces better physical properties than any system can produce by itself. These include impact resistance, flame retardancy, and thermal stability. Alloying is generally done with intensive mixing or screw extruders. Polyvinyl chloride and ABS are frequently blended to provide rigidity, toughness, flame retardancy, and chemical resistance. Polycarbonate can be blended with ABS to provide better heat resistance and toughness. Polyurethane improves the abrasion resistance and toughness of ABS while retaining the advantage of reduced cost. The impact strength of polypropylene is increased by alloying with polyisobutylene. Alloying is generally done on a relatively small scale, varying from as low as 0.01% up to as high as 9%.

Also see "Xenoy," "Cycoloy," and "Triax."

## THERMOPLASTIC COMPOSITES

See "Composite Laminates."

## THERMOPLASTIC ELASTOMERS (TPE), OLEFINIC TYPE

This family of elastomers is based on cross-linked polyolefin alloys compounded with common fillers (pigments), plasticizers, stabilizers, and cross-linking agents. The plasticizers and fillers are used to tailor properties to specific applications. These materials can be injection molded, blow molded, and extruded on conventional thermoplastic equipment. Vulcanization is not required. See Table T.7.

**Table T.7** Physical and Mechanical Properties of Thermoplastic Elastomers (TPE), Olefinic Type[a]

| | |
|---|---|
| Specific gravity | 0.88–1.0 |
| Brittle point | –67 to –76°F (–55 to –60°C) |
| Tensile strength, psi | |
| at 73°F (23°C) | 1700–2150 |
| at 212°F (100°C) | 1040–1170 |
| at 277°F (136°C) | 730–770 |
| at 302°F (150°C) | 640–750 |
| Elongation, at break | |
| at 73°F (23°C) | 210–300 |
| at 212°F (100°C) | 290–670 |
| at 277°F (136°C) | 380–870 |
| at 302°F (150°C) | 300–750 |
| Hardness, Shore | 92A–54D |
| Abrasion resistance | Good |
| Maximum temperature, continuous use | 277°F (136°C) |
| Compression set, method A,% | |
| after 22 h at 73°F (23°C) | 8–18 |
| after 22 h at 212°F (100°C) | 47–48 |
| Tear resistance | Good |
| Resistance to sunlight | Good |
| Resistance to heat | Good |
| Effect of aging | Small |
| Electrical properties | Excellent |

[a]These are representative values since they may be altered by compounding.

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### Resistance to Sun, Weather, and Ozone

The TPEs possess good resistance to sun and ozone and have excellent weatherability. Their water resistance is excellent, showing essentially no property changes after prolonged exposure to water at elevated temperatures.

### Chemical Resistance

The thermoplastic elastomers display reasonably good resistance to oils and automotive fluids, comparable to that of neoprene. However, they do not have the outstanding oil resistance of the polyester elastomers. They do have excellent water resistance, even at elevated temperatures.

### Applications

These elastomeric compounds are found in a variety of applications including reinforced hose, seals, gaskets and profile extrusions, flexible and supported tubing, automotive trim, functional parts and under-hood components, mechanical goods, and wire and cable jacketing.

See Refs. 4 and 6.

## THERMOPLASTIC POLYMERS

See "Thermoplasts."

## THERMOPLASTS

See also "Polymers" and individual thermoplasts. Thermoplasts arc thermoplastic polymers that can be repeatedly re-formed by the application of heat, similar to metallic materials. They are long-chain linear molecules that are easily formed by the application of heat and pressure at temperatures above a critical temperature referred to as the "glass temperature." Because of the ability to be re-formed by heat, these materials can be recycled.

The most common thermoplasts are shown in Table T.8 along with their abbreviations. Table T.9 lists the heat distortion temperatures of the common thermoplasts, while the tensile strengths are given in Table T.10 and the maximum operating temperatures are shown in Table T.11

See Ref. 14.

**Table T.8** Abbreviations Used for Plastics

| | |
|---|---|
| ABS | Acrylonitrile-butadiene-styrene |
| CPVC | Chlorinated polyvinyl chloride |
| ECTFE | Ethylene-chlorotrifluorethylene |
| FEP | Perfluoroethylenepropylene |
| HDPE | High-density polyethylene |
| PEEK | Polyetheretherketone |
| PES | Polyethersulfone |
| PFA | Perfluoroalkoxy |
| PA | Polyamide |
| PB | Polybutylene |
| PC | Polycarbonate |
| PF | Phenol formaldehyde |

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**Table T.8** Abbreviations Used for Plastics (Continued)

| | |
|---|---|
| PP | Polypropylene |
| PPS | Polyphenyl sulfide |
| PTFE | Polytetrafluoroethylene |
| PVC | Polyvinyl chloride |
| PVDC | Polyvinylidene chloride |
| PVDF | Polyvinylidene fluoride |
| UHMWPE | Ultra-high molecular weight polyethylene |

**Table T.9** Heat Distortion Temperature of the Common Plastics (°F/°C)

| | Pressure (psi) | | |
|---|---|---|---|
| Polymer | 66 | 264 | Melt point |
| PTFE | 250/121 | 132/56 | 620/327 |
| PVC | 135/57 | 140/60 | 285/141 |
| LDPE | — | 104/40 | 221/105 |
| UHMW PE | 155/68 | 110/43 | 265/129 |
| PP | 225/107 | 120/49 | 330/160 |
| PFA | 164/73 | 118/48 | 590/310 |
| FEP | 158/70 | 124/51 | 554/290 |
| PVDF | 248/148 | 235/113 | 352/178 |
| ECTFE | 240/116 | 170/77 | 464/240 |
| ETFE | 220/104 | 165/74 | 518/270 |
| PEEK | — | 320/160 | 644/340 |
| PES | — | 410/210 | — |
| PC | 280/138 | 265/129 | — |

**Table T.10** Tensile strength of Plastics at 73°F (25°C) at Break

| Plastic | Strength (psi) |
|---|---|
| PVDF | 8000 |
| ETFE | 6500 |
| PFA | 4000–4300 |
| ECTFE | 7000 |
| PTFE | 2500–6000 |
| FEP | 2700–3100 |
| PVC | 6000–7500 |
| PE | 1200–4550 |
| PP | 4500–6000 |
| UHMW PE | 5600 |
| PEEK | 13,200–23,800 |
| PES | 12,200–20,300 |
| PC | 10,000 |

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**Table T.11** Maximum Operating Temperature of the Common Thermoplasts

| Thermoplast | °F/°C |
|---|---|
| PVC | 140/160 |
| CPVC | 180/82 |
| HMW PE | 140/60 |
| UHMW PE | 180–220/82–104 |
| ABS | 140/60 |
| PP | 180–220/82–104 |
| PB | 220/104 |
| ECTFE | 300/149 |
| ETFE | 300/149 |
| FEP | 375/190 |
| PEEK | 480/250 |
| PES | 390/200 |
| PFA | 500/260 |
| PA | 212–250/100–121 |
| PC | 210–265/99–128 |
| PPS | 450/230 |
| PTFE | 450/230 |
| PVDF | 320/160 |

## THERMOSET COMPOSITES

Three general types of construction are used to produce thermoset composites to resist corrosion. They are hand-laid-up, filament-winding, and chop-hoop construction.

In hand-laid-up construction, a corrosion barrier of 100 mils (one layer C glass plus two layers of 1½ oz mat) is followed by a structural laminate of alternate layers of rove mat to the desired thickness. This is to provide the optimum in corrosion resistance, but it is not the lowest in cost.

Filament-winding construction starts with a 10-mil corrosion barrier as in hand- laid-up construction, followed by a structural laminate of filament winding to the desired thickness.

With chop-hoop construction, a corrosion barrier of 100 mils is followed by alternate layers of filament winding and chopped glass. The advantage is that the chopped layers provide extra axial strength.

All three methods rely on the corrosion barrier to provide protection for the structural laminate. Only the hand-laid-up construction lends itself to easy repair. When splits occur in the latter two constructions, they invariably follow the wind angle, making field repair difficult, since the corrosion barrier has been breached.

There are several corrosion-resistant laminate surfacing systems that are used. These are shown in the table.

| Type of surface layer | Thickness, mils | Description | Specific uses |
|---|---|---|---|
| Gel coat | 10–20, at times 60 | Unreinforced layer of resin | Commonly used on expoxy piping systems |
| Type C glass surface mat | 10–20 | 10-mil type C mat | Used with reinforcement for chemical plant applications |

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| Type of surface layer | Thickness, mils | Description | Specific uses |
|---|---|---|---|
| Organic veil | 10–20 | Dacron, acrylic, polypropylene, orlon | Good weathering properties, standard for hydrogen fluoride or caustic applications |
| Carbon mat | 3 | 0.2 oz/yd$^2$ | Provides high surface electrical conductivity |

## THERMOSET LAMINATES

See "Thermoset Composites."

## THERMOSET POLYMERS

Also see "Polymers."

Once formed, thermoset polymers, unlike the thermoplasts, cannot be heated to change their shape. Consequently, they cannot be recycled. These resins are initially liquid at room temperature and then by adding a catalyst or accelerator they are changed into a rigid product that sets or cures into its final shape. The thermoset resins are high-molecular-weight polymers that are reinforced with glass or other suitable material to provide mechanical strength. The most commonly used resins are the vinyl esters, epoxies, polyesters, and furans.

For reinforcing these polymers, fibrous glass in the F and C grades are the most commonly used. Other reinforcing materials used include boron nitride, carbon fiber, ceramic fibers, graphite jute, Kevlar, metallic wire or sheet, monacrylic fiber, polyester fiber, polypropylene fiber, quartz, sapphire whiskers, and S-grade glass.

The advantages of the thermosets are many. They

1. Are less expensive than the stainless steels.
2. Have a wide range of corrosion resistance.
3. Are light in weight.
4. Possess exceptional strength.
5. Do not require painting.
6. May be formulated to be fire retardant.

Unreinforced, unfilled thermoset polymers can corrode by several mechanisms. The type of corrosion can be divided into two main categories: physical and chemical.

Physical corrosion is the interaction of a thermoset polymer with its environment so that its properties are altered but no chemical reactions take place. The diffusion of a liquid into the polymer is a typical example. In many cases, physical corrosion is reversible, once the liquid is removed, the original properties are restored.

When a polymer absorbs a liquid or a gas resulting in plasticization or swelling of the thermoset network, physical corrosion has taken place. For a crosslinked thermoset, swelling caused by solvent absorption will be at a maximum when the solvent and polymer solubility parameters are exactly matched.

Chemical corrosion takes place when the bonds in the thermoset are broken by means of a chemical reaction with the polymer's environment. There may be more than one form of chemical corrosion taking place at the same time. Chemical corrosion is usually not reversible.

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As a result of chemical corrosion, the polymer itself may be affected in one or more ways. For example, the polymer may be embrittled, softened, charred, crazed, delaminated, discolored, dissolved, blistered, or swollen. All thermosets will be attacked in essentially the same manner. However, certain chemically resistant types suffer negligible attack or exhibit significantly lower rates of attack under a wide range of severely corrosive conditions. This is the result of the unequal molecular structure of the resins, including built-in protection of ester groups.

Cure of the resin plays an important part in the chemical resistance of the thermoset. Improper curing will result in a loss of corrosion-resistant properties. Construction of the laminate and the type of reinforcing used also affect the corrosion resistance of the laminate. The degree and nature of the bond between the resin and the reinforcement also plays an important role.

The various modes of attack affect the strength of the laminate in different ways, depending upon the environment, other service conditions, and the mechanisms or combination of mechanisms that are at work.

Some environments may weaken primary and/or secondary polymer linkages with resulting depolymerization. Other environments may cause swelling or microcracking, while still others may hydrolyze ester groupings or linkages. In certain environments, repolymerization can occur, with a resultant change in structure. Other results may be chain scission and decrease in molecular weight or simple solvent action. Attack or absorption at the interface between the reinforcing material and the resin will result in weakening.

In general, chemical attack on thermoset polymers is a go/no-go situation. With an improper environment, attack on the reinforced polyester will occur in a relatively short time. Experience has indicated that if an installation has operated successfully for 12 months, in all probability it will continue to operate satisfactorily for a substantial period of time.

Thermoset polymers are not capable of handling concentrated sulfuric acid (93%) and concentrated nitric acid. Pyrolysis or charring of the resin quickly occurs, so that within a few hours the laminate is destroyed. Polyesters and vinyls can handle 70% sulfuric acid for long periods of time.

The attack of aqueous solutions on reinforced thermosets occurs through hydrolysis, with water degrading bonds in the backbone of the resin molecules. The ester linkage is the most susceptible.

The attack by solvents is of a different nature. The solvent penetrates the resin matrix of the polymer through spaces between the polymer chains. Penetration between the polymer chains causes the laminate surface to swell, soften, and crack.

Organic compounds with carbon–carbon unsaturated double bonds, such as carbon disulfide, are powerful swelling solvents and show greater swelling action than their saturated counterparts. Smaller solvent molecules can penetrate a polymer matrix more effectively. The degree of similarity between solvent and resin is important. Slightly polar resins, such as the polyesters and the vinyl esters, are attacked by mildly polar solvents.

Generally, saturated, long-chain organic molecules, such as the straight-chain hydrocarbons, are handled well by the polyesters.

Orthophthalic, isophthalic, bisphenol, and chlorinated or brominated polyesters exhibit poor resistance to such solvents as acetone, carbon disulfide, toluene, trichloroethylene,

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trichloroethane, and methyl ethyl ketone. The vinyl esters show improved solvent resistance. Heat-cured epoxies exhibit better solvent resistance. However, the furan resins offer the best all-around solvent resistance.

Stress corrosion is another factor to consider. The failure rate of glass-reinforced composites can be significant. This is particularly true of composites exposed to the combination of acid and stress.

Under stress, an initial fiber fracture occurs, which is a tensile type of failure. If the resin matrix surrounding the failed fiber fractures, the acid is allowed to attack the next available fiber, which subsequently fractures. The process continues until total failure occurs.

See Refs. 7–9 and 14.

## THERMOSET REINFORCING MATERIALS

The purpose of adding reinforcing to the thermoset resins is to provide mechanical strength and dimensional stability, which is not possible with the resin alone. Physical and chemical characteristics of the structure can be modified by changing the quantity and/or type of reinforcing. The most widely used reinforcing material for use with thermosetting resins is fibrous glass (fiberglass). Although glass itself is over 3000 years old, fiberglass was not commercialized until 1939 at the New York World's Fair. Other reinforcing materials that also find application are the following:

Boron carbide
Silicon carbide
Carbon fiber
Ceramic fibers
Graphite
Polyester fibers
Aramid fibers
Polypropylene fibers
Acrylic fibers

Most composite materials manufactured use fiberglass for reinforcing. One of the main advantages in their use is that the fibers remain largely intact. The resin in liquid form can be made to flow around the fibers at room temperature and pressure. Any desired size or shape can be produced by building up layer by layer. Glass retains its strength only to a temperature of 752°F (400°C). Above this temperature, it is necessary to use another type of reinforcing material, such as boron, carbon, or silicon carbide. The dangers of asbestos (mesothelioma, etc.) have eliminated the use of asbestos as a reinforcing material, although it was widely used during the 1960s and 1970s.

### Properties of Reinforcing Materials

As mentioned previously, there is a relatively wide choice of materials that can be used for reinforcing. Of these materials, glass is the most often used where corrosion resistance is required. It is available in several grades.

#### *E-Glass*

This is a boroaluminosilicate glass with excellent water resistance, strength, low elongation, and reasonable cost. Practically all glass mat, continuous filaments, and woven rovings come from this source.

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### C-Glass

C-glass is a calcium aluminosilicate glass used for surfacing mats, flakes, or flake glass linings and for acid-resistant cloths. It has poor water resistance and carries a premium cost. Until the development of synthetic veils, 10-mil C-glass surfacing mats were widely used. It is available in 10, 15, 20, and 30 mil thicknesses.

### S-Glass

S-glass has excellent resistance to acids and water with exceptional strength, comparable to an aramid fiber. Because of its cost, which is several times greater than that of E-glass, it is not used in the corrosion industry.

### Boron Carbide

Boron carbide is used for applications at elevated temperatures or for those requiring high strength. It is used with epoxy resin to produce helicopter rotor blades that turn at high speed.

### Silicon Carbide

Silicon carbide is used as a reinforcing material for applications above 752°F (400°C). It is resistant to hydrochloric, sulfuric, hydrofluoric, and nitric acids but will be attacked by mixtures of hydrofluoric and nitric acids.

### Carbon Fibers

Carbon fibers are inert to most chemicals. Their use also imparts surface conductivity to FRP laminates. It is also used at temperatures above 752°F (400°C) to impart strength. Carbon fibers in epoxy resin provide compressor blades in lightweight jet engines.

In-depth grounding systems and static control in hazardous areas where static sparks may result in fires or explosions are provided when carbon fiber mat, either alone or in conjunction with graphite or ground carbon, is used for reinforcing.

### Graphite Fibers

Graphite fibers, like carbon fibers, are inert to most chemicals and produce an inert conductive pathway. Applications are the same as for carbon fibers.

### Polyester Fibers

Polyester is used primarily as a surfacing mat for the resin-rich inner surfaces of filament-wound or contact-molded structures. The nexus veil (registered trademark of Burlington Industries) possesses a relatively high degree of elongation that makes it compatible with the higher elongation resin and reduces the potential for checking, crazing, and cracking in temperature-cycling applications.

Nexus veiling exhibits excellent resistance to alcohols, bleaching agents, water, hydrocarbons, and aqueous solutions of most weak acids at boiling. It is not resistant to strong acids, such as 93% sulfuric acid.

### Aramid Fibers

The most popular aramid fiber is Kevlar (trademark of E.I. DuPont de Nemours). It is a high-strength fiber. As such, it is used in the manufacture of bulletproof vests, canoe and boat construction, and other areas where its high strength is required in the laminate. It is available both as a surfacing mat and in cloth form. Kevlar cloth is used occasionally as

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reinforcement for high-stress areas in the corrosion industry, such as the vertical corners of rectangular tanks.

### *Polypropylene Fibers*

Polypropylene fibers do not develop the strength of glass, but they do have a relatively wide range of corrosion resistance and are less expensive.

See Refs. 7 and 10.

## TIN COATINGS (TIN PLATE)

Tin plate is produced mainly by the electroplating process. Alkaline and acid baths are used in the production line. The acid baths are classified as either ferrostan or halogen baths.

A thermal treatment above the melting point of tin follows the electrolytic deposition. The intermetallic compound $FeSn_2$ forms at the interface between the iron and tin during this thermal processing. The corrosion behavior of the tin plate is determined by the quality of the $FeSn_2$ formed, particularly when the amount of the free tin is small. The best performing tin plate is that in which the $FeSn_2$ uniformly covers the steel so that the area of exposed iron is very small in case the tin should dissolve. Good coverage requires good and uniform nucleation of $FeSn_2$. Many nuclei form when electrodeposition of tin is carried out from the alkaline stannate bath.

Compared with either iron or tin, $FeSn_2$ is chemically inert to all but the strongest oxidizing environments.

Most of the tin plate (tin coating on steel) produced is used for the manufacture of food containers (tin cans). The nontoxic nature of tin salts makes tin an ideal material for the handling of food and beverages.

An inspection of the galvanic series will indicate that tin is more noble than steel and, consequently, the steel would corrode at the base of the pores. On the outside of a tinned container, this is what happens; the tin is cathodic to the steel. However, on the inside of the container, there is a reversal of polarity because of the complexing of the stannous ions by many food products. This greatly reduces the activity of the stannous ions, resulting in a change in the potential of tin in the active direction.

This change in polarity is absolutely necessary because most tin coatings are thin and therefore porous. To avoid perforation of the can, the tin must act as a sacrificial coating. Figure T.4 illustrates the reversal of activity between the outside and inside of the can.

The environment inside a hermetically sealed can varies depending upon the contents, which could include general foods, beverages, oils, aerosol products, liquid gases, etc. For example, pH values vary for different contents as shown below:

| | |
|---|---|
| Acidic beverage | 2.4–4.5 |
| Beer and wine | 3.5–4.5 |
| Meat, fish, marine products, and vegetables | 4.1–7.4 |
| Fruit juices, fruit products | 3.1–4.3 |
| Nonfood products | 1.2–1.5 |

The interior of a can is subject to general corrosion, localized corrosion, and discoloring. The coating system for tin plate consists of tin oxide, metallic tin, and alloy. The dissolution of the tin layer in acidic fruit products is caused by acids such as citric acid. In acidic

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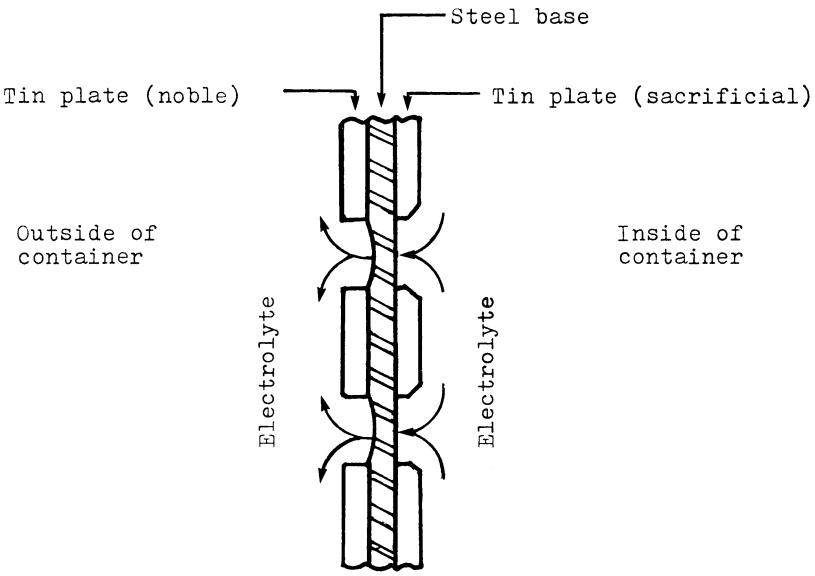



**Figure T.4** Tin acting as both a noble and a sacrificial coating on a "tin" can.

fruit products, the potential reversal occurs between the tin layer and the steel substrate, as shown in Fig. T.5. The potential reversal of a tin layer for steel substrate occurs at a pH range <3.8 in a citric acid solution. This phenomenon results from the potential shift of the tin layer to a more negative direction. Namely, the activity of the stannous ion, $Sn^{2+}$, is reduced by the formation of double complexes, and thereby the corrosion potential of the tin layer becomes more negative than that of steel. Thus, the tin layer acts as a sacrificial anode for steel so that the thickness and density of the pores in the tin layer are important factors affecting the service life of the coating. A thicker tin layer prolongs the service life of a tin can. The function of the alloy layer (FeSn) is to reduce the active area of steel by covering it, since it is inert in acidic fruit products. When some parts of the steel substrate are exposed, the corrosion of the tin layer is accelerated by galvanic coupling with the steel. The corrosion potential of the alloy layer is between that of the tin layer and that of the steel. A less defective layer exhibits potential closer to that of the tin layer. Therefore, the covering with alloy layer is important to decrease the dissolution of the tin layer.

In carbonated beverages, the potential reversal does not take place; therefore, the steel dissolves preferentially at the defects in the tin layer. Under such conditions, pitting corrosion sometimes results in perforation. Consequently, except for fruit cans, almost all tin plate cans are lacquered.

When tin plate is to be used for structural purposes, such as roofs, an alloy of 12–25 parts of tin to 88–75 parts of lead is frequently used. This is called terneplate. It is less expensive and more resistant to weather than a pure tin coating.

Terneplate exhibits excellent corrosion resistance, especially under wet conditions, with only small amounts of corrosion products forming. A thin nickel deposit can be applied as an undercoat for the terne layer. Nickel reacts rapidly with the tin–lead alloy to form a nickel–tin alloy layer. This layer provides good corrosion resistance and inhibits localized corrosion.

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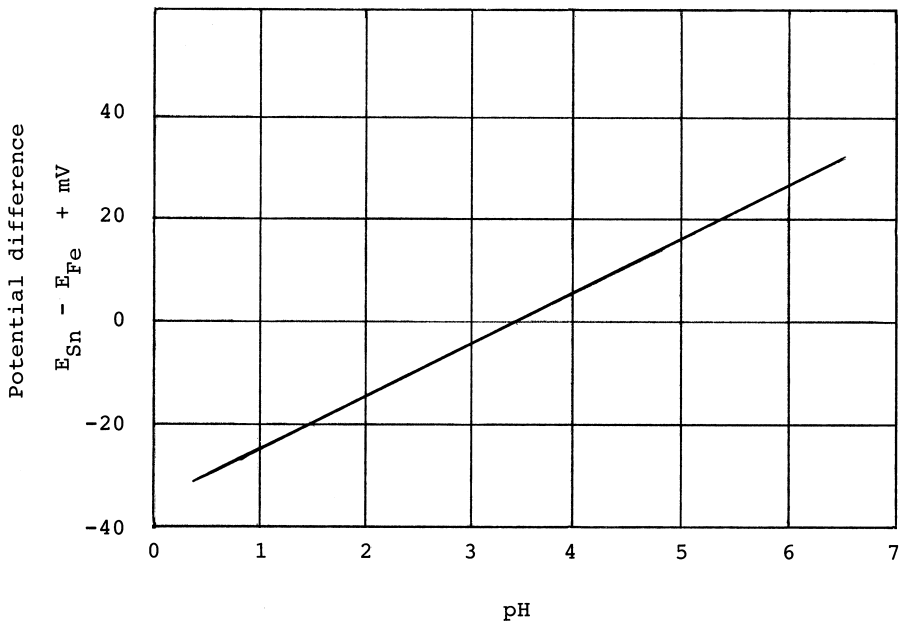



**Figure T.5** Potential reversal in tin plate.

Terneplate is used for fuel tanks of automobiles and is also used in the manufacture of fuel lines, brake lines, and radiators in automobiles.

See Refs. 11 and 12.

## TITANIUM

Titanium is the ninth most abundant element on earth and the fourth most abundant metal. It is more plentiful than chromium, copper, or nickel, which are commonly employed as alloys to resist corrosion. Titanium and its alloys are noted for their high strength-to-weight ratios and excellent corrosion resistance. Although the needs of the aerospace industry for better strength-to-weight ratio structured materials was recognized, little use was made of titanium until the commercialization of the Kroll process, which made titanium sponge available in about 1950.

Although it has the advantages of being highly corrosion resistant in oxidizing environments, a low density (specific gravity 4.5, approximately 60% that of steel), and a high tensile strength (60,000 psi), its widespread use has been limited somewhat by cost. However, as consumption has increased and new technologies have been developed to reduce the high cost, usage has increased and will probably continue to increase further. At the present time, it is competitive with nickel-base alloys. Thinner sections, coupled with decreased maintenance requirements and longer life expectancy in many applications, permit titanium equipment installations to be cost effective despite a higher initial cost. Increasing usage has been found in automotive applications, chemical processing equipment, pulp and paper industry, marine vehicles, medical prostheses, and sporting goods. Applications for some of the more popular alloys are shown in Table T.12.

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**Table T.12** Applications of Titanium Alloys

| Alloy | Applications |
|---|---|
| ASTM grade 12 | |
| UNS R53400 | Chemical process industries. Used in hot brines, heat exchangers, and chlorine cells. |
| ASTM grade 9 | |
| UNS R56320 | Chemical processing and handling equipment. Has high degree of immunity to attack by most mineral acids and chlorides, boiling seawater, and organic compounds. |
| UNS R54210 | Cryogenic applications. |
| UNS R56210 | Marine vehicle hulls. Has high fracture toughness. |
| TI 6211 and UNS R56400 | Aerospace industry, medical prostheses, marine equipment, chemical pumps, high performance automotive components. |
| ASTM grade 5 | |
| UNS R56400 | Golf club heads, auto parts, working tools. |
| UNS R58030 | Aircraft fasteners, springs, orthodontic appliances. |
| UNS R54810 | Airframe and turbines. |

The titanium alloys, unlike other nonferrous alloys, are not separated into wrought and cast categories. Most of the widely used casting alloys are based on the traditional wrought compositions.

Metallurgists have separated titanium alloys into categories according to the phases present:

1. Commercially pure or modified titanium
2. Alpha and near-alpha alloys
3. Alpha-beta alloys
4. Beta alloys

## TITANIUM ALLOYS

These alloys have strengths comparable to alloy steels, while the weight is only 60% that of steel. In addition, the corrosion resistance of titanium alloys is superior to aluminum and stainless steels under most conditions. Titanium's low magnetic permeability is also notable.

The chemical composition of unalloyed titanium grades and titanium alloys are covered by ASTM specifications. Table T.13 lists the compositions of representative grades. These alloys are all available in various product forms covered by ASTM specifications as shown in Table T.14.

**Table T.13** Chemical Composition of Titanium Alloys

| Element | Ti-50A[a] (ASTM grade 2) | Ti-6Al-V[a] (ASTM grade 5) | Ti-Pd (ASTM grade 7) | Ti-Code 12[a] (ASTM grade 12) |
|---|---|---|---|---|
| Nitrogen, max. | 0.03 | 0.05 | 0.03 | 0.03 |
| Carbon, max. | 0.10 | 0.10 | 0.10 | 0.08 |
| Hydrogen, max. | 0.015 | 0.015 | 0.015 | 0.015 |
| Iron, max. | 0.30 | 0.40 | 0.30 | 0.30 |
| Oxygen, max. | 0.25 | 0.20 | 0.25 | 0.25 |
| Aluminum | — | 5.5–6.75 | — | — |

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**Table T.13** Chemical Composition of Titanium Alloys (Continued)

| Element | Ti-50A[a] (ASTM grade 2) | Ti-6Al-V[a] (ASTM grade 5) | Ti-Pd (ASTM grade 7) | Ti-Code 12[a] (ASTM grade 12) |
|---|---|---|---|---|
| Vanadium | — | 3.5–4.5 | — | — |
| Palladium | — | — | 0.12–0.25 | — |
| Molybdenum | — | — | — | 0.2–0.4 |
| Nickel | — | — | — | 0.6–0.9 |
| Titanium | Remainder | Remainder | Remainder | Remainder |

[a]Timet designation.

**Table T.14** ASTM Titanium Specifications

| | |
|---|---|
| ASTM B 265-76 | Titanium and titanium alloy strip, sheet, and plate |
| ASTM B 337-76 | Seamless and welded titanium and titanium alloy pipe |
| ASTM B 338-76 | Seamless and welded titanium and titanium alloy tubes for condensers and heat exchangers |
| ASTM B 348-76 | Titanium and titanium alloy bars and billets |
| ASTM B 363-76 | Seamless and welded unalloyed titanium welding fittings |
| ASTM B 367-69 | (1974) Titanium and titanium alloy castings |
| ASTM B 381-76 | Titanium and titanium alloy forgings |

ASTM grades 1, 2, 3, and 4 cover unalloyed titanium. Grade 2 is most often used for corrosion resistance. Grade 1 possesses better ductility but lower strength; grades 3 and 4 possess higher strength.

Grade 7 alloy, compared with unalloyed titanium, possesses an improved corrosion resistance. This alloy, as grade 11, is used for improved formability.

Grade 12 is a lower-cost alternative to grades 7 and 11 and is suitable for some applications. The palladium of alloys 7 and 11 has been replaced with 0.8% nickel and 0.3% molybdenum.

Grade 5 is an alloy having high strength and toughness and is a general-purpose alloy finding numerous applications in the aerospace industry. Its corrosion resistance is inferior to the unalloyed grades.

The general properties of titanium alloys are shown in Table T.15.

**Table T.15** General Properties of Titanium Alloys

| ASTM grade | UNS no. | Properties |
|---|---|---|
| 1 (CP) | R50250 | Ductility, lower strength |
| 2 (CP) | R50400 | Good balance of moderate strength and ductility |
| 3 (CP) | R50550 | Moderate strength |
| 7 and 11 | R52400 | Improved resistance to reducing acids and |
| | R52250 | superior crevice corrosion resistance |
| 16 | — | Resistance similar to grade 7, but at lower cost |
| 12 | R53400 | Reasonable strength and improved crevice corrosion resistance; lower cost |
| 9 | R56320 | Medium strength and superior pressure code design allowances |
| 18 | — | Same as grade 9 but with improved resistance to reducing acids and crevice corrosion |
| 5 | R56400 | High strength and toughness |

CP = chemically pure.

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**Table T.16** Mechanical and Physical Properties of Titanium (Grade 2)

| | |
|---|---|
| Modulus of elasticity psi $\times 10^6$ | 14.9 |
| Tensile strength psi $\times 10^3$ | 50 |
| Yield strength 0.2% offset psi $\times 10^3$ | 40 |
| Elongation in 2 in., % | 20 |
| Density, lb/in.$^3$ | 0.163 |
| Specific gravity | 4.48 |
| Specific heat at 75°F, Btu/lb °F | 0.125 |
| Thermal conductivity at 75°F, Btu/ft$^2$/h/°F/in. | 114 |
| Coefficient of thermal expansion at 32–600°F, in./in. °F $\times 10^{-6}$ | 5.1 |

## Physical and Mechanical Properties

Titanium is a light metal with a density slightly over half that of iron- or copper-based alloys. The modulus of elasticity is also approximately half that of steel, while its specific heat and thermal conductivity are similar to those of stainless steel. Titanium has a low expansion coefficient, and a relatively high electrical resistivity.

The mechanical and physical properties are shown in Table T.16.

### *Types of Corrosion*

Titanium, like any other metal, is subject to corrosion in certain environments. The corrosion resistance of titanium is the result of a stable, protective, strongly adherent oxide film. This film forms instantly when a fresh surface is exposed to air or moisture. Additions of alloying elements to titanium affect the corrosion resistance because these elements alter the composition of the oxide film

The oxide film of titanium is very stable, though relatively thin, and is attacked by only a few substances, most notable of which is hydrofluoric acid. Because of its strong affinity for oxygen, titanium is capable of healing ruptures in this film almost instantly in any environment where a trace of moisture or oxygen is present.

Anhydrous conditions, in the absence of a source of oxygen, should be avoided because the protective film may not he regenerated if damaged. The protective oxide film of most metals is subject to being swept away above a critical water velocity. Once this takes place, accelerated corrosion attack occurs. This is known as erosion corrosion. For some metals, this can occur at velocities as low as 2 to 3 ft/s. The critical velocity for titanium in seawater is in excess of 90 ft/s. Numerous corrosion erosion tests have been conducted, and all have shown that titanium has outstanding resistance to this form of corrosion.

### *General Corrosion*

This form of corrosion is characterized by a uniform attack over the entire exposed surface of the metal. The severity of this kind of attack can be expressed by a corrosion rate. With titanium, this type of corrosion is most frequently encountered in hot reducing acid solutions. In environments where titanium would be subject to this type of corrosion, oxidizing agents and certain multivalent metal ions have the ability to passivate the titanium. Many process streams, particularly sulfuric and hydrochloric acid solutions, contain enough impurities in the form of ferric or cupric ions, etc., to passivate titanium and give trouble-free service.

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### Galvanic Corrosion

The coupling of titanium with dissimilar metals usually does not accelerate the corrosion of titanium. The exception is in reducing environments where titanium does not passivate. Under these conditions, titanium has a potential similar to aluminum and will undergo accelerated corrosion when coupled to more noble metals.

For most environments, titanium will be the cathodic member of any galvanic couple. It may accelerate the corrosion of the other member of the couple but in most cases the titanium will be unaffected. As a result of this, hydrogen will be evolved on the surface of the titanium proportional to the galvanic current flow. This may result in the formation of surface hydride films that are generally stable and cause no problems. However, if the temperature exceeds 170°F (77°C), hydriding can cause embrittlement.

The surest way to avoid problems with galvanic corrosion is to construct equipment of a single metal. If this is not practical, select two metals that are close in the galvanic series. If contact of dissimilar metals with titanium is necessary, the critical parts should be constructed of titanium, since this is not usually attacked.

### Hydrogen Embrittlement

The oxide film on titanium in most cases acts as an effective barrier to penetration by hydrogen. However, embrittlement can occur under conditions that allow hydrogen to enter titanium and exceed the concentration needed to form a hydride phase (about 100 to 150 ppm). Hydrogen absorption has been observed in alkaline solutions at temperatures above the boiling point. Acidic conditions that cause the oxide films to be unstable may also result in embrittlement under conditions in which hydrogen is generated on the titanium surface. In any event, it appears that embrittlement occurs only if the temperature is sufficiently high above 170°F (75°C) to allow hydrogen to diffuse into the titanium. Otherwise, if surface hydride films do form, they are not detrimental.

Gaseous hydrogen has had no embrittlement effects on titanium. The presence of as little as 2% moisture effectively prevents the absorption of molecular hydrogen up to a temperature as high as 600°F (315°C). This may reduce the ability of the titanium to resist erosion, resulting in a higher corrosion rate.

### Crevice Corrosion

Crevice corrosion of titanium is most often observed in hot chloride solutions. However, it has also been observed in bromide, iodide, and sulfate solutions.

Dissolved oxygen or other oxidizing species present in the solution are depleted in the restricted volume of solution in the crevice. These species are consumed faster than they can be replenished by diffusion from the bulk solution. As a result, the potential of the metal in the crevice becomes more negative than the metal exposed to the bulk solution. This establishes an electrolytic cell with the metal in the crevice acting as the anode and the metal outside the crevice acting as the cathode. Metal dissolves at the anode under the influence of the resulting current, Titanium chlorides formed in the crevice are unstable and tend to hydrolyze, forming small amounts of hydrochloric acid. This reaction is very slow at first, but in the very restricted volume of the crevice it can reduce the pH of the solution to a value as low as 1. This reduces the potential still further until corrosion becomes quite severe.

Alloying with elements such as nickel, molybdenum, or palladium improves the crevice corrosion resistance of titanium. Consequently, Ti-Code 12 and the titanium–palladium alloys are much more resistant to crevice corrosion than unalloyed titanium.

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### *Stress Corrosion Cracking (SCC)*

Unalloyed titanium with an oxygen content of less than 0.2% (ASTM grades 1 and 2) is susceptible to cracking only in absolute methanol and higher alcohols, certain liquid metals such as cadmium and possibly mercury, red fuming nitric acid, and nitrogen tetraoxide. The presence of halides in the alcohols accelerates cracking tendencies. The presence of water (>2%) tends to inhibit stress cracking in alcohols and red fuming nitric acid. Titanium is not recommended for use in these environments under anhydrous conditions.

## Corrosion Resistance

In general, titanium offers excellent resistance in oxidizing environments and poor resistance in reducing environments. It has excellent resistance to moist chlorine gas, chlorinated brines, and hypochlorites. Some corrosion rates for titanium in hypochlorite solutions are given in Table T.17. Titanium is not resistant to dry chlorine gas. It is attacked rapidly and can ignite and burn if the moisture content is sufficiently low. Approximately 1% water is required under static conditions at room temperature. Somewhat less is required if the chlorine is flowing. Approximately 1.5% water is required at 392°F (200°C).

Titanium is immune to all forms of corrosive attack in seawater and chloride salt solutions at ambient temperatures. It is also very resistant to attack in most chloride solutions at elevated temperatures.

Titanium offers excellent resistance to oxidizing acids such as nitric and chromic acids. It is not recommended for use in red fuming nitric acid, particularly if the water content is below 1.5% and the nitrogen dioxide content is above 2.5%. Pyrophoric reactions have occurred in this environment.

Titanium will be attacked by reducing acids such as hydrochloric, sulfuric, and phosphoric acids.

It is also quite resistant to organic acids that are oxidizing. Only a few organic acids are known to attack titanium; these are hot, nonaerated formic acid, hot oxalic acid, concentrated trichloracetic acid, and solutions of sulfamic acid.

Titanium is resistant to acetic acid, teraphthalic acid, and adipic acids. It also exhibits good resistance to citric, tartaric, carbolic, stearic, lactic, and tannic acids. Good corrosion resistance is also shown to organic compounds. In anhydrous environments when the temperature is high enough to cause dissociation of the organic compound, hydrogen embrittlement of the titanium is a consideration.

The compatibility of titanium with selected corrodents is given in Table T.18.

See Refs. 4 and 13.

**Table T.17** Corrosion of Titanium in Hypochlorite Solutions

| Environment | Temperature (°F) | Test duration (days) | Corrosion rate (mpy) | Pitting |
|---|---|---|---|---|
| 17% hypochlorous acid, with free chlorine and chlorine monoxide | 50 | 203 | < 0.1 | — |
| 16% sodium hypochlorite | 70 | 170 | < 0.1 | None |
| 18–20% calcium hypochlorite | 70–75 | 204 | Nil | None |
| 1.5–4% sodium hypochlorite, 12–15% sodium chloride, 1% sodium hydroxide | 150–200 | 72 | 0.1 | None |

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**Table T.18** Compatibility of Titanium, Zirconium, and Tantalum with Selected Corrodents[a]

| | Maximum temperature (°F/°C) | | |
|---|---|---|---|
| Chemical | Titanium | Zirconium | Tantalum |
| Acetaldehyde | 300/104 | 250/121 | 90/32 |
| Acetamide | | | |
| Acetic acid 10% | 260/127 | 220/104 | 302/150 |
| Acetic acid 50% | 260/127 | 230/110 | 302/150 |
| Acetic acid 80% | 260/127 | 230/110 | 302/150 |
| Acetic acid, glacial | 260/127 | 230/110 | 302/150 |
| Acetic anhydride | 280/138 | 250/121 | 302/150 |
| Acetone | 290/88 | 190/88 | 302/150 |
| Acetyl chloride | | 80/27 | 80/27 |
| Acrylic acid | | | |
| Acrylonitrile | 210/93 | 210/93 | 210/93 |
| Adipic acid | 450/232 | | 210/93 |
| Allyl alcohol | 200/93 | 200/93 | 300/149 |
| Allyl chloride | | 200/93 | |
| Alum | 200/93 | 210/99 | 90/32 |
| Aluminum acetate | | | |
| Aluminum chloride, aqueous | 10% | 40% | 302/150 |
| | 310/154 | 200/93 | |
| Aluminum chloride, dry | | 37% | |
| | 200/93 | 210/99 | 302/150 |
| Aluminum fluoride | 80/27 | x | x |
| Aluminum hydroxide | 190/88 | 200/93 | 100/38 |
| Aluminum nitrate | 200/93 | | 80/27 |
| Aluminum oxychloride | | | |
| Aluminum sulfate | 210/99 | 210/99 | 302/150 |
| Ammonia gas | | 200/38 | |
| Ammonium bifluoride | | | |
| Ammonium carbonate | 200/93 | | 200/93 |
| Ammonium chloride 10% | 210/99 | 210/99 | 302/150 |
| Ammonium chloride 50% | 190/88 | 220/104 | 302/150 |
| Ammonium chloride, sat. | 203/93 | | 302/150 |
| Ammonium fluoride 10% | 90/32 | x | x |
| Ammonium fluoride 25% | 80/27 | x | x |
| Ammonium hydroxide 25% | 80/27 | 210/99 | 302/150 |
| Ammonium hydroxide, sat. | 210/99 | 210/99 | 302/150 |
| Ammonium nitrate | 210/99 | 210/99 | 210/99 |
| Ammonium persulfate | 80/27 | 220/104 | 90/32 |
| Ammonium phosphate 10% | 210/99 | 210/99 | 302/150 |
| Ammonium sulfate 10–40% | 210/99 | 210/99 | 302/150 |
| Ammonium sulfide | | | 90/32 |
| Ammonium sulfite | | | 210/99 |
| Amyl acetate | 210/99 | 210/99 | 302/150 |
| Amyl alcohol | 200/93 | 200/93 | 320/160 |
| Amyl chloride | | 210/99 | 302/150 |
| Aniline | 210/99 | 210/99 | 210/99 |
| Antimony trichloride | 110/43 | | 210/99 |
| Aqua regia 3:1 | 80/27 | x | 302/150 |
| Barium carbonate | 80/27 | 210/99 | 90/32 |

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**Table T.18** Compatibility of Titanium, Zirconium, and Tantalum with Selected Corrodents[a] (Continued)

| | Maximum temperature (°F/°C) | | |
|---|---|---|---|
| Chemical | Titanium | Zirconium | Tantalum |
| Barium chloride 25% | 210/99 | 210/99 | 210/99 |
| Barium hydroxide | 210/99 | 200/93 | 302/150 |
| Barium sulfate | 210/99 | 210/99 | 210/99 |
| Barium sulfide | 90/32 | 90/32 | 90/32 |
| Benzaldehyde | 100/38 | 210/99 | 210/99 |
| Benzene | 230/110 | 230/110 | 230/110 |
| Benzene sulfonic acid 10% | | 210/99 | 210/99 |
| Benzoic acid | 400/204 | 400/204 | 210/99 |
| Benzyl alcohol | 210/99 | 210/99 | 210/99 |
| Benzyl chloride | | | 230/110 |
| Borax | 190/88 | | x |
| Boric acid | 210/99 | 210/99 | 300/149 |
| Bromine gas, dry | x | x | 302/150 |
| Bromine gas, moist | 190/88 | 60/16 | 302/150 |
| Bromine liquid | x | 60/16 | 570/299 |
| Butadiene | | | 80/27 |
| Butyl acetate | 210/99 | 210/99 | 80/27 |
| Butyl alcohol | 200/93 | 200/93 | 80/27 |
| *n*-Butylamine | 210/99 | | |
| Butyl phthalate | 210/99 | 210/99 | 210/99 |
| Butyric acid | 210/99 | 210/99 | 302/150 |
| Calcium bisulfide | | | |
| Calcium bisulfite | 210/99 | 90/32 | 80/27 |
| Calcium carbonate | 230/110 | 230/110 | 230/110 |
| Calcium chlorate | 140/60 | | 210/99 |
| Calcium chloride | 310/154 | 210/99 | 302/150 |
| Calcium hydroxide 10% | 210/99 | 210/99 | 302/150 |
| Calcium hydroxide, sat. | 230/110 | 210/99 | 302/150 |
| Calcium hypochlorite | 200/93 | 200/93 | 302/150 |
| Calcium nitrate | 210/99 | | 80/27 |
| Calcium oxide | | | |
| Calcium sulfate | 210/99 | 210/99 | 210/99 |
| Caprylic acid | 210/99 | 210/99 | 300/149 |
| Carbon bisulfide | 210/99 | | 210/99 |
| Carbon dioxide, dry | 90/32 | 410/210 | 310/154 |
| Carbon dioxide, wet | 80/27 | | 300/149 |
| Carbon disulfide | 210/99 | | 210/99 |
| Carbon monoxide | 300/149 | | |
| Carbon tetrachloride | | | 302/150 |
| Carbonic acid | 210/99 | 210/99 | 300/149 |
| Cellosolve | 210/99 | 210/99 | 210/99 |
| Chloracetic acid, 50% water | 210/99 | 210/99 | 210/99 |
| Chloracetic acid | 210/99 | 210/99 | 302/150 |
| Chlorine gas, dry | x | 90/32 | 460/238 |
| Chlorine gas, wet | 390/199 | x | 570/299 |
| Chlorine, liquid | | x | 300/149 |
| Chlorobenzene | 200/93 | 200/93 | 300/149 |
| Chloroform | 210/99 | 210/99 | 210/99 |

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**Table T.18** Compatibility of Titanium, Zirconium, and Tantalum with Selected Corrodents[a] (Continued)

| | Maximum temperature (°F/°C) | | |
|---|---|---|---|
| Chemical | Titanium | Zirconium | Tantalum |
| Chlorosulfonic acid | 210/99 | | 210/99 |
| Chromic acid 10% | 210/99 | 210/99 | 302/150 |
| Chromic acid 50% | 210/99 | 210/99 | 302/150 |
| Chromyl chloride | 60/16 | | 210/99 |
| Citric acid 15% | 210/99 | 210/99 | 302/150 |
| Citric acid, concentrated | 180/82 | 180/82 | 302/150 |
| Copper acetate | | 200/93 | 300/149 |
| Copper carbonate | 80/27 | | 300/149 |
| Copper chloride | 200/93 | x | 300/149 |
| Copper cyanide | 90/32 | x | 300/149 |
| Copper sulfate | 210/99 | 210/99 | 300/149 |
| Cresol | 210/99 | | |
| Cupric chloride 5% | 210/99 | x | 300/149 |
| Cupric chloride 50% | 210/99 | 190/88 | 90 /32 |
| Cyclohexane | | | |
| Cyclohexanol | | | |
| Dichloroacetic acid | 280/138 | 350/177 | 260/127 |
| Dichloroethane | | | |
| Ethylene glycol | 210/99 | 210/99 | 90/32 |
| Ferric chloride | 300/149 | x | 302/150 |
| Ferric chloride 50% in water | 210/99 | x | 302/150 |
| Ferric nitrate 10–50% | 90/32 | | 210/99 |
| Ferrous chloride | 210/99 | 210/99 | 210/99 |
| Ferrous nitrate | | | |
| Fluorine gas, dry | x | x | x |
| Fluorine gas, moist | x | x | x |
| Hydrobromic acid, dilute | 90/32 | 80/27 | 302/150 |
| Hydrobromic acid 20% | 200/93 | x | 302/150 |
| Hydrobromic acid 50% | 200/93 | x | 302/150 |
| Hydrochloric acid 20% | x | 300/149 | 302/150 |
| Hydrochloric acid 38% | x | 140/60 | 302/150 |
| Hydrocyanic acid 10% | | | |
| Hydrofluoric acid 30% | x | x | x |
| Hydrofluoric acid 70% | x | x | x |
| Hydrofluoric acid 100% | x | x | x |
| Hypochlorous acid | 100/38 | | 302/150 |
| Iodine solution 10% | 90/32 | | |
| Ketones, general | 90/32 | | |
| Lactic acid 25% | 210/99 | 300/149 | 302/150 |
| Lactic acid, concentrated | 300/149 | 300/149 | 300/149 |
| Magnesium chloride | 300/149 | | 302/150 |
| Malic acid | 210/99 | 210/99 | 210/99 |
| Manganese chloride 5–20% | 210/99 | 210/99 | 210/99 |
| Methyl chloride | 210/99 | | 210/99 |
| Methyl ethyl ketone | 210/99 | 210/99 | 210/99 |
| Methyl isobutyl ketone | 200/93 | 200/93 | 210/99 |
| Muriatic acid | x | | 302/150 |
| Nitric acid 5% | 360/182 | 500/260 | 302/150 |

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**Table T.18** Compatibility of Titanium, Zirconium, and Tantalum with Selected Corrodents[a] (Continued)

| | Maximum temperature (°F/°C) | | |
|---|---|---|---|
| Chemical | Titanium | Zirconium | Tantalum |
| Nitric acid 20% | 400/204 | 500/260 | 302/150 |
| Nitric acid 70% | 390/199 | 500/260 | 302/150 |
| Nitric acid, anhydrous | 210/99 | 90/32 | 302/150 |
| Nitrous acid, concentrated | | | 300/149 |
| Oleum | | | x |
| Perchloric acid 10% | x | | 302/150 |
| Perchloric acid 70% | x | 210/99 | 302/150 |
| Phenol | 90/32 | 210/99 | 302/150 |
| Phosphoric acid 50–80% | x | 180/82 | 302/150 |
| Picric acid | 90/32 | | 200/93 |
| Potassium bromide 30% | 200/93 | 200/93 | 90/32 |
| Salicylic acid | 90/32 | | 210/99 |
| Silver bromide 10% | | | 90/32 |
| Sodium carbonate | 210/99 | 210/99 | 210/99 |
| Sodium chloride | 210/99 | 250/121 | 302/150 |
| Sodium hydroxide 10% | 210/99 | 210/99 | x |
| Sodium hydroxide 50% | 200/93 | 200/93 | x |
| Sodium hydroxide, concentrated | 200/93 | 210/99 | x |
| Sodium hypochlorite 20% | 200/93 | 100/38 | 302/150 |
| Sodium hypochlorite, concentrated | | | 302/150 |
| Sodium sulfide to 10% | 210/99 | x | 210/99 |
| Stannic chloride 20% | 210/99 | 210/99 | 300/149 |
| Stannous chloride | 90/32 | | 210/99 |
| Sulfuric acid 10% | x | 300/149 | 302/150 |
| Sulfuric acid 50% | x | 300/149 | 302/150 |
| Sulfuric acid 70% | x | 210/99 | 302/150 |
| Sulfuric acid 90% | | | 302/150 |
| Sulfuric acid 98% | x | x | 302/150 |
| Sulfuric acid 100% | x | x | 300/149 |
| Sulfuric acid, fuming | x | | x |
| Sulfurous acid | 170/77 | 370/188 | 300/149 |
| Thionyl chloride | | | 300/149 |
| Toluene | 210/99 | 80/27 | 300/149 |
| Trichloroacetic acid | x | x | 300/149 |
| White liquor | | 250/121 | |
| Zinc chloride | | | 210/99 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable. When compatible, corrosion rate is <20 mpy.
*Source:* PA Schweitzer. *Corrosion Resistance Tables.* 4th ed. Vols. 1–3. New York: Marcel Dekker, 1995.

## TRANSGRANULAR CORROSION

Transgranular corrosion is a form of localized corrosion in the form of subsurface attack where a narrow path is corroded at random across the grain structure of a metal, disregarding the grain boundaries.

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**Table T.19** Range of Physical and Mechanical Properties of Triax Based on Formulation

| Property | Value | Units |
|---|---|---|
| Specific gravity | 1.06–1.07 | |
| Water absorption (immersion at 73°F (25°C) 24 h) | 1.1–1.5 | % |
| Tensile stress at yield | 4.3–6.3 | psi × $10^3$ |
| Tensile elongation at break | 1.4–3.6 | psi × $10^3$ |
| Tensile stress at break | 6.3–5.8 | psi × $10^3$ |
| Tensile modulus | 245–295 | psi × $10^3$ |
| Flexural modulus | 1.7–3.00 | psi × $10^2$ |
| Impact strength, notched | | |
| Izod, 0.125 in. thickness at 73°F (25°C) | 15–20 | ft-lb/in. |
| Deflection temperature | | |
| 0.125 in. thickness, 264 psi | 207–210 | ft-lb/in. |
| 0.125 in. thickness, 66 psi | 183–144 | ft-lb/in. |

## TRIAX

Triax is the trademark for Bayer's polyamide/acrylonitrile-butadiene-styrene thermoplastic alloy. It has high impact strength, excellent abrasion characteristics, good chemical resistance, and good fatigue performance. The range of physical and mechanical properties that can be achieved through formulation are shown in Table T.19. See "Polyamides" and "Acrylonitrile-Butadiene-Styrene."

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# U

## ULTRASONIC MEASUREMENT

Ultrasonic measurement is one method used to determine the effects of corrosion. Special equipment is required for ultrasonic measurements, and there are several types. The three types of equipment available are the A-scan, the B-scan, and the C-scan systems. The A-scan provides a simple depth measurement from the exterior surface of a pipe or vessel to the next interface that reflects sound waves. Generally, this measures wall thickness, but the A-scan can be fooled occasionally by mid-wall pipe flaws.

B-scan instruments are more powerful, since they produce cross-sectional images similar to x-rays.

The C-scan instruments produce a three-dimensional view of a surface using complex and expensive equipment. C-scan systems can be very useful for large critical surfaces such as aircraft skins but are less likely to be used in process plants at this time because of cost, speed of coverage, and the very large quantity of data produced.

## ULTRAVIOLET LIGHT DEGRADATION

Polymeric materials in outdoor applications are exposed to weather extremes that can be extremely deleterious to the material. The most harmful weather component, exposure to ultraviolet (UV) radiation, can cause embrittlement, fading, surface cracking, and chalking. After exposure to direct sunlight for a period of years, most polymers exhibit reduced impact resistance, lower overall mechanical performance, and a change in appearance.

The electromagnetic energy from sunlight is normally divided into ultraviolet light, visible light, and infrared energy. Infrared energy consists of wavelengths longer than visible red wavelengths and starts above 760 nanometers (nm). Visible light is defined as radiation between 400 and 760 nm. Ultraviolet (UV) light consists of radiation below 400 nm. The UV portion of the spectrum is further divided into UV-A, UV-B, and UV-C. The effects of the various wavelengths are shown in Table U.1.

**Table U.1** Wavelength Regions of the UV Spectrum

| Region | Wavelength (nm) | Characteristics |
|---|---|---|
| UV-A | 400–315 | Causes polymer damage. |
| UV-B | 315–280 | Includes the shortest wavelengths found at the earth's surface. Causes severe polymer damage. Absorbed by window glass. |
| UV-C | 280–100 | Filtered by the earth's atmosphere. Found only in outer space. |



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Since UV light is easily filtered out by air masses, cloud cover, pollution, and other factors, the amount and spectrum of natural UV exposure is extremely variable. Because the sun is lower in the sky during the winter months, it is filtered through a greater air mass. This creates two important differences between summer and winter sunlight: changes in the intensity of the light and in the spectrum. During the winter months, much of the damaging short-wavelength UV light is filtered out. For example, the intensity of UV at 320 nm changes about 8 to 1 from summer to winter. In addition, the short-wavelength solar cutoff shifts from approximately 295 nm in summer to approximately 310 nm in winter. As a result, materials sensitive to UV below 320 nm, would degenerate only slightly, if at all, during the winter months.

Photochemical degradation is caused by photons or light breaking chemical bonds. For each type of chemical bond there is a critical threshold wavelength of light with enough energy to cause a reaction. Light of any wavelength shorter than the threshold can break a bond, but longer wavelengths of light cannot break it. Therefore, the short-wavelength cutoff of a light source is of critical importance. If a particular polymer is sensitive only to UV light below 295 nm (the solar cutoff point), it will never experience photochemical deterioration outdoors.

The ability to withstand weathering varies with the polymer type and among grades of a particular resin. Many resin grades are available with UV-absorbing additives to improve weatherability. However, the higher-molecular-weight grades of resin generally exhibit better weatherability than lower-molecular-weight grades with comparable additives. In addition, some colors tend to weather better than others.

## ULTRAVIOLET STABILIZER

An ultraviolet stabilizer is any material added to a plastic that helps the plastic resist degradation from exposure to sunlight and ultraviolet radiation.

## UNDERFILM CORROSION

Underfilm corrosion is corrosion that occurs under paint coatings and other organic films at exposed edges or due to filiform corrosion. See "Filiform Corrosion."

## UNIFIED NUMBERING SYSTEM

Identification of metallic alloys is covered by the unified numbering system (UNS), whereby an alloy identification number begins with a letter followed by a five-digit number. For stainless steels most of the old AISI designations were retained as the first three digits of the UNS number, such that the old type 304 stainless steel is designated S30400, with S being used for all stainless steels. Copper and copper alloys are designated by C, high-nickel alloys by N, titanium alloys by R with digits in the 50 thousand range and zirconium alloys by R with digits in the 60 thousand range.

Typical UNS designations are as shown in the table.

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| Alloy | UNS number | Reference |
|---|---|---|
| Coppers (minimum of 99.3% copper) | C10200 through C14200 | 1, 2 |
| High-copper alloys (minimum of 96% copper if in wrought form and 94% copper in cast form) | C17000 through C19400 | 1, 2 |
| Brasses | C27000 through C68700 | 1, 2 |
| Tin bronzes (phosphor bronzes) | | |
| wrought | C51000 through C54400 | 1, 2 |
| cast | C90300 through C94700 | 1, 2 |
| Aluminum bronzes | | |
| wrought | C60800 through C63200 | 1, 2 |
| cast | C95200 through C95800 | 1, 2 |
| Copper-nickel | | |
| wrought | C70600 through C71900 | 1, 2 |
| cast | C96200 through C96400 | 1, 2 |
| Stainless steels (ferritic) | | |
| 405 | S40500 | 3 |
| 409 | S40900 | 3 |
| 430 | S43000 | 3 |
| 446 | S44600 | 3 |
| Stainless steels (martensitic) | | |
| 410 | S41000 | 3 |
| 416 | S41600 | 3 |
| 440 | S44000 | 3 |
| Stainless steels (austenitic) | | |
| 201 | S20100 | 3 |
| 303 | S30300 | 3 |
| 304 | S30400 | 3 |
| 304L | S30403 | 4 |
| 321 | S32100 | 3 |
| 347 | S34700 | 3 |
| 316L | S31603 | 4 |
| 316 | S31600 | 3 |
| 317 | S31700 | 4 |
| 317L | S31703 | 4 |
| 321 | S32100 | 4 |
| Duplex stainless steels | | |
| 329 | S32900 | 4 |
| 2205 | S31803 | 4 |
| 255 | S32550 | 4 |
| 2507 | S32750 | 3 |
| Precipation-hardening stainless steels | | |
| 17-4PH | S17400 | 4 |
| 17-7PH | S17700 | 4 |
| 15-7Mo | S15700 | 4 |
| Specialty grades of stainless steels | | |
| 317 LM | S31725 | 4 |
| 317 LN | S31753 | 4 |
| 254 SMO | S31254 | 4 |
| High-nickel alloys | | |
| 800 | N08800 | 4 |
| 20Cb3 | N08020 | 4 |
| 367 XN | N08367 | 4 |

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| Alloy | UNS number | Reference |
|---|---|---|
| 825 | N08825 | 4 |
| 904 L | N08904 | 4 |
| alloy 28 | N08028 | 4 |
| 20 Mod | N08320 | 4 |
| 20Mo4 | N08024 | 4 |
| 20Mo6 | N08026 | 4 |
| alloy G | N06007 | 4 |
| alloy G-3 | N06985 | 4 |
| alloy G-30 | N06030 | 4 |
| Titanium alloys | | |
| Ti 50A | R50400 | 5 |
| Ti 6A14V | R56400 | 5 |
| TiPd | R52400 | 5 |
| Ti code 12 | R53400 | 5 |
| Zirconium alloys | | |
| Zr702 | R60702 | 6 |
| Zr705 | R60705 | 6 |
| Zr704 | R60704 | 6 |
| Zr706 | R60706 | 6 |
| Zircalloy 2 | R60802 | 6 |
| Zircalloy 4 | R60804 | 6 |
| Zr2.5Nb | R60901 | 6 |

## UNIFORM CORROSION

A metal resists corrosion by forming a passive film on the surface. This film is formed naturally when the metal is exposed to air for a period of time. It can also be formed more quickly by a chemical treatment. For example, nitric acid if applied to an austenitic stainless steel will form this protective film. Such a film is actually a form of corrosion, but once formed it prevents the further degradation of the metal, as long as the film remains intact. It does not provide an overall resistance to corrosion, since it may be subject to chemical attack. The immunity of the film to attack is a function of the film composition, the temperature, and the aggressiveness of the chemical. Examples of such films are the patina formed on copper, the rusting of iron, the tarnishing of silver, the fogging of nickel, and the high-temperature oxidation of metals.

### Passive Films

There are two theories regarding the formation of these films. The first theory states that the film formed is a metal oxide or other reaction compound. This is known as the "oxide film theory." The second theory states that oxygen is adsorbed on the surface, forming a chemisorbed film. However, all chemisorbed films react over a period of time with the underlying metal to form metal oxides. Oxide films are formed at room temperature. Metal oxides can be classified as network formers, intermediates, or modifiers. This division can be related to thin oxide films on metals. The metals that fall into network-forming or intermediate classes tend to grow protective oxides that support anion or mixed anion/cation movement. The network formers are neocrystalline, while the intermediates tend to be microcrystalline at low temperatures.

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### Passive Film on Iron

Iron in iron oxides can assume a valence of 2 or 3. The former acts as a modifier and the latter as a network former. The iron is protected from the corrosion environment by a thin oxide film 1–4 mm in thickness with a composition of $\sqrt{Fe_2O_3}/Fe_3O_4$. This is the same type of film formed by the reaction of clean iron with oxygen in dry air. The $\sqrt{Fe_2O_3}$ layer is responsible for the passivity, while the $Fe_3O_4$ provides the basis for the formation of a higher oxidizing state. Iron is more difficult to passivate than nickel because with iron it is not possible to go directly to the passivation species $\sqrt{Fe_2O_3}$. Instead, a lower oxidation state of $Fe_3O_4$ is required, and this film is highly susceptible to chemical dissolution. The $\sqrt{Fe_2O_3}$ layer will not form until the $Fe_3O_4$ phase has existed on the surface for a reasonable period of time. During this time the $Fe_3O_4$ layer continues to form.

### Passive Film on Nickel

The passive film on nickel can be achieved quite readily, in contrast to the formation of the passive film on iron. Differences in the nature of the oxide film on iron and nickel are responsible for this phenomenon. The film thickness on nickel is between 0.9 and 1.2 mm, while the iron oxide film is between 1.5 and 4.5 mm. There are two theories as to exactly what the passive film on nickel is. It is either entirely NiO with a small amount of nonstoichiometry giving rise to $Ni^{3+}$ and cation vacancies, or it consists of an inner layer of NiO and an outer layer of anhydrous $Ni(OH)_2$. The passive oxide film on nickel, once formed, cannot be easily removed by either cathodic treatment or chemical dissolution.

The passive film formed on nickel will not protect the nickel in oxidizing environments, such as nitric acid. When alloyed with chromium, a much-improved stable film results, producing a greater corrosion resistance to a variety of oxidizing media. However, these alloys are subject to attack in environments containing chloride or other halides, especially if oxidizing agents are present. Corrosion will be in the form of pitting. The addition of molybdenum or tungsten will improve the corrosion resistance.

### Passive Film on Austenitic Stainless Steel

The passive film formed on stainless steel is duplex in nature, consisting of an inner-barrier oxide film and an outer deposit hydroxide of salt film. Passivation takes place by the rapid formation of surface-absorbed hydrated complexes of metals which are sufficiently stable on the alloy surface that further reaction with water enables the formation of a hydroxide phase that rapidly deteriorates to form an insoluble surface oxide film. The three most commonly used austenite stabilizers, nickel, manganese, and nitrogen, all contribute to the passivity. Chromium, a major alloying ingredient, is in itself very corrosion resistant and is found in greater abundance in the passive film than iron, which is the majority element in the alloy.

### Passive Film on Copper

When exposed to the atmosphere over long periods of time, copper will form a coloration on the surface known as patina, which in reality is a corrosion product that acts as a protective film against further corrosion. When first formed, the patina has a dark color that gradually turns green. The length of time required to form the patina depends on the atmosphere because the coloration is given by copper hydroxide compounds. In a marine

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atmosphere the compound is a mixture of copper hydroxide, and sulfate. These compounds will form in approximately seven years. In a clean rural atmosphere, tens or hundreds of years may be required for patina to form.

### *Passive Film on Aluminum*

Aluminum forms a thin, compact, and adherent oxide film on the surface that limits further corrosion. When formed in air at atmospheric temperature, it is approximately 5 mm thick. If formed at elevated temperatures or in the presence of water or water vapor, it will be thicker. This oxide film is stable in the pH range of 4–9. With a few exceptions, the film will dissolve at lower or high pH ranges. Exceptions are concentrated nitric acid (pH 1) and concentrated ammonium hydroxide (pH 13). In both cases the oxide film is stable.

The oxide film is not homogeneous and contains weak points. Breakdown of the oxide film at weak points leads to localized corrosion. With increasing alloy content and on heat-treatable alloys, the oxide film becomes more homogeneous.

### *Passive Film on Titanium*

Titanium forms a stable, protective, strongly adherent oxide film. This film forms instantly when a fresh surface is exposed to air or moisture. Addition of alloying elements to titanium affect the corrosion resistance because these elements alter the composition of the oxide film.

The oxide film of titanium is very thin and is attacked by only a few substances, most notably hydrofluoric acid. Because of its strong affinity for oxygen, titanium is capable of healing ruptures in this film almost instantly in any environment when a trace of moisture or oxygen is present.

### *Passive Film on Tantalum*

When exposed to oxidizing or slightly anodic conditions, tantalum forms a thin, impervious layer of tantalum oxide. This passivating oxide has the broadest range of stability with regard to chemical attack or thermal breakdown compared with other metallic films. Chemicals or conditions that attack tantalum, such as hydrofluoric acid, are those that penetrate or dissolve the oxide film.

## Uniform Corrosion Rates

When exposed to a corrosion medium, metals tend to enter into a chemical union with the elements of the corrosion medium, forming stable compounds similar to those found in nature. When metal loss occurs in this manner, the compound formed is referred to as the corrosion product and the metal surface is referred to as being corroded. An example of such an attack is that of halogens, particularly chlorides. They will react with and penetrate the film on stainless steel, resulting in general corrosion. Corrosion tables are developed to indicate the interaction between a chemical and a metal. This type of attack is termed uniform corrosion. It is one of the most easily measured and predictable forms of corrosion. Many references exist that report average or typical rates of corrosion for various metals in common media. One such source is Ref. 8.

Since corrosion is so uniform, corrosion rates for materials are often expressed in terms of metal thickness lost per unit of time. One common expression is mils per year

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(mpy); sometimes millimeters per year is used. Because of its predictability, low rates of corrosion are often tolerated, and catastrophic failures are rare if planned inspections and monitoring are implemented. For most chemical process equipment and structures, general corrosion rates of less than 3 mpy are considered acceptable. Materials with rates between 2 and 20 mpy are routinely considered useful engineering materials for the given environment. In severe environments, materials exhibiting high general corrosion rates between 20 and 50 mpy might be considered economically justifiable. Materials that exhibit rates of general corrosion beyond this are usually unacceptable. It should be remembered that in addition to the metal loss, where the metal is going must be considered. Contamination of product, even at low concentrations, can be more costly than replacement of the corroded component.

Uniform corrosion is generally viewed in terms of metal loss due to chemical attack or dissolution of the metallic component onto metallic ions. In high-temperature situations uniform loss is more commonly preceded by its combination with another element than by its oxidation to a metallic ion. Combination with oxygen to form metallic oxide, or scale, results in loss of the material in its useful engineering form, as it ultimately flakes off to return to nature.

To determine the corrosion rate, a prepared specimum is exposed to the test environment for a period of time and then removed to determine how much metal has been lost. The exposure time, weight loss, surface area exposed, and density of the metal are used to calculate the corrosion rate of the metal using the formula

$$\text{mpy} = \frac{22.273\text{WL}}{DAT}$$

where

WL = weight loss, g; $A$ = area, in.$^2$; $D$ = density, g/cm$^3$; and $T$ = time, days.

The corrosion rates calculated from the formula or taken from the tables will assist in determining how much corrosion allowance should be included in the design based on the expected lifetime of the equipment.

To convert from mpy to ipy (inches per year), divide the mpy value by 1000. On occasion the uniform rate of attack will be reported as milligrams per square decimeter per day (mdd). Converting from ipy to mdd or vice versa requires knowledge of the metal density. Conversion factors are given in Table U.2.

**Table U.2** Conversion Factors from Inches per Year (ipy) to Milligrams per Square Decimeter per Day (mdd)[a]

| Metal | Density (g/cc) | $\frac{0.00144}{\text{density}}$ ($\times 10^{-3}$) | 696 × density |
|---|---|---|---|
| Aluminum | 2.72 | 0.529 | 1890 |
| Brass (red) | 8.75 | 0.164 | 6100 |
| Brass (yellow) | 8.47 | 0.170 | 5880 |
| Cadmium | 8.65 | 0.167 | 6020 |
| Columbium | 8.4 | 0.171 | 5850 |
| Copper | 8.92 | 0.161 | 6210 |

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**Table U.2** Conversion Factors from Inches per Year (ipy) to Milligrams per Square Decimeter per Day (mdd)[a] (Continued)

| Metal | Density (g/cc) | $\frac{0.00144}{\text{density}}$ ($\times 10^{-3}$) | 696 × density |
|---|---|---|---|
| Copper–nickel (70/30) | 8.95 | 0.161 | 6210 |
| Iron | 7.87 | 0.183 | 5480 |
| Duriron | 7.0 | 0.205 | 4870 |
| Lead (chemical) | 11.35 | 0.127 | 7900 |
| Magnesium | 1.74 | 0.826 | 1210 |
| Nickel | 8.89 | 0.162 | 6180 |
| Monel | 8.84 | 0.163 | 6140 |
| Silver | 10.50 | 0.137 | 7300 |
| Tantalum | 16.6 | 0.0868 | 11550 |
| Titanium | 4.54 | 0.317 | 3160 |
| Tin | 7.29 | 0.198 | 5070 |
| Zinc | 7.14 | 0.202 | 4970 |
| Zirconium | 6.45 | 0.223 | 4490 |

[a]Multiply ipy by (696 × density) to obtain mdd. Multiply mdd by (0.00144/density) to obtain ipy.

## URETHANE (AU) RUBBERS

The urethane rubbers are produced from a number of polyurethane polymers. The properties exhibited are dependent upon the specific polymer and the compounding. Urethane (AU) rubber is a unique material that combines many of the advantages of rigid plastics, metals, and ceramics yet still has the extensibility and elasticity of rubber. It can be formulated to provide a variety of products with a wide range of physical properties.

Composition with a Shore A hardness of 95 (harder than a typewriter platen) are elastic enough to withstand stretching to more than four times their own lengths.

At room temperature a number of raw polyurethane polymers are liquid, simplifying the production of many large and intricately shaped molded products. When cured, these elastomeric parts are hard enough to be machined on standard metalworking equipment. Cured urethane does not require fillers or reinforcing agents.

### Physical and Mechanical Properties

The urethane rubbers are known for their toughness and durability. Because of the high resistance to abrasion, urethane rubbers are used where severe wear is a problem. Urethane rubber, in actual service, has outworn ordinary rubbers and plastics by a factor as high as 8 to 1. One such application is that of wearpads used to prevent the marring of multi-ton rolls of sheet metal.

Most applications use material with a hardness of from 80 Shore A to 75 Shore D. The D scale is used to measure hardnesses greater than 95 Shore A. Most elastomers have hardnesses between 30 and 80 on the A scale, while structural plastics begin at 55 on the D scale. It can be seen that the urethane rubbers bridge this gap.

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Depending upon the formulation, resilience values as low as 15% or as high as 80% can be achieved. Urethane rubbers operate through the range of 50–212°F (10–100°C). This stability is valuable in certain shock mounting applications.

Specific polymers and/or formulations of these rubbers can produce appreciably better impact resistance than structural plastics. Standard compounds, including the hardest types, exhibit good low-temperature impact resistance and low brittle points.

Urethane has a low unlubricated coefficient of friction that decreases sharply as hardness increases. This property, combined with its abrasion resistance and load-carrying ability, is an important reason why urethane elastomer is used in bearings and bushings. If necessary, special compounding can lower the coefficient of friction even further.

### Applications

The versality of urethane has led to a wide variety of applications. Products made from urethane rubber are available in three basic forms: solid, cellular, and films and coatings.

Included under the solid category are those products that are cast or molded, comprising such items as large rolls, impellers, abrasion-resistant parts for textile machines, O-rings, electrical encapsulations, gears, tooling pads, and small intricate parts.

Cellular products are such items as shock mountings, impact mountings, shoe soles, contact wheels for belt grinders, gaskets, and other similar items.

It is possible to apply uniform coatings or films of urethane rubber to a variety of substrate materials, including metal, glass, wood, fabrics, and paper. Examples of products to which a urethane film or coating is often applied are tarpaulins, bowling pins, pipe linings, tank linings, and exterior coatings for protection against atmospheric corrosion. These films also provide abrasion resistance.

Filtration units, clarifiers, holding tanks, and treatment sumps constructed of reinforced concrete are widely used in the treatment of municipal, industrial, and thermal generating station wastewater. In many cases, particularly in anaerobic, industrial, and thermal generating systems, urethane linings are used to protect the concrete from severe chemical attack and prevent seepage into the concrete of chemicals that can attack the reinforcing steel. These linings provide protection from abrasion and erosion and act as a waterproofing system to combat leakage of the equipment resulting from concrete movement and shrinkage.

The use of urethane rubbers in manufactured products has been established as a result of their high tensile and tear strengths, resiliency, impact resistance, and load-bearing capacity. Other products made from urethane rubbers include bearings, gear couplings, mallets and hammers, solid tires, conveyor belts, and many other miscellaneous items.

See Ref. 7.

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# V

## VAPOR

Vapor is the gaseous state of matter that normally exists in a liquid or solid state. It also applies to gas close to the liquid state, e.g., water in the atmosphere. The terms gas and vapor are often used interchangeably.

## VAPOR BARRIER

A vapor barrier is a coating or layer that prevents the passage of vapor or moisture into a material or structure.

## VAPOR CORROSION

Contaminants in the atmosphere such as sulfur dioxide, nitrogen-containing compounds, hydrogen chloride, phenol, hydrogen sulfide, nitric acid, ammonia, and other, similar materials act as stimulants to atmospheric corrosion. This acceleration to corrosion is known as vapor corrosion. Refer to "Atmospheric Corrosion."

## VAPOR PHASE CORROSION INHIBITORS

Vapor phase corrosion inhibitors are solid or liquid volatile organic compounds with corrosion-inhibitive behaviors. These compounds have a significantly high vapor pressure at room temperature. They are used within sealed enclosures to protect metallic articles. The most common organic compounds used are dicyclohexylamine nitrite and cyclohexylamine carbonate. Refer to "Corrosion Inhibitors."

## VERDIGRIS

Verdigris is the green patina of basic copper salts formed on copper due to atmospheric corrosion. The basic copper salts are primarily basic carbonate, basic sulfate, and in some cases the basic chloride. Refer to "Copper and Copper Alloys."

## VINYL ESTER RESINS

Also see "Polymers" and "Thermoset Polymers." There are a wide variety of vinyl ester resins. As a result, there can be a difference in the compatibility of formulations between manufacturers. When checking compatibility tables, it must be kept in mind that all formulations may not act as shown. An indication that vinyl ester is compatible



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generally means that at least one formulation is compatible. The resin manufacturer must be checked to verify the resistance.

In general vinyl esters can be used to handle most hot, highly chlorinated, and acidic mixtures at elevated temperatures. They also provide excellent resistance to strong mineral acids and bleaching solutions. The vinyl esters excel in alkaline and bleach environments and are used extensively in the very corrosive conditions found in the pulp and paper industry. Refer to Table V.1 for the compatibility of the vinyl esters with a wide range of selected corrodents. Reference 1 provides a wider range of compatibilities.

See also Refs. 2–4.

**Table V.1** Compatibility of Vinyl Ester with Selected Corrodents[a]

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Acetaldehyde | x | x | Ammonium sulfate 10–40% | 220 | 104 |
| Acetamide | | | Ammonium sulfide | 120 | 49 |
| Acetic acid 10% | 200 | 93 | Ammonium sulfite | 220 | 104 |
| Acetic acid 50% | 180 | 82 | Amyl acetate | 110 | 43 |
| Acetic acid 80% | 150 | 66 | Amyl alcohol | 210 | 99 |
| Acetic acid, glacial | 150 | 66 | Amyl chloride | 120 | 49 |
| Acetic anhydride | 100 | 38 | Aniline | x | x |
| Acetone | x | x | Antimony trichloride | 160 | 71 |
| Acetyl chloride | x | x | Aqua regia 3:1 | x | x |
| Acrylic acid | 100 | 38 | Barium carbonate | 260 | 127 |
| Acrylonitrile | x | x | Barium chloride | 200 | 93 |
| Adipic acid | 180 | 82 | Barium hydroxide | 150 | 66 |
| Allyl alcohol | 90 | 32 | Barium sulfate | 200 | 93 |
| Allyl chloride | 90 | 32 | Barium sulfide | 180 | 82 |
| Alum | 240 | 116 | Benzaldehyde | x | x |
| Aluminum acetate | 210 | 99 | Benzene | x | x |
| Aluminum chloride, aqueous | 260 | 127 | Benzene sulfonic acid 10% | 200 | 93 |
| Aluminum chloride, dry | 140 | 60 | Benzoic acid | 180 | 82 |
| Aluminum fluoride | 100 | 38 | Benzyl alcohol | 100 | 38 |
| Aluminum hydroxide | 200 | 93 | Benzyl chloride | 90 | 32 |
| Aluminum nitrate | 200 | 93 | Borax | 210 | 99 |
| Aluminum oxychloride | | | Boric acid | 200 | 93 |
| Aluminum sulfate | 250 | 121 | Bromine gas, dry | 100 | 38 |
| Ammonia gas | 100 | 38 | Bromine gas, moist | 100 | 38 |
| Ammonium bifluoride | 150 | 66 | Bromine liquid | x | x |
| Ammonium carbonate | 150 | 66 | Butadiene | | |
| Ammonium chloride 10% | 200 | 93 | Butyl acetate | 80 | 27 |
| Ammonium chloride 50% | 200 | 93 | Butyl alcohol | 120 | 49 |
| Ammonium chloride, sat. | 200 | 93 | *n*-Butylamine | x | x |
| Ammonium fluoride 10% | 140 | 60 | Butyl phthalate | 200 | 93 |
| Ammonium fluoride 25% | 140 | 60 | Butyric acid | 130 | 54 |
| Ammonium hydroxide 25% | 100 | 38 | Calcium bisulfide | | |
| Ammonium hydroxide, sat. | 130 | 54 | Calcium bisulfite | 180 | 82 |
| Ammonium nitrate | 250 | 121 | Calcium carbonate | 180 | 82 |
| Ammonium persulfate | 180 | 82 | Calcium chlorate | 260 | 127 |
| Ammonium phosphate | 200 | 93 | Calcium chloride | 180 | 82 |

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**Table V.1** Compatibility of Vinyl Ester with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Calcium hydroxide 10% | 180 | 82 | Fluorine gas, moist | x | x |
| Calcium hydroxide, sat. | 180 | 82 | Hydrobromic acid, dilute | 180 | 82 |
| Calcium hypochlorite | 180 | 82 | Hydrobromic acid 20% | 180 | 82 |
| Calcium nitrate | 210 | 99 | Hydrobromic acid 50% | 200 | 93 |
| Calcium oxide | 160 | 71 | Hydrochloric acid 20% | 220 | 104 |
| Calcium sulfate | 250 | 116 | Hydrochloric acid 38% | 180 | 82 |
| Caprylic acid | 220 | 104 | Hydrocyanic acid 10% | 160 | 71 |
| Carbon bisulfide | x | x | Hydrofluoric acid 30% | x | x |
| Carbon dioxide, dry | 200 | 93 | Hydrofluoric acid 70% | x | x |
| Carbon dioxide, wet | 220 | 104 | Hydrofluoric acid 100% | x | x |
| Carbon disulfide | x | x | Hypochlorous acid | 150 | 66 |
| Carbon monoxide | 350 | 177 | Iodine solution 10% | 150 | 66 |
| Carbon tetrachloride | 180 | 82 | Ketones, general | x | x |
| Carbonic acid | 120 | 49 | Lactic acid 25% | 210 | 99 |
| Cellosolve | 140 | 60 | Lactic acid, concentrated | 200 | 93 |
| Chloracetic acid | 200 | 93 | Magnesium chloride | 260 | 127 |
| Chloracetic acid, 50% water | 150 | 66 | Malic acid 10% | 140 | 60 |
| Chlorine gas, dry | 250 | 121 | Manganese chloride | 210 | 99 |
| Chlorine gas, wet | 250 | 121 | Methyl chloride | | |
| Chlorine liquid | x | x | Methyl ethyl ketone | x | x |
| Chlorobenzene | 110 | 43 | Methyl isobutyl ketone | x | x |
| Chloroform | x | x | Muriatic acid | 180 | 82 |
| Chlorosulfonic acid | x | x | Nitric acid 5% | 180 | 82 |
| Chromic acid 10% | 150 | 66 | Nitric acid 20% | 150 | 66 |
| Chromic acid 50% | x | x | Nitric acid 70% | x | x |
| Chromyl chloride | 210 | 99 | Nitric acid, anhydrous | x | x |
| Citric acid 15% | 210 | 99 | Nitrous acid 10% | 150 | 66 |
| Citric acid, concentrated | 210 | 99 | Oleum | x | x |
| Copper acetate | 210 | 99 | Perchloric acid 10% | 150 | 66 |
| Copper carbonate | | | Perchloric acid 70% | x | x |
| Copper chloride | 220 | 104 | Phenol | x | x |
| Copper cyanide | 210 | 99 | Phosphoric acid 50–80% | 210 | 99 |
| Copper sulfate | 240 | 116 | Picric acid | 200 | 93 |
| Cresol | x | x | Potassium bromide 30% | 160 | 71 |
| Cupric chloride 5% | 260 | 127 | Salicylic acid | 150 | 66 |
| Cupric chloride 50% | 220 | 104 | Silver bromide 10% | | |
| Cyclohexane | 150 | 66 | Sodium carbonate | 180 | 82 |
| Cyclohexanol | 150 | 66 | Sodium chloride | 180 | 82 |
| Dichloroacetic acid | 100 | 38 | Sodium hydroxide 10% | 170 | 77 |
| Dichloroethane (ethylene dichloride) | 110 | 43 | Sodium hydroxide 50% | 220 | 104 |
| Ethylene glycol | 210 | 99 | Sodium hydroxide, concentrated | | |
| Ferric chloride | 210 | 99 | Sodium hypochlorite 20% | 180 | 82 |
| Ferric chloride 50% in water | 210 | 99 | Sodium hypochlorite, concentrated | 100 | 38 |
| Ferric nitrate 10–50% | 200 | 93 | Sodium sulfide to 50% | 220 | 104 |
| Ferrous chloride | 200 | 93 | Stannic chloride | 210 | 99 |
| Ferrous nitrate | 200 | 93 | Stannous chloride | 200 | 93 |
| Fluorine gas, dry | x | x | Sulfuric acid 10% | 200 | 93 |

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**Table V.1** Compatibility of Vinyl Ester with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. °F | °C | Chemical | Maximum temp. °F | °C |
|---|---|---|---|---|---|
| Sulfuric acid 50% | 210 | 99 | Sulfurous acid 10% | 120 | 49 |
| Sulfuric acid 70% | 180 | 82 | Thionyl chloride | x | x |
| Sulfuric acid 90% | x | x | Toluene | 120 | 49 |
| Sulfuric acid 98% | x | x | Trichloroacetic acid 50% | 210 | 99 |
| Sulfuric acid 100% | x | x | White liquor | 180 | 82 |
| Sulfuric acid, fuming | x | x | Zinc chloride | 180 | 82 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. A blank space indicates that data are unavailable.
*Source:* PA Schweitzer. *Corrosion Resistance Tables,* Vols 1 and 2. New York: Marcel Dekker, 1991.

## VINYLIDENE FLUORIDE ELASTOMERS (HFP, PVDF)

Polyvinylidene fluoride (PVDF) is a homopolymer of 1,1-difluorethene with alternating $CH_2$ and $CF_2$ groups along the polymer chain. These groups impart a unique polarity that influences its solubility and electrical properties. The polymer has the characteristic stability of fluoropolymers when exposed to aggressive thermal, chemical, and ultraviolet conditions.

In general, PVDF is one of the easiest fluoropolymers to process, and it can be easily recycled without affecting its physical and chemical properties. As with other elastomeric materials, compounding can be used to improve certain specific properties. Cross-linking of the polymer chain and control of the molecular weight are also done to improve particular properties.

PVDF possesses mechanical strength and toughness, high abrasion resistance, high thermal stability, high dielectric strength, high purity, resistance to most chemicals and solvents, resistance to ultraviolet and nuclear radiation, resistance to weathering, and resistance to fungi. It can be used in applications intended for repeated contact with food per Title 21, Code of Federal Regulations, Chapter 1, Part 177.2520. PVDF is also permitted for use in processing or storage areas in contact with meat or poultry food products prepared under federal inspection according to the U.S. Department of Agriculture (USDA). Use is also permitted under "3-A Sanitary Standards for Multiple-Use Plastic Materials Used as Product Contact Surfaces for Dairy Equipment Serial No. 2000." This material has the ASTM designation of MFP.

### Physical and Mechanical Properties

PVDF elastomers have high tensile and impact strengths. The ambient-temperature tensile strength at yield of 4000–7000 psi (28–48 MPa) and the unnotched impact strength, 15–80 ft-lb/in. (800–4270 kJ/m), indicate that all grades of this polymer are strong and tough. These properties are retained over a wide temperature range.

Excellent resistance to creep and fatigue are also exhibited by PVDF, while thin sections such as films, filament, and tubing are flexible and transparent. PVDF wire insulation has excellent resistance to cut-through. Where load bearing is important, these polymers are rigid and resistant to creep under mechanical load. Resistance to deformation under load is extremely good over the temperature range of –112 to 302°F (–80 to 150°C).

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PVDF finds application as thin-wall primary insulation and as a jacket for control wiring as a result of its high dielectric strength and good mechanical properties. Because of its high dissipation factor, PVDF has limited use at high frequencies. However, this property becomes an advantage in components utilizing dielectric heating techniques.

In order for PVDF to burn, it is necessary to have a 44% oxygen environment. The Underwriters Laboratories give PVDF a vertical burn rating of 94-V-O. PVDF is fire resistant and self-extinguishing.

PVDF will not support the growth of fungi. However, if additives that will support the growth of fungi are used in compounding, then fungicides should also be added to overcome this problem.

Because of its extremely low weight loss when exposed to high vacuum, PVDF can be used in high-vacuum applications. At 212°F (100°C) and a pressure of $5 \times 10^{-6}$ torr, the measured rate of weight loss is $13 \times 10^{-11}$ g/cm$^2$-s.

PVDF can also be pigmented.

The physical and mechanical properties of PVDF are given in Table V.2.

**Table V.2** Physical and Mechanical Properties of Vinylidene Fluoride (PVDF) Elastomer[a]

| | |
|---|---|
| Specific gravity | 1.76–1.78 |
| Refractive index | 1.42 |
| Specific heat, Btu/lb-°F | 0.30–0.34 |
| Brittle point | –80°F (–62°C) |
| Coefficient of linear expansion | |
| per °F | $7.8 \times 10^{-5}$ |
| per °C | $1.4 \times 10^{-4}$ |
| Thermal conductivity | |
| Btu-in/h-ft$^2$ °F | 0.70–0.87 |
| cal/cm$^2$-s-°C | $3 \times 10^{-4}$ |
| Dielectric strength, kV/mm | 63–67 |
| Dielectric constant at 77°F (23°C) | |
| at 100 Hz, ohm-cm | 9.9 |
| at 1 kHz, ohm-cm | 9.3 |
| at 100 kHz, ohm-cm | 8.5 |
| Tensile strength, psi | 4000–7000 |
| Elongation, % at break | 25–650 |
| Hardness, Shore A | 77–83 |
| Abrasion resistance, Armstrong (ASTM D 1242) 30-lb load volume loss, cm$^3$ | 0.3 |
| Maximum temperature, continuous use | 302°F (150°C) |
| Impact resistance, Izod notched, ft-lb/in. | 3–18 |
| Compression set | Good |
| Machining qualities | Excellent |
| Resistance to sunlight | Excellent |
| Effect of aging | Nil |
| Resistance to heat | Good |

[a]These are representative values since they may be altered by compounding.

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PVDF is suitable for applications where load-bearing characteristics are important, particularly at elevated temperatures. Long-term deflections at 140°F (60°C) with a load of 172 psi vary from 0.8% to 119%, while at 194°F (90°C) with a load of 530 psi the deflection ranges from 1.2% to 3.6%.

PVDF has a wide useful temperature range with a brittle point at –80°F (–62°C) and a maximum continuous operating temperature of 302°F (150°C). Over this entire range its properties remain virtually unaffected.

Special formulations are available for use in plenum cable applications. These formulations produce products having impact strengths of 12–18 ft-lb/in. and elongations of 400–650%. They also have improved stress crack resistance.

### Resistance to Sun, Weather, and Ozone

PVDF is highly resistant to the effects of sun, weather, and ozone. Its mechanical properties are retained while the percent elongation to break decreases to a lower level and then remains constant.

### Chemical Resistance

In general, PVDF is completely resistant to chlorinated solvents, aliphatic solvents, weak bases and salts, strong acids, halogens, strong oxidants, and aromatic solvents. Strong bases will attack the material.

The broader molecular weight of PVDF gives it a greater resistance to stress cracking than many other materials, but it is subject to stress cracking in the presence of sodium hydroxide.

PVDF also exhibits excellent resistance to nuclear radiation. The original tensile strength is essentially unchanged after exposure to 1000 Mrad of gamma irradiation from a cobalt-60 source at 122°F (50°C) and in high vacuum ($10^{-6}$ torr). Because of crosslinking, the impact strength and elongation are slightly reduced. This resistance makes PVDF useful in plutonium reclamation operations.

### Applications

PVDF finds many applications where its corrosion resistance, wide allowable operating temperature range, mechanical strength and toughness, high abrasion resistance, high dielectric strength, and resistance to weathering, ultraviolet light, radiation, and fungi are useful.

In the electrical and electronics fields PVDF is used for multi-wire jacketing, plenum cables, heat-shrinkable tubing, anode lead wire, computer wiring, and cable and cable ties. Because of its acceptance in the handling of foods and pharmaceuticals, transfer hoses are lined with PVDF. Its corrosion resistance is also a factor in these applications.

In fluid-handling systems PVDF finds applications as gasketing material, valve diaphragms, and membranes for microporous filters and ultrafiltration.

As a result of its resistance to fungi and its exceptional corrosion resistance, it is also used as the insulation material for underground anode bed installations.

See Refs. 1 and 5.

## VITON

See “Fluoroelastomers.”

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## VITREOUS ENAMEL

See "Glass Linings."

## VITREOUS ENAMEL COATINGS

Vitreous enamels, glass linings, or porcelain enamels are all essentially glass coatings that have been fused on metals. Powdered glass is applied to a pickled or otherwise prepared metal surface and heated in a furnace at a temperature that softens the glass and permits it to bond to the metal. Several thin coats are applied to provide the required final thickness. These coatings are normally applied to steel, but some coatings can be applied to brass, aluminum, and copper.

There are many glass formulations, but those with very high silica (>96% $S_1O_2$), aluminosilicate, and borosilicate compositions have the highest corrosion resistance to a wide range of corrosive environments. Glass is assumed to be inert to most liquids, but in reality it slowly dissolves.

The greatest danger of failure of a glass coating comes from mechanical damage or from cracking as a result of thermal shock. Thus, care must be taken in handling glassed equipment so as not to damage the lining, and sudden temperature changes in the operation must be avoided, particularly cold shock, which poses a greater danger of failure than hot shock.

Cold shock is the sudden introduction of a cold material onto a hot glassed surface; hot shock is the reverse. Manufacturers of this type of equipment will specify the maximum allowable thermal shock. These precautions must be followed.

See "Glass Linings."

## VITRIFIED CLAY PIPE

Vitrified clay pipe is virtually impervious to every chemical except hydrofluoric acid. It was and still is used for the handling of sewage. With the advent of the problems of cleaning up toxic dumps and landfills, new applications have arisen. The primary reasons for using clay pipe in these new applications are that it

1. Is chemically inert, unaffected by sewer gases and acids
2. Is rigid and will not flatten or sag
3. Is rustproof
4. Is unaffected by harsh household cleaning compounds and solvents
5. Withstands the extra stresses of heavy backfill loads
6. Will not soften or swell under any conditions
7. Is durable, will not roughen, erode, or wear out
8. Is unaffected by gases and acids generated by ground garbage
9. Is made impervious through vitrification

Vitrified clay pipe is presently being used to conduct the leachate from Love Canal to holding tanks for processing.

Though salt-glazed pipe may be used for sanitary sewers, unglazed pipe should be employed when handling industrial wastes. Clay pipe is normally applied for gravity flow lines. However, they should be designed for heads of 5–10 feet to guard against the possibility of blockage or of the sudden or abrupt introduction of material into the line. Table V.3 provides the compatibility of vitrified clay with selected corrodents.

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**Table V.3** Compatibility of Vitrified Clay with Selected Corrodents[a]

| Chemical | Maximum temperature (°F/°C) |
|---|---|
| Acetic acid 5% | 150/66 |
| Acetone | 73/23 |
| Aluminum chloride | x |
| Aluminum sulfate 5% | 150/66 |
| Ammonium chloride 5% | 150/66 |
| Ammonium chloride 10% | x |
| Ammonium chloride 25% | x |
| Ammonium hydroxide 5% | 73/23 |
| Ammonium hydroxide 10% | 73/23 |
| Aniline | 73/23 |
| Benzene | 73/23 |
| Borax 3% | 150/66 |
| Carbon tetrachloride | 73/23 |
| Chromic acid 40% | 150/66 |
| Citric acid 10% | 150/66 |
| Copper sulfate 3% | 150/66 |
| Ferric chloride 1% | 150/66 |
| Hydrochloric acid 10% | 120/49 |
| Hydrofluoric acid 30% | x |
| Hydrofluoric acid 70% | x |
| Hydrofluoric acid 100% | x |
| Nitric acid 1% | 150/66 |
| Nitric acid 10% | 150/66 |
| Nitric acid 20% | 150/66 |
| Sodium carbonate 20% | 150/66 |
| Sodium chloride 30% | 150/66 |
| Sodium hydroxide 10% | 150/66 |
| Sulfuric acid 20% | 150/66 |
| Sulfuric acid 30% | 150/66 |
| Toluene | 120/49 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown with an x.

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# W

## WATERLINE ATTACK

When a metal is partially submerged in an aqueous system with air above the metal, it undergoes simultaneous differential aeration cell and crevice corrosion at the waterline junction. This is referred to as waterline attack.

## WEATHERING

Weathering is the process of decomposition and disintegration from the chemical action of sunlight, frost, water, and heat resulting from exposure to the atmosphere.

It is also a method of removing mill scale from heavy structural steel members by exposing them outdoors for a period of several months to allow mill scale to crack off under the stress of expansion and contraction.

## WEATHERING STEELS

When small amounts of copper, chromium, nickel, phosphorus, silicon, manganese, or various combinations thereof are added to conventional carbon steel, a low-alloy carbon steel results that has an improved corrosion resistance. These steels are known as weathering steels. The corrosion resistance of these steels is dependent upon the climatic conditions, the pollution levels, the degree of sheltering from the atmosphere, and the specific composition of the steel.

Upon exposure to most atmospheres, the corrosion rate becomes stabilized within 3 to 5 years. A dark brown to violet patina, or protective film, develops over this period. This patina is a rust formation that is tightly adhered to the surface and cannot be wiped off. In rural areas with little or no pollution, a longer period may be required to form this protective film. In areas that are highly polluted with $SO_2$, the weathering steels exhibit a much higher corrosion rate, and loose rust particles are formed. Under these conditions, the film formed offers little to no protection.

These steels will not produce this protective film in marine environments where chlorides are present. Corrosion rates will be as high as for conventional carbon steels.

The formation of the patina is dependent upon a series of wet and dry periods, because periodic flushing followed by a period of drying is necessary. In areas where the steel is sheltered from the rain, the dark patina is not formed. In its place, a layer of rust in lighter colors forms, which has the same effect. With continued exposure to wetness, such as in water or soil, the corrosion rate for the weathering steels is equal to that of plain carbon steel.



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Because the patina formed has a pleasant aesthetic appearance, the weathering steels can be used without the application of any protective coating of antirust paint, zinc, or aluminum. This is particularly true in urban or rural areas.

When employing these weathering steels, design consideration should be given to the elimination of possible areas where water, dirt, and corrosion products can accumulate. If pockets are present, the time of wetness will be increased, which will lead to the development of corrosive conditions. The design should make maximum use of exposure to the weather. Sheltering from rain should be avoided.

The designer should also be aware that during the period over which this protective film is forming, rusting will proceed at a relatively high rate, during which time rusty water is produced. This rusty water may stain masonry, pavements, and the like. In view of this, precautions should be taken to prevent detrimental staining effects, such as coloring the masonry brown so that any staining will not be obvious.

The weathering steels are used primarily for buildings, bridges, structures, and guard rails.

## WELD RUSTING

Locally chromium depleted iron–nickel alloys are subject to slow rusting by mildly acidic liquids, such as the weld metal rusting of stainless steel by dew (containing dissolved carbon dioxide) condensing on the outside of a pipe. Even though this is primarily an aesthetic problem, in some applications it would be unacceptable. If chlorides are present, such corrosion could become aggresive because of the formation of ferric chloride.

## WET STORAGE STAIN

Wet storage stain, or white rust, is a white, crumbly, and porous coating that forms on zinc. It occurs in storage where there is access for water but limited supply of oxygen and carbon dioxide. The presence of chlorides and sulfates accelerates wet storage stain formation. This coating of white rust is not protective and consists of $2ZnCO_3 \cdot 3Zn(OH)_2$ together with ZnO and voluminous $\beta$-$Zn(OH_2)$. The surface underneath the white products is often dark gray.

The coating is usually found on newly galvanized bright surfaces and particularly in crevices between closely packed sheets, angle bars, etc. if the surfaces come into contact with condensate or rain water and the moisture cannot dry up quickly. Zinc surfaces that have a normal protective layer of corrosion product are seldom attacked.

When zinc or zinc coatings corrode in open air, zinc hydroxide and zinc oxide are normally formed. When the supply of air to the surface is restricted, as in a narrow crevice, there is insufficient carbon dioxide to allow the formation of a zinc carbonate layer.

Zinc oxide and zinc hydroxide layers are voluminous and porous and adhere only loosely to the zinc surface. As a result, the zinc surface is not protected against oxygen in the water. Corrosion can therefore proceed as long as there is moisture on the surface.

When wet storage staining has taken place, the objects should be arranged to allow their surfaces to dry rapidly. The attack will stop, and since there is a free supply of air to the surfaces, the normal protective layer of corrosion products can be washed off.

Chromating or phosphating will supply short-term protection. Painting after galvanizing also provides protection. The most effective way to prevent wet storage stain is by

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preventing new zinc surfaces from coming into contact with rain or condensate water during storage and transport. Materials stored outdoors should be arranged so that water can easily run off the surfaces. Refer to Fig. Z.1.

Also refer to "White Rust."

## WHITE IRON

When cooled, the carbon in white iron forms a hard, abrasion-resistant, iron–chromium carbide, instead of forming free graphite. White irons are used primarily for abrasive applications. They are very brittle. There is very little difference in corrosion resistance between the white irons and gray irons. The high chromium content provides only slightly better corrosion resistance. See "Cast Iron."

See Refs. 1 and 2.

## WHITE RUST

White rust is the name applied to zinc corrosion products that appear as a white to dirty gray deposit found on galvanized steel surfaces below the waterline, when exposed to recirculated water. The deposit is zinc carbonate, which does not form a protective film on the galvanized surface. Because of this, the white rust corrosion will continue until all of the protective zinc is entirely removed from the base metal.

White rust occurs when galvanized steel or zinc is exposed to water having a pH value above 8.2. The alkalinity of the water and the presence of any accelerating agents such as phosphates or phosphonates will govern the rate of corrosion. Higher alkalinity and the presence of accelerating agents will increase the corrosion rate.

Prevention of white rust is possible by maintaining pH control to hold the alkalinity level below the critical 8.2 and by the use of inhibitors. See "Wet Storage Stain."

## WOOD

Wood is a naturally formed organic material composed of cells arranged in a parallel manner. The chemical composition of the woody cell walls is approximately 40% to 50% cellulose, 15% to 30% lignin, less than 1% mineral, 25% to 35% hemicellulose, and the remainder extractable matter of various types. Softwoods and hardwoods contain approximately the same cellulose content.

Timber is classified as hardwood and softwood. Hardwood comes from the broad-leaved trees such as oak, maple, and ash. Softwood is the product of coniferous trees such as pines, birch, spruce, and hemlock. The terms hardwood and softwood have no relation to the actual hardness of the wood.

Sapwood is the living wood on the outside of the stem. Heartwood is the inner core of physiologically inactive wood in the tree. Heartwood is usually darker in color than sapwood.

Wood is relatively inert chemically but is readily dehydrated by concentrated solutions and consequently shrinks badly when subjected to the actions of such solutions. It is slowly hydrolyzed by acids and alkalies, particularly when hot. In tank construction, if sufficient shrinkage takes place to permit crystals to form between the staves, it becomes

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very difficult to make the tank tight again. Wood can be impregnated to resist acids or alkalies and the effects of high temperatures.

Wood deteriorates from two principal causes, chemical and biological attack. The chemical resistance of the wood is dependent upon the ability of the wood's cell walls to resist chemical action, and the extent that the chemical penetrates into the wood.

Wood is most resistant to chemical attack in the pH range of 2 through 9, and in certain conditions can be used up to a pH of 11. Wood is resistant to weak acids, but concentrated mineral acids tend to hydrolyze the cellulose and hemicellulose constituents. The lignin in the wood that binds the fibers together is attacked by oxidizing agents such as ozone. Strong oxidizing agents such as nitric acid, chromates, potassium permanganate, and chlorinated water can also oxidize the cellulose. Aqueous solutions of sodium hydroxide, nitric acid, sulfuric acid, and hydrochloric acid can cause the most damage, since swelling and degradation are simultaneous.

Wood can be used to handle dilute hydrochloric acid (<5%) and sulfuric acids at ambient temperature, phosphoric acid up to 30% at ambient temperature, organic acids, aldehydes, alcohols, and acid salts.

Various types of wood are used depending upon the service. Cypress is used for general chemical service; redwood and fir are used for sulfite liquors from the pulp and paper industries; pine is used in acid mine waters, dilute mineral acids, and mildly alkaline solutions; maple because of its hardness is used for abrasive slurries; oak is used to store and age whiskey and wine; and redwood, red cedar, Douglas fir, and various pines are generally used for cooling towers and many chemical exposures.

Biological deterioration of wood is caused by aquatic organisms, insects, and fungi. This deterioration can be delayed or prevented by pressure treating the wood with creosote or some other preservative.

## WORM TRACK CORROSION

This is another name for "Filiform Corrosion."

## WROUGHT IRON

Wrought iron is a highly refined form of iron containing less than 0.03% carbon and with 1% to 3% slag which is evenly distributed throughout the material in threads and fibers so that the product has a fibrous structure quite dissimilar to that of crystalline cast iron. It is a mechanical mixture of slag and low-carbon steel. Wrought iron generally rusts less readily than other forms of metallic iron. See "Cast Irons."

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# Z

## ZINC AND ZINC ALLOYS

Zinc as a pure metal finds relatively few applications because of its poor mechanical properties. It is relatively weak. The single largest use of zinc is in the application of zinc coatings (galvanizing) to permit the most efficient use of steel and to conserve energy.

### Corrosion of Zinc

Depending upon the nature of the environment, zinc has the ability to form a protective layer made up of basic carbonates, oxides, or hydrated sulfates. Once the protective layers have formed, corrosion proceeds at a greatly reduced rate. Consideration of the corrosion of zinc is primarily related to show general dissolution from the surface. Even air is only slightly corrosive to zinc. Below 390°F (200°C) the film grows very slowly and is very adherent. Zinc-coated steel behaves similarly to pure zinc.

The pH of the environment governs the film. Within the pH range of 6 to 12.5 the corrosion rate is low. Corrosive attack is most severe at pH values below 6 and above 12.5.

Uniform corrosion rates of zinc are not appreciably affected by the purity of zinc. However, the addition of some alloying elements can increase the corrosion resistance of zinc.

### White Rust (Wet Storage Stain)

White rust is a form of general corrosion that is not protective. It is more properly called wet storage stain because it occurs in storage where water is present but only a limited supply of oxygen and carbon dioxide is available. Wet stain formation will be accelerated by the presence of chlorides and sulfates.

White rust is a white, crumbly, and porous coating. The surface underneath the white product is often dark gray.

This coating is found on newly galvanized bright surfaces, particularly in crevices between closely packed sheets whose surfaces have come into contact with condensate or rainwater and the moisture can not dry up quickly. If the zinc surfaces have already formed a protective film prior to storage, chances are that no attack will take place.

Short-term protection against wet storage stain can be provided by chromating or phosphating. Painting after galvanizing will also provide protection.

Materials stored outdoors should be arranged so that all surfaces are well ventilated and that water can easily run off of the surfaces. If possible, new zinc surfaces should not be allowed to come into contact with rain or condensate water during transit or storage. This is the best way of preventing wet storage stain. Fig. Z.1 illustrates the stacking of galvanized parts out of doors.



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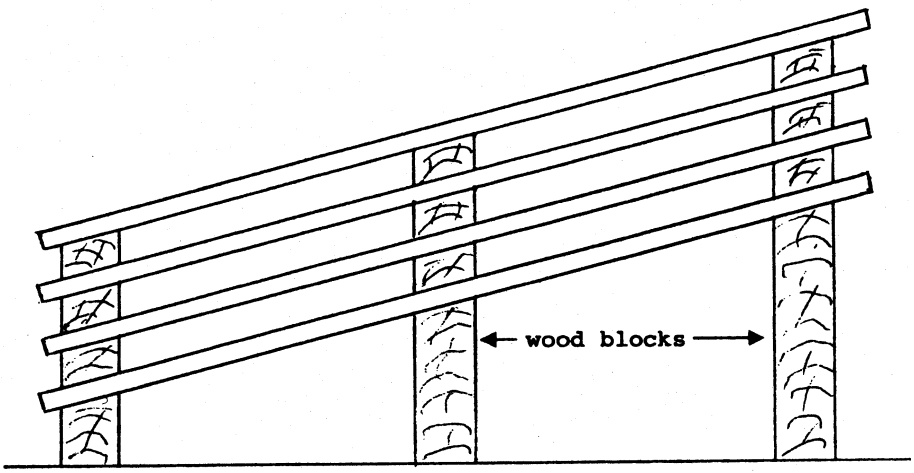



**Figure Z.1** Stacking of galvanized parts out of doors.

## Bimetallic Corrosion

The ratio of the areas of metals in contact, the duration of wetness, and the conductibility of the electrolyte will determine the severity of corrosive attack. Seawater, which is a highly conductive solution, will produce a more severe bimetallic corrosion than most fresh waters, which generally have a lower conductivity. A film of moisture condensed from the air or rainwater can dissolve contaminants and produce conditions conducive to bimetallic corrosion. See Ref. 5.

Bimetallic corrosion is less severe under atmospheric exposure than under immersed conditions. In the former, attack will occur only when the surface is wet, which depends on several factors such as the effectiveness of drainage, the presence or retention of moisture in crevices, and the speed of evaporation.

Under normal circumstances galvanized steel surfaces may safely be in contact with types 304 and 316F stainless steel, most aluminum alloys, chrome steel (>12% Cr) and tin, provided the area ratio of zinc to metal is 1:1 or lower, and oxide layers are present on both aluminum alloys and the two stainless steels.

Prevention of bimetallic corrosion can be accomplished by preventing the flow of the corrosion currents between the dissimilar metals in contact. This can be done by either insulating the dissimilar metals from each other (breaking the metallic path) or by preventing the formation of a continuous bridge of conductive solution between the two metals (breaking the electrolytic path).

If electrical bonding is not required, the first method may be achieved by providing insulation under immersed conditions. For example, a zinc-coated steel bolt and nut may be fitted with an insulating bushing and washers where it passes through a steel surface that cannot be coated.

The second method may be accomplished by the application of paint or plastic coatings to the immersed parts of the metal. If it is not practical to coat both metals, it is preferable to coat the more noble metal, not the zinc.

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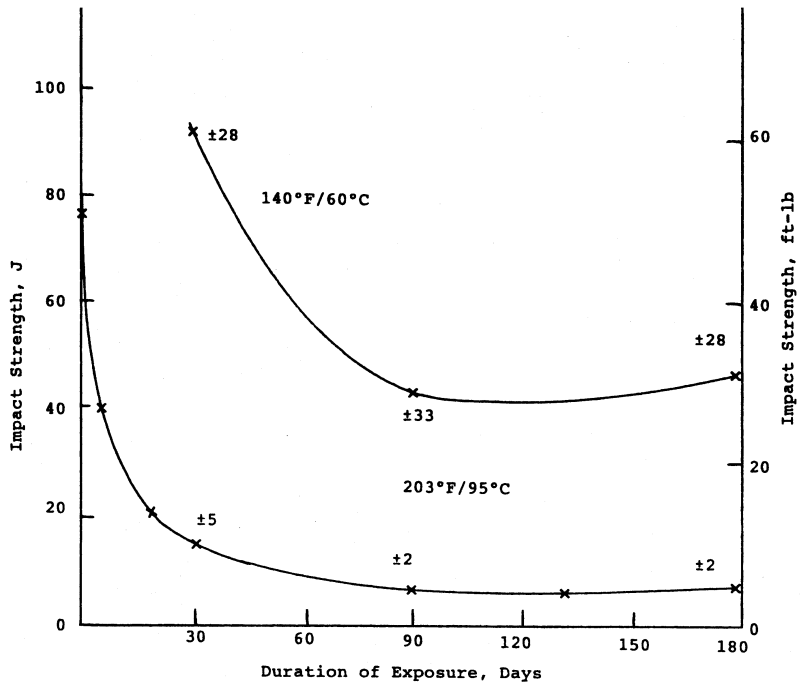



**Figure Z.2** Effect of intergranular corrosion of zinc–aluminum alloys on impact strength.

## Intergranular Corrosion

If pure zinc–aluminum alloys are exposed to temperatures in excess of 160°F/70°C under wet or damp conditions, intergranular corrosion may take place. The use of these alloys should be restricted to temperatures below 160°F/70°C and impurities controlled to specific limits of 0.006% each for lead and cadmium and to 0.003% for tin.

Impact strength can decrease as a result of intergranular corrosion as well as by aging. At 140°F/60°C, in high humidity, the loss is minimal. At 203°F/95°C, intergranular attack is ten times greater and loss of impact strength increases. Refer to Fig. Z.2.

## Corrosion Fatigue

Galvanized coatings can stop corrosive fatigue by preventing contact of the corrosive substance with the base metal. Zinc, which is anodic to the base metal, provides electrochemical protection after the mechanical protection has ceased.

## Stress Corrosion

Zinc or zinc-coated steels are not usually subjected to stress corrosion. Zinc can also prevent stress corrosion cracking in other metals.

## Zinc Coatings

Zinc coatings protect the substrate by means of cathodic control. Cathodic overpotential of the surface is increased by the coating, which makes the corrosion potential

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more negative than that of the substrate. The coating layer acts as a sacrificial anode for iron and steel substrates when the substrates are exposed to the atmosphere. The coating layer provides cathodic protection for the substrate by galvanic action. Zinc is therefore considered a sacrificial metal.

The electrical conductivity of the electrolyte, the temperature, and the surface condition determine the galvanic action of the coating. An increase in the cathodic overpotential is responsible for the corrosion resistance of the coating layer. Fig. Z.3 illustrates the principle of cathodic control protection by a sacrificial metal coating.

The corrosion of zinc-coated iron $i_{corr}$ is lower than that of uncoated iron since the cathodic overpotential of the surface is increased by the zinc coating and the exchange current density of dissolved oxygen $i_{oc}$ on zinc is lower than that on iron.

If a small part of iron is exposed to the atmosphere, the electrode potential of the exposed iron is equal to the corrosion potential of the zinc coating since the exposed iron is polarized cathodically by the surrounding zinc, so that little corrosion occurs on the exposed iron. Zinc ions dissolved predominantly from the zinc coating form the surrounding barrier of corrosion products at the defect, thereby protecting the exposed iron.

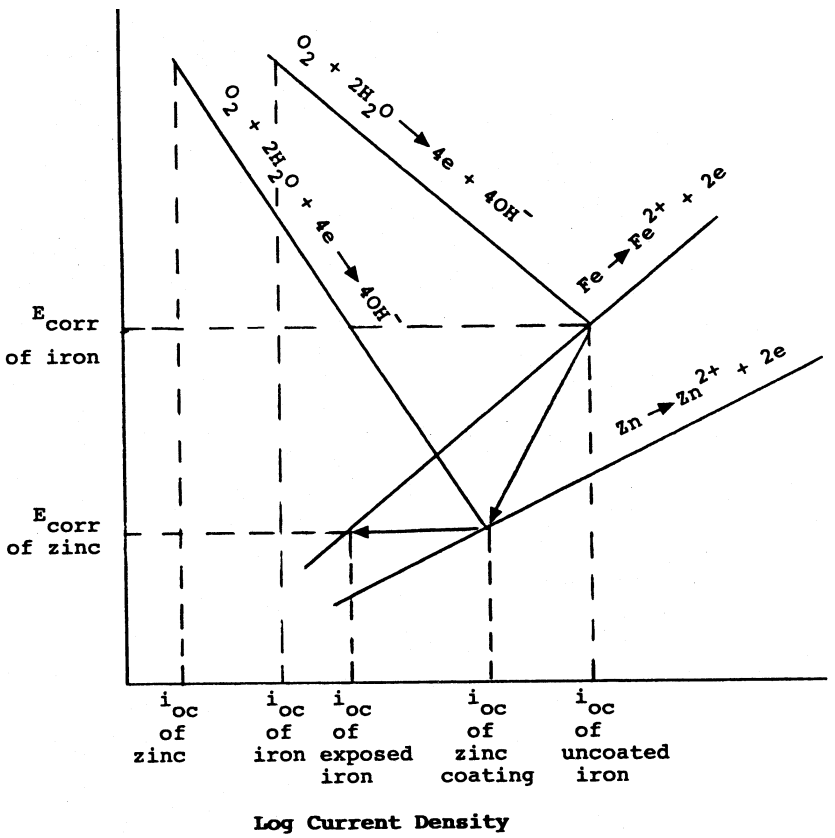



**Figure Z.3** Cathodic control protection.

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Sacrificial metal coatings protect iron and steel via two or three mechanisms:

1. Original barrier action of coating layer
2. Secondary barrier action of corrosion product layer
3. Galvanic action of coating layer

The surface oxide film and the electrochemical properties based on the metallography of the coating material provide the original barrier action. The original barriers of zinc and zinc alloy coatings result from electrochemical properties based on the structure of the coating layer.

Nonuniformity of the surface condition generally induces the formation of a corrosion cell. Such nonuniformity results from defects in the surface oxide film, localized distribution of elements, and differences in crystal face or phase. These nonuniformities cause a potential difference between portions of the surface, promoting the formation of a corrosion cell.

Many corrosion cells are formed on the surface, accelerating the corrosion rate, as a sacrificial metal and its alloy-coated materials are exposed in the natural atmosphere. During this time corrosion products are gradually formed and converted to a stable layer after a few months of exposure. Once the stable layer has been formed, the corrosion rate becomes constant. This secondary barrier of corrosion protection regenerates continuously over a long period of time. In most cases the service life of a sacrificial metal coating depends on the secondary barrier action of the corrosion product layer.

Zinc metal coatings are characterized by their galvanic action. Exposure of the base metal as a result of mechanical damage polarizes the base metal cathodically to the potential of the coating layer, as shown in Fig. Z.3, so that little corrosion takes place on the exposed base metal. A galvanic couple is formed between the exposed part of the base metal and the surrounding coating metal. Since zinc is more negative in electrochemical potential than iron or steel, the zinc acts as an anode and the exposed base metal behaves as a cathode. Consequently, the dissolution of the zinc layer around the defect is accelerated and the exposed part of base metal is protected against corrosion.

Figure Z.4 is a schematic illustration of the galvanic action of a zinc coating.

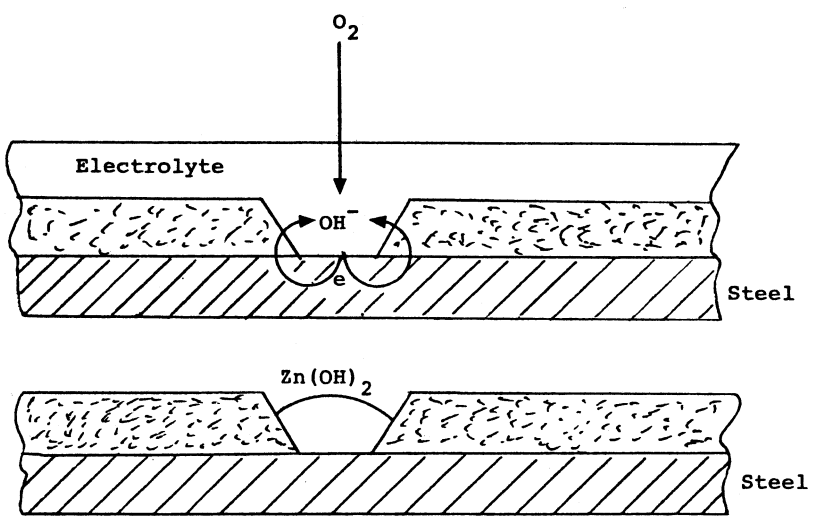



**Figure Z.4** Schematic illustration of the galvanic action of a zinc metallic coating.

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## Corrosion of Zinc Coatings

In general, zinc coatings corrode in a similar manner as solid zinc. However, there are some differences. For example, the iron–zinc alloy present in most galvanized coatings has a higher corrosion resistance than solid zinc in neutral and acid solutions. At points where the zinc coating is defective, the bare steel is cathodically protected under most conditions.

The corrosion rate of zinc coatings in air is an approximate straight-line relationship between weight loss and time. Since the protective film on zinc increases with time in rural and marine atmospheres of certain types, under these conditions the life of the zinc may increase more than proportionately to thickness. However, this does not always happen.

Zinc coatings are used primarily to protect ferrous parts against atmospheric corrosion. These coatings have good resistance to abrasion by solid pollutants in the atmosphere. General points to consider are

1. Corrosion increases with time of wetness.
2. The corrosion rate increases with an increase in the amount of sulfur compounds in the atmosphere. Chlorides and nitrogen oxides usually have a lesser effect but are often very significant in combination with sulfates.

Zinc coatings resist atmospheric corrosion by forming protective films consisting of basic salts, notably carbonate. The most widely accepted formula is $3Zn(OH)_2 \cdot 2ZnCO_3$. Environmental conditions that prevent the formation of such films, or conditions that lead to the formation of soluble films, may cause rapid attack on the zinc.

Duration and frequency of moisture contact is one such factor. Another factor is the rate of drying, because a thin film of moisture with high oxygen concentration promotes reaction. For normal exposure conditions the films dry quite rapidly. It is only in sheltered areas that drying times are slow, so that the attack on zinc is accelerated significantly.

The effect of atmospheric humidity on the corrosion of a zinc coating is related to the conditions that may cause condensation of moisture on the metal surface and to the frequency and duration of the moisture contacts. If the air temperature drops below the dew point, moisture will be deposited. The thickness of the piece, its surface roughness, and its cleanliness also influence the amount of dew deposited. Lowering the temperature of a metal surface below the air temperature in a humid atmosphere will cause moisture to condense on the metal. If the water evaporates quickly, corrosion is usually not severe and a protective film is formed on the surface. If water from rain or snow remains in contact with zinc when access to air is restricted and the humidity is high, the resulting corrosion can appear to be severe (wet storage stain) since the formation of a protective basic zinc carbonate is prevented.

In areas having atmospheric pollutants, particularly sulfur oxides and other acid-forming pollutants, time of wetness becomes of secondary importance. These pollutants can also make rain more acid. In less corrosive areas, time of wetness assumes a greater proportional significance.

In the atmospheric corrosion of zinc, the most important atmospheric contaminant to be considered is sulfur dioxide. At relative humidities of about 70% or above, it usually controls the corrosion rate.

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Sulfur oxides and other corrosive species react with the zinc coating in two ways: dry deposition and wet deposition Sulfur dioxide can deposit on a dry surface of galvanized steel panels until a monolayer of $SO_2$ is formed. In either case the sulfur dioxide that deposits on the surface of the zinc forms a sulfurous or other strong acid, which reacts with the film of zinc oxide, hydroxide, or basic carbonate to form zinc sulfate. The conversion of sulfur dioxide to sulfur-based acids may be catalyzed by nitrogen compounds in the air ($NO_x$ compounds). This factor may affect corrosion rates in practice. The acids partially destroy the film of corrosion products, which will then reform from the underlying metal, thereby causing continuous corrosion by an amount equivalent to the film dissolver, and hence the amount of $SO_2$ absorbed.

Chloride compounds have less effect than sulfur compounds in determining the corrosion rate of zinc. Chloride is most harmful when combined with acidity due to sulfur gases. This condition is prevalent on the coast in highly industrial areas.

Atmospheric chlorides will lead to the corrosion of zinc, but to a lesser degree than the corrosion of steel, except in brackish water and flowing seawater. Any salt deposit should be removed by washing. The salt content of the atmosphere will usually decrease rapidly inland farther from the coast. Corrosion also decreases with distance from the coast, but the change is more gradual and erratic because chloride is not the primary pollutant affecting zinc corrosion. Chloride is most harmful when combined with acidity resulting from sulfur gases.

Other pollutants also have an effect on the corrosion of galvanized surfaces. Deposits of soot or dust can be detrimental because they have the potential to increase the risk of condensation onto the surface and hold more water in position. This is prevalent on upward-facing surfaces. Soot (carbon) absorbs large quantities of sulfur, which is released by rainwater.

In rural areas overmanuring of agricultural land tends to increase the ammonia content of the air. The presence of normal atmospheric quantities of ammonia does not accelerate zinc corrosion, and petroleum plants where ammonium salts are present show no appreciable attack on galvanized steel. However, ammonia will react with atmospheric sulfur oxides, producing ammonium sulfate, which accelerates paint film corrosion as well as zinc corrosion. When ammonia reacts with $NO^-_x$ compounds in the atmosphere, ammonium nitrite and nitrate are produced. Both compounds increase the rate of zinc corrosion, but less so than $SO_2$ or $SO_3$.

Because of the Mears effect (wire corrodes faster per unit of area than more massive materials), galvanized wire corrodes some 10–80% faster than galvanized sheet. However, the life of rope made from galvanized steel wires is greater than the life of the individual wire. This is explained by the fact that the parts of the wire that lie on the outside are corroded more rapidly, and when the zinc film is penetrated in these regions, the uncorroded zinc inside the rope provides cathodic protection for the outer regions.

Galvanized steel also finds application in the handling of various media. Table Z.1 gives the compatibility of galvanized steel with selected corrodents.

**Table Z.1** Compatibility of Galvanized Steel with Selected Corrodents

| | | | |
|---|---|---|---|
| Acetic acid | U | Acrylic latex | U |
| Acetone | G | Aluminum chloride 26% | U |
| Acetonitrile | G | Aluminum hydroxide | U |
| Acrylonitrile | G | Aluminum nitrate | U |

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**Table Z.1** Compatibility of Galvanized Steel with Selected Corrodents (Continued)

| | | | |
|---|---|---|---|
| Ammonia, dry vapor | U | Ethyl acetate | G |
| Ammonium acetate solution | U | Ethyl acrylate | G |
| Ammonium bisulfate | U | Ethyl amine 69% | G |
| Ammonium bromide | U | *N*-Ethyl butylamine | G |
| Ammonium carbonate | U | 2-Ethyl butyric acid | G |
| Ammonium chloride 10% | U | Ethyl ether | G |
| Ammonium dichloride | U | Ethyl hexanol | G |
| Ammonium hydroxide | | Fluorine, dry, pure | G |
| Vapor | U | Formaldehyde | G |
| Reagent | U | Fruit juices | S |
| Ammonium molybdate | G | Hexanol | G |
| Ammonium nitrate | U | Hexylamine | C |
| Argon | G | Hexylene glycol | C |
| Barium hydroxide | | Hydrochloric acid | U |
| Barium nitrate solution | S | Hydrogen peroxide | S |
| Barium sulfate solution | S | Iodine, gas | U |
| Beeswax | U | Isohexanol | G |
| Borax | S | Isooctanol | G |
| Bromine, moist | U | Isopropyl ether | G |
| 2-Butanol | G | Lead sulfate | U |
| Butyl acetate | G | Lead sulfite | S |
| Butyl chloride | G | Magnesium carbonate | S |
| Butyl ether | G | Magnesium chloride 42.5% | U |
| Butylphenol | G | Magnesium fluoride | G |
| Cadmium chloride solution | U | Magnesium hydroxide sat. | S |
| Cadmium nitrate solution | U | Magnesium sulfate | |
| Cadmium sulfate solution | U | 2% solution | S |
| Calcium hydroxide | | 10% solution | U |
| sat. solution | U | Methyl amyl alcohol | G |
| 20% solution | S | Methyl ethyl ketone | G |
| Calcium sulfate, sat. solution | U | Methyl propyl ketone | G |
| Cellosolve acetate | G | Methyl isobutyl ketone | G |
| Chloric acid 20% | U | Nickel ammonium sulfate | U |
| Chlorine, dry | G | Nickel chloride | U |
| Chlorine water | U | Nickel sulfate | S |
| Chromium chloride | U | Nitric acid | U |
| Chromium sulfate solution | U | Nitrogen, dry, pure | G |
| Copper chloride solution | U | Nonylphenol | G |
| Decyl acrylate | G | Oxygen | |
| Diamylamine | G | dry, pure | G |
| Dibutylamine | G | moist | U |
| Dibutyl cellosolve | G | Paraldehyde | G |
| Dibutyl phthalate | G | Perchloric acid solution | S |
| Dichloroethyl ether | G | Permanganate solution | S |
| Diethylene glycol | G | Peroxide | |
| Dipropylene glycol | G | pure, dry | S |
| Ethanol | G | moist | U |

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**Table Z.1** Compatibility of Galvanized Steel with Selected Corrodents (Continued)

| | | | |
|---|---|---|---|
| Phosphoric acid 0.3–3% | G | moist, wet | U |
| Polyvinyl acetate latex | U | Silver nitrate solution | U |
| Potassium carbonate | | Sodium acetate | S |
| 10% solution | U | Sodium aluminum sulfate | U |
| 50% solution | U | Sodium bicarbonate solution | U |
| Potassium chloride solution | U | Sodium bisulfate | U |
| Potassium bichromate | | Sodium carbonate solution | U |
| 14.7% | G | Sodium chloride solution | U |
| 20% | S | Sodium hydroxide solution | U |
| Potassium disulfate | S | Sodium nitrate solution | U |
| Potassium fluoride 5–20% | G | Sodium sulfate solution | U |
| Potassium hydroxide | U | Sodium sulfide | U |
| Potassium nitrate | | Sodium sulfite | U |
| 5–10% solution | S | Styrene, monomeric | G |
| Potassium peroxide | U | Styrene oxide | G |
| Potassium persulfate 10% | U | Tetraethylene glycol | G |
| Propyl acetate | G | 1, 1, 2-Trichloroethane | G |
| Propylene glycol | G | 1, 2, 3-Trichloropropane | G |
| Propionaldehyde | G | Vinyl acetate | G |
| Propionic acid | U | Vinyl ethyl ether | G |
| Silver bromide | U | Vinyl butyl ether | G |
| Silver chloride | | Water | |
| pure, dry | S | potable, hard | G |

G = Suitable application; S = Borderline application; U = Not suitable.

## Zinc Alloys

Small alloy additions are made to zinc to improve grain size, give work hardening, and improve properties such as creep resistance and corrosion resistance. There are a number of proprietary compositions available containing additions of copper, manganese, magnesium, aluminum, chromium, and titanium

## Zinc–5% Aluminum Hot Dip Coatings

This zinc alloy coating is known as Galfan. Galfan coatings have a corrosion resistance up to three times that of galvanized steel. The main difference between these two coatings lies in the degree of cathodic protection they afford. This increase in corrosion protection is evident both in a relatively mild urban industrial atmosphere and in a marine atmosphere, as can be seen in Table Z.2. The latter is particularly significant because unlike the case for galvanizing, the corrosion rate appears to slow after about 4 years, and conventional galvanized steel would show rust in 5 years. See Fig. Z.5. The slower rate of corrosion also means that the zinc–5% aluminum coatings provide full cathodic protection to cut edges over a longer period. Refer to Table Z.3.

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**Table Z.2** Five-Year Outdoor Exposure Results of Galfan Coating

| Atmosphere | Thickness loss (μm) | | Ratio of improvement |
|---|---|---|---|
| | Galvanized | Galfan | |
| Industrial | 15.0 | 5.2 | 2.9 |
| Severe marine | >20.0 | 9.5 | >2.1 |
| Marine | 12.5 | 7.5 | 1.7 |
| Rural | 10.5 | 3.0 | 3.5 |

*Source:* Ref. 1.

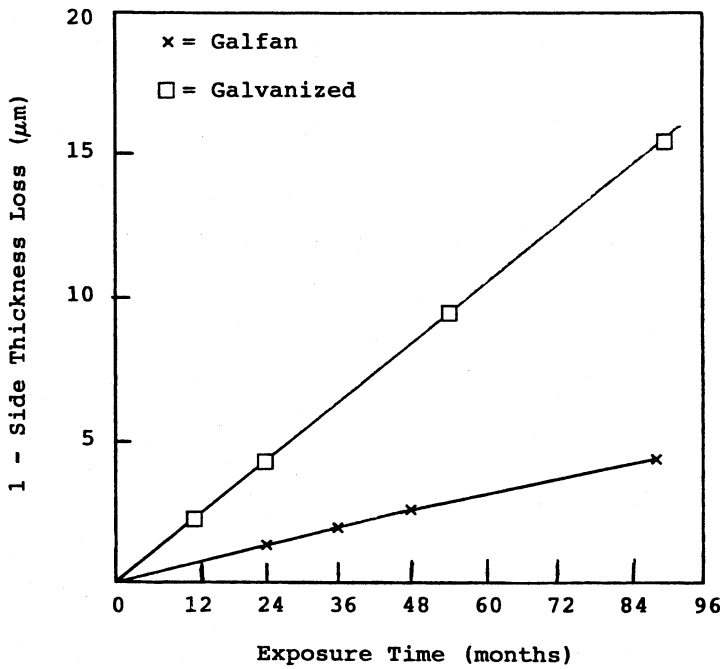



**Figure Z.5** Seven-year exposure of Galfan and galvanized steel in a severe marine atmosphere.

**Table Z.3** Comparison of Cathodic Protection for Galvanized and Galfan Coatings

| Environment | Amount of bare edges exposed after 3 years (coating recession from edge) (mm) | |
|---|---|---|
| | Galvanized | Galfan |
| Severe marine | 1.6 | 0.1 |
| Marine | 0.5 | 0.06 |
| Industrial | 0.5 | 0.05 |
| Rural | 0.1 | 0.0 |

*Source:* Ref. 1.

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Because Galfan can be formed with much smaller cracks than can be obtained in conventional galvanized coatings, it provides excellent protection at panel bulges. This reduced cracking means that less zinc is exposed to the environment, which increases the relative performance factor compared with galvanized steel.

### Zinc–55% Aluminum Hot Dip Coatings

These coatings are known as Galvalume and consist of zinc–55% aluminum–1.5% silicon. This alloy is sold under such trade names as Zaluite, Aluzene, Alugalva, Algafort, Aluzink, and Zincalume. Galvalume exhibits superior corrosion resistance over galvanized coatings in rural, industrial, marine, and severe marine environments. However, this alloy has limited cathodic protection and less resistance to some alkaline conditions and is subject to weathering discoloration and wet storage staining. The latter two disadvantages can be overcome by chromate passivation, which also improves atmospheric corrosion resistance.

Initially, a relatively high corrosion loss is observed for Galvalume sheet as the zinc-rich portion of the coating corrodes and provides sacrificial protection at cut edges. This takes place in all environments. After approximately 3 years, the corrosion–time curves take on a more gradual slope, reflecting a change from active, zinc-like behavior to passive aluminum-like behavior as the interdentric regions fill with corrosion products. It has been predicted that Galvalume sheets should outlast galvanized sheets of equivalent thickness by at least two to four times over a wide range of environments.

Galvalume sheets provide excellent cut-edge protection in very aggressive conditions, where the surface does not remain too passive. However, it does not offer as good protection on the thicker sheets in mild rural conditions, where zinc–5% aluminum coatings provide good general corrosion resistance. When sheared edges are exposed or localized damage to the coating occurs during fabrication or service, the galvanic protection is retained for a longer period.

### Zinc–15% Aluminum Thermal Spray

Zinc–15% aluminum coatings are available as thermally sprayed coatings. These coatings have a two-phase structure consisting of a zinc-rich and an aluminum-rich phase. The oxidation products formed are encapsulated in the porous layer formed by the latter and do not build up a continuous surface layer as with pure zinc coatings. As a result, no thickness or weight loss is observed even after several years of exposure in atmospheric field testing.

It is normally recommended that thermally sprayed coatings be sealed to avoid initial rust stains, to improve appearance, and to facilitate maintenance painting. Sealing is designed to fill pores and give only a thin overall coating, too thin to be directly measurable. Epoxy or acrylic system resins, having a low viscosity, are used as a sealer.

### Zinc-Iron Alloy Coatings

Compared with pure zinc, the zinc–iron alloy coatings provide increased corrosion resistance in acid atmospheres but slightly reduced corrosion resistance in alkaline atmospheres.

Electroplated zinc–iron alloy layers containing more than 20% iron provide a corrosion resistance 30% higher than zinc in industrial atmospheres. In other atmospheres the zinc–iron galvanized coatings are as good as coatings with an outer zinc layer. Sheradized coatings are superior to electroplated coatings and equal to galvanized coatings of the same thickness. However, the structure of the layer and its composition affect the corrosion resistance.

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If the zinc layer of a galvanized coating has weathered, or if the zinc–iron alloy layer forms the top layer after galvanizing, brown areas may form. Brown staining can occur on sheradized or hot dip galvanized coatings in atmospheric corrosion through the oxidation of iron from the zinc–iron alloy layers or from the substrate. Such staining is usually a dull brown rather than the bright red-brown of uncontrolled rust. Usually there is a substantial intact galvanized layer underneath, leaving the life of the coating unchanged. Unless the aesthetic appearance is undesirable, no action need be taken.

See Refs. 1–3.

## ZINCATING

This is an immersion coating of aluminum base materials with zinc to facilitate electroplating of other metals on the aluminum article. Zincating is a chemical replacement where aluminum ions replace zinc ions in an aqueous solution of zinc salts, thus depositing a thin adherent film of metallic zinc on the aluminum surface. Adhesion of the zinc depends on metallurgical bonding.

## ZINC EMBRITTLEMENT

This is a form of liquid metal embrittlement of austenitic stainless steels. It most commonly occurs in fire exposure or welding of these steels while in contact with galvanized steel parts.

## ZIRCALOYS

These are zirconium alloys Zr2.5Nb and Zr-1Nb, which are hafnium free and are classified as nuclear grade. See "Zirconium and Zirconium Alloys."

## ZIRCONIUM AND ZIRCONIUM ALLOYS

Zirconium and its alloys can be classified into two major categories: nuclear and nonnuclear. The major difference between these two categories is in the hafnium content. Nuclear grades of zirconium are essentially free of hafnium (<100 ppm). Nonnuclear grades of zirconium may contain as much as 4.5% hafnium, which has an enormous effect on zirconium's nuclear properties but little effect on its mechanical and chemical properties. The commercially available grades of zirconium alloys are shown in Table Z.4.

The majority of the nuclear-grade material is produced as tubing, which is used for nuclear fuel rod claddings, guide tubes, pressure tubes, and ferrule spacer grids. Sheets and plates are used for spacer grids, water channels, and channel boxes for nuclear fuel bundles.

Nonnuclear zirconium applications make use of ingots, forgings, pipes, tubes, plates, sheet, foils, bars, wires, and castings to construct highly corrosion-resistant equipment. Included are heat exchangers, condensers, reactors, columns, piping systems, agitators, evaporators, tanks, pumps, valves, and packing.

In spite of the reactive nature of zirconium metal, the zirconium oxide ($ZnO_2$) film that forms on the surface is among the most insoluble compounds in a broad range of chemicals. Excellent corrosion protection is provided in most media. When mechanically destroyed, the oxide film will regenerate itself in many environments. When placing zirconium in a corrosive medium, there is no need to thicken this film.

Several methods are available to produce the oxide film. They include anodizing, autoclaving in hot water or steam, formation in air, and formation in molten salts.

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**Table Z.4** Commercially Available Grades of Zirconium Alloys

| Alloy designation (UNS no.) | Composition (%) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Zr + Hf, min. | Hf, max. | Sn | Nb | Fe | Cr | NI | Fe + Cr | Fe + Cr + Ni | 0, max. |
| *Nuclear grades* | | | | | | | | | | |
| Zircaloy-2 (R60802) | — | 0.010 | 1.20–1.70 | — | 0.07–0.20 | 0.05–0.15 | 0.03–0.08 | — | 0.18–0.38 | — |
| Zircaloy-4 (R60804) | — | 0.010 | 1.20–1.70 | — | 0.18–0.24 | 0.07–0.13 | — | 0.28–0.37 | — | — |
| Zr-2.5Nb (R60901) | — | 0.010 | — | 2.40–2.80 | — | — | — | — | — | — |
| *Chemical grades* | | | | | | | | | | |
| Zr 702 (R60702) | 99.2 | 4.5 | — | — | — | — | — | 0.2 max. | — | 0.16 |
| Zr 704 (R60704) | 97.5 | 4.5 | 1.0–2.0 | — | — | — | — | 0.2–0.4 | — | 0.18 |
| Zr 705 (R60705) | 95.5 | 4.5 | — | 2.0–3.0 | — | — | — | 0.2 max. | — | 0.18 |
| Zr 706 (R60706) | 95.5 | 4.5 | — | 2.0–3.0 | — | — | — | 0.2 max. | — | 0.16 |





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### Anodizing

A very thin film(<0.5μm) is formed by anodizing. As the thickness of the film grows, the color changes. Although the film formed is attractive, it does not have the adhesion of thermally produced films and has very limited ability to protect the metal from mechanical damage.

### Autoclave Film Formation

The nuclear industry uses this method. These films, in addition to providing a slower corrosion rate, reduce the rate of hydrogen absorption.

### Film Formation in Air or Oxygen

This is the most common method used in the chemical process industry. The film is formed during the final stress relief of a component in air at 1022°F (550°C) for 0.5 to 4 h. It ranges in color from straw yellow to an iridescent blue or purple to a powdery tan or light gray. These colors are not indications of metal contamination. This treatment does not cause significant penetration of oxygen into the metal, but it does form an oxide layer that is diffusion bonded to the base metal.

### Film Formation in Molten Salts

In this process, developed and patented by TWC, zirconium subjects are treated in a fused sodium cyanide containing 1–3% sodium carbonate or in a eutetic mixture of sodium and potassium chlorides with 5% sodium carbonate. Treatment is carried out at temperatures ranging from 1112 to 1472°F (600–800°C) for several hours. A thick protective, strongly cohesive oxide film ranging from 20 to 30μm is formed. This film has improved resistance to abrasion and galling over thick films produced by other methods.

### Electrochemical Protection

Zirconium performs well in most reducing environments as a result of its ability to take oxygen from water to form stable passive films. Most passive metals and alloys require the presence of an oxidizing agent such as oxygen in order to form a protective oxide film. Zirconium's corrosion problems can be controlled by converting the corrosive condition to a more reducing condition.

By impressing a potential that is arbitrarily 50–100 mV below its corrosion potential, zirconium becomes corrosion resistant in oxidizing chloride solutions. Tables Z.5 and Z.6 demonstrate the benefits of electrochemical protection in controlling pitting and stress corrosion cracking. Pitting penetration in oxidizing chloride solutions is considerably higher than general corrosion rates, which may be low for unprotected zirconium. Electrochemical protection eliminates this local attack.

**Table Z.5** Corrosion Rate of Zirconium in 500 ppm $Fe^{3+}$ Solution after 32 Days

| | | | Penetration rate (mpy) | |
|---|---|---|---|---|
| Environment | Acidity | Temperature (°C) | Unprotected | Protected |
| 10% HCl | 3 N | 60 | 7.1 | <0.1 |
| | | 120 | 51 | <0.1 |
| Spent acid (15% Cl) | 5 N | 65 | 36 | <0.1 |
| | | 80 | 36 | <0.1 |
| 20% HCl | 6 N | 60 | 3.6 | <0.1 |
| | | 107 | 59 | <0.1 |

*Source:* Ref. 4.

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**Table Z.6** Time to Failure of Welded Zirconium U Bends in 500 ppm $Fe^{3+}$ Solution after 32 Days

| Environment | Acidity | Temperature (°C) | Time to failure (days) | |
|---|---|---|---|---|
| | | | Unprotected | Protected |
| 10% HCl | 3 N | 60 | <0.1 | NF |
| | | 120 | <0.1 | NF |
| Spent acid (15% Cl) | 5 N | 65 | <0.3 | NF |
| 20% HCl | 6 N | 60 | NF | NF |
| | | 107 | <0.1 | NF |
| 28% HCl | 9 N | 60 | 2 | NF |
| | | 94 | <0.1 | NF |
| 32% HCl | 10 N | 53 | 1 | 32 |
| | | 77 | <0.1 | 20 |
| 37% HCl | 12 N | 30 | 0.3 | NF |
| | | 53 | 1 | NF |

NF = no failure.
*Source:* Ref. 4.

As can be seen from Table Z.6, unprotected welded zirconium U bends cracked in all but one case shortly after exposure. Protected U bends resisted cracking for the 32-day test period in all but one acid concentration. From these tests it is obvious that electrochemical protection provides an improvement to the corrosion properties of zirconium in oxidizing solutions.

## Forms of Corrosion

The more common forms of corrosion, to which zirconium is susceptible, other than general (uniform) corrosion, include pitting, stress corrosion cracking (SCC), fretting, galvanic, and crevice corrosion.

### *Pitting*

Zirconium will pit in acidic chloride solutions because its pitting potential is greater than its corrosion potential. The presence of oxidizing ions, such as ferric and cupric ions, in acidic chloride solutions may increase the corrosion potential to exceed the pitting potential. Therefore, pitting may occur. However, zirconium does not pit in most other halide solutions. Under certain conditions nitrate and sulfate ions can inhibit the pitting.

One of the critical factors in pitting is surface condition. A metal with a homogeneous surface is less likely to pit and less likely to be vulnerable to other forms of localized corrosion. A common method used to homogenize a metal's surface is pickling. Results of tests show that pickled zirconium may perform well in boiling 10% $FeCl_3$ and even $ClO_2$, while zirconium with a normal surface finish is unsuitable for handling these solutions.

### *Stress Corrosion Cracking*

Zirconium and its alloys resist SCC in many media, such as NaCl, $MgCl_2$, NaOH, and $H_2S$, which cause SCC on common metals and alloys. However, zirconium is susceptible to SCC environments such as $FeCl_3$, $CuCl_2$, halide or halide-containing methanol, concentrated $HNO_3$, 64–69% $H_2SO_4$, and liquid mercury or cesium.

Stress corrosion cracking of zirconium can be prevented by

1. Avoiding high sustained tensile stresses
2. Modifying the environment, e.g., changing pH concentration or adding an inhibitor

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3. Maintaining a high-quality surface film (one low in impurities, defects, and mechanical damage)
4. Applying electrochemical techniques
5. Shot peening
6. Achieving a crystallographic texture with the hexagonal basal planes perpendicular to the cracking path

### *Fretting Corrosion*

When the protective oxide coating of zirconium is damaged or removed, fretting may occur. It takes place when vibration contact is made at the interface of tight-fitting, highly bonded surfaces. If the vibration cannot be removed mechanically, the addition of a heavy oxide coating on the zirconium may eliminate the problem. This coating reduces friction and prevents the removal of the passive film.

### *Galvanic Corrosion*

The protective oxide film that forms on zirconium causes zirconium to assume a noble potential similar to that of silver. It is possible for zirconium to become activated and corrode at vulnerable areas when in contact with a noble metal. Vulnerable areas include areas with damaged oxide films and grain boundaries.

Other, less noble metals will corrode in contact with zirconium when its oxide film is intact.

### *Crevice Corrosion*

Zirconium is among the most resistant of all the corrosion-resistant metals to crevice corrosion. However, it is not completely immune to crevice corrosion in the broad sense. For example, crevice corrosion will occur when a dilute sulfuric acid solution is allowed to concentrate within a crevice.

## General Corrosion Resistance

Zirconium is a highly corrosion-resistant metal. It reacts with oxygen at ambient temperatures and below to form an adherent, protective oxide film on its surface. Said film is self-healing and protects the base metal from chemical and mechanical attack at temperatures as high as 662°F (350°C). In a few media, such as hydrofluoric acid, concentrated sulfuric acid, and oxidizing chloride solutions, it is difficult to form this protective film. Therefore, zirconium cannot be used in these media without the use of protective measures previously discussed. Refer to Table Z.7 for the compatibility of zirconium with selected corrodents. The corrosion resistance of all zirconium alloys is similar.

**Table Z.7** Compatibility of Zirconium, with Selected Corrodents[a]

| Chemical | Maximum temp. (°F/°C) |
|---|---|
| Acetaldehyde | 250/121 |
| Acetic acid, 10% | 220/104 |
| Acetic acid, 50% | 230/110 |
| Acetic acid, 80% | 230/110 |
| Acetic acid, glacial | 230/110 |

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**Table Z.7** Compatibility of Zirconium, with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. (°F/°C) |
|---|---|
| Acetic anhydride | 250/121 |
| Acetone | 190/88 |
| Acetyl chloride | 80/27 |
| Acrylonitrile | 210/93 |
| Allyl alcohol | 200/93 |
| Allyl chloride | 200/93 |
| Alum | 210/99 |
| Aluminum chloride, aqueous | 40% |
| | 200/93 |
| Aluminum chloride, dry | 37% |
| | 210/99 |
| Aluminum fluoride | x |
| Aluminum hydroxide | 200/93 |
| Aluminum sulfate | 210/99 |
| Ammonia gas | 100/38 |
| Ammonium chloride, 10% | 210/99 |
| Ammonium chloride, 50% | 220/104 |
| Ammonium fluoride, 10% | x |
| Ammonium fluoride, 25% | x |
| Ammonium hydroxide, 25% | 210/99 |
| Ammonium hydroxide, sat. | 210/99 |
| Ammonium nitrate | 210/99 |
| Ammonium persulfate | 220/104 |
| Ammonium phosphate, 10% | 210/99 |
| Ammonium sulfate, 10–40% | 210/99 |
| Ammonium sulfide | |
| Amyl acetate | 210/99 |
| Amyl alcohol | 200/93 |
| Amyl chloride | 210/99 |
| Aniline | 210/99 |
| Aqua regia, 3:1 | x |
| Barium carbonate | 210/99 |
| Barium chloride, 25% | 210/99 |
| Barium hydroxide | 200/93 |
| Barium sulfate | 210/99 |
| Barium sulfide | 90/32 |
| Benzaldehyde | 210/99 |
| Benzene | 230/110 |
| Benzene sulfonic acid, 10% | 210/99 |
| Benzoic acid | 400/204 |
| Benzyl alcohol | 210/99 |
| Boric acid | 210/99 |
| Bromine gas, dry | x |

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**Table Z.7** Compatibility of Zirconium, with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. (°F/°C) |
|---|---|
| Bromine gas, moist | 60/16 |
| Bromine, liquid | 60/16 |
| Butyl acetate | 210/99 |
| Butyl alcohol | 200/93 |
| Butyl phthalate | 210/99 |
| Butyric acid | 210/99 |
| Calcium bisulfite | 90/32 |
| Calcium carbonate | 230/110 |
| Calcium chloride | 210/99 |
| Calcium hydroxide, 10% | 210/99 |
| Calcium hydroxide, sat. | 210/99 |
| Calcium hypochlorite | 200/93 |
| Calcium sulfate | 210/99 |
| Caprylic acid | 210/99 |
| Carbon dioxide, dry | 410/210 |
| Carbonic acid | 210/99 |
| Cellosolve | 210/99 |
| Chloracetic acid, 50% water | 210/99 |
| Chloracetic acid | 210/99 |
| Chlorine gas, dry | 90/32 |
| Chlorine gas, wet | x |
| Chlorine, liquid | x |
| Chlorobenzene | 200/93 |
| Chloroform | 210/99 |
| Chromic acid, 10% | 210/99 |
| Chromic acid, 50% | 210/99 |
| Citric acid, 15% | 210/99 |
| Citric acid, conc. | 180/82 |
| Copper acetate | 200/93 |
| Copper chloride | x |
| Copper cyanide | x |
| Copper sulfate | 210/99 |
| Cupric chloride, 5% | x |
| Cupric chloride, 50% | 190/88 |
| Dichloroacetic acid | 350/177 |
| Ethylene glycol | 210/99 |
| Ferric chloride | x |
| Ferric chloride, 50% in water | x |
| Ferrous chloride | 210/99 |
| Fluorine gas, dry | x |
| Fluorine gas, moist | x |
| Hydrobromic acid, dilute | 80/27 |
| Hydrobromic acid, 20% | x |

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**Table Z.7** Compatibility of Zirconium, with Selected Corrodents[a] (Continued)

| Chemical | Maximum temp. (°F/°C) |
|---|---|
| Hydrobromic acid, 50% | x |
| Hydrochloric acid, 20% | 300/149 |
| Hydrochloric acid, 38% | 140/60 |
| Hydrofluoric acid, 30% | x |
| Hydrofluoric acid, 70% | x |
| Hydrofluoric acid, 100% | x |
| Lactic acid, 25% | 300/149 |
| Lactic acid, conc. | 300/149 |
| Malic acid | 210/99 |
| Manganese chloride, 5–20% | 210/99 |
| Methyl ethyl ketone | 210/99 |
| Methyl isobutyl ketone | 200/93 |
| Nitric acid, 5% | 500/260 |
| Nitric acid, 20% | 500/260 |
| Nitric acid, 70% | 500/260 |
| Nitric acid, anhydrous | 90/32 |
| Perchloric acid, 70% | 210/99 |
| Phenol | 210/99 |
| Phosphoric acid, 50–80% | 180/82 |
| Potassium bromide, 30% | 200/93 |
| Sodium carbonate | 210/99 |
| Sodium chloride | 250/151 |
| Sodium hydroxide, 10% | 210/99 |
| Sodium hydroxide, 50% | 200/93 |
| Sodium hydroxide, conc. | 200/99 |
| Sodium hypochlorite, 20% | 100/38 |
| Sodium sulfide, to 10% | x |
| Stannic chloride, 20% | 210/99 |
| Sulfuric acid, 10% | 300/149 |
| Sulfuric acid, 50% | 300/149 |
| Sulfuric acid, 70% | 210/99 |
| Sulfuric acid, 98% | x |
| Sulfuric acid, 100% | x |
| Sulfurous acid | 370/188 |
| Toluene | 80/27 |
| Trichloroacetic acid | x |
| White liquor | 250/121 |

[a]The chemicals listed are in the pure state or in a saturated solution unless otherwise indicated. Compatibility is shown to the maximum allowable temperature for which data are available. Incompatibility is shown by an x. When compatible, corrosion rate is <20 mpy.
*Source:* Ref. 3.

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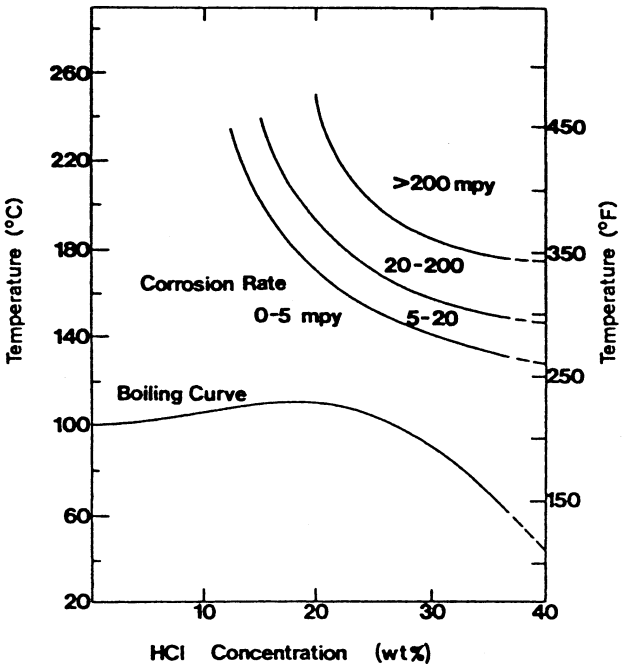



**Figure Z.6** Isocorrosion diagram for zirconium in HCl (from Ref. 4).

Zirconium has excellent resistance to seawater, brackish water, and polluted water. It is sensitive to such changes as chloride concentration, temperature, pH, crevice formation, flow velocity, and sulfur-containing organisms.

Zirconium will resist attack by all halogen acids except hydrofluoric, which will attack zirconium at all concentrations. One of the most impressive corrosion-resistant properties is its resistance to hydrochloric acid at all concentrations, even above boiling. The isocorrosion diagram for zirconium is shown in Fig. Z.6.

Nitric acid poses no problem for zirconium. It can handle 9% $HNO_3$ below the boiling point and 70% $HNO_3$ up to 482°F (250°C) with corrosion rates of less than 5 mpy. Refer to Fig. Z.7.

The nature of sulfuric acid is complicated. Dilute solutions are reducing in nature. At or above 65%, sulfuric acid solutions become increasingly oxidizing. In Fig. Z.8 it will be noted that zirconium resists attack by $H_2SO_4$ at all concentrations up to 70% and at temperatures to boiling and above. In the 70–80% range of concentration, the corrosion resistance of zirconium depends strongly on temperature. In higher concentrations the corrosion rate of zirconium increases rapidly as the concentration increases. The presence of chlorides in $H_2SO_4$ has little effect on the corrosion resistance of zirconium unless oxidizing agents are also present.

Zirconium resists attack in phosphoric acid at concentrations up to 55% and temperatures exceeding the boiling point. Above 55% concentration the corrosion rate may increase greatly with increasing temperature. Zirconium performs ideally in handling dilute acid at elevated temperatures. If the phosphoric acid contains more than a trace of fluoride ions, zirconium may be attacked.

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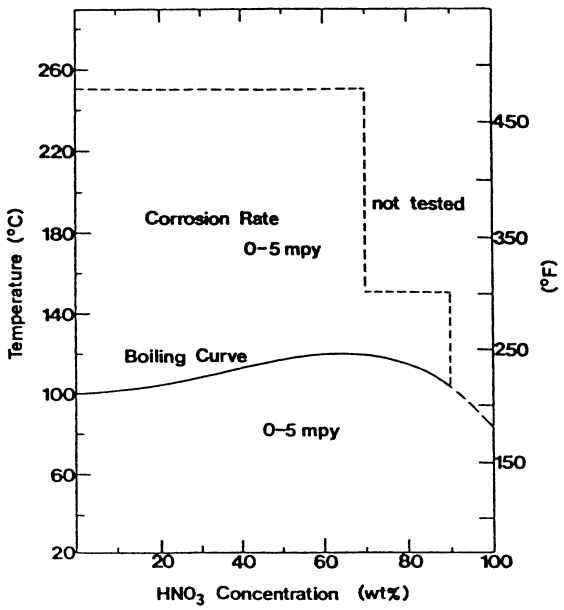



**Figure Z.7** Isocorrosion diagram for zirconium in $HNO_3$ (from Ref. 4).

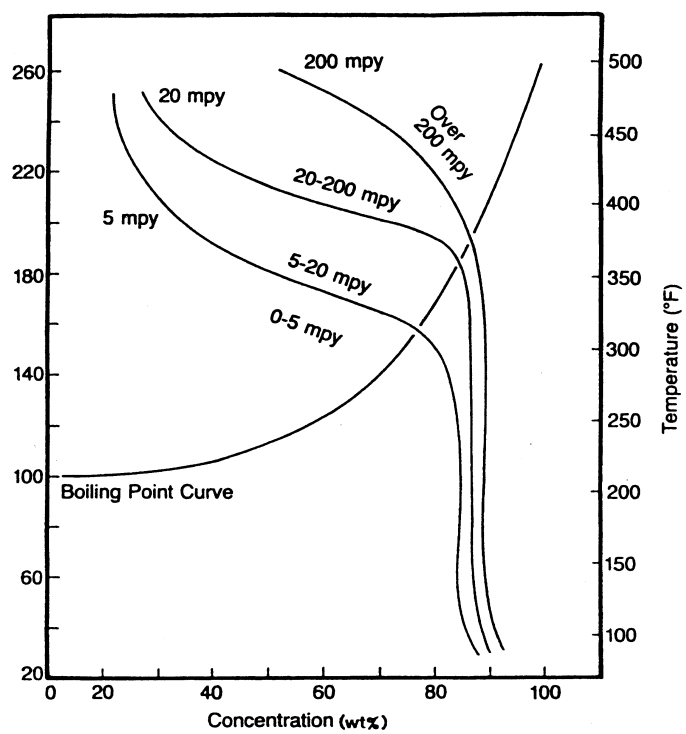



**Figure Z.8** Isocorrosion diagram for zirconium in $H_2SO_4$ (from Ref. 4).

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Zirconium is resistant to most alkalies, including sodium hydroxide, potassium hydroxide, calcium hydroxide, and ammonium hydroxide.

Most salt solutions, including halogen, nitrate, carbonate, and sulfate, will not attack zirconium. Corrosion rates are usually very low up to the boiling point. The exceptions are strong oxidizing chloride salts such as $FeCl_3$ and $CuCl_2$. In these media the corrosion resistance of zirconium is dependent on the surface conditions. When the zirconium has a good surface finish, it becomes quite resistant to pitting.

Zirconium possesses excellent resistance to most organic solutions. Corrosion is experienced when halogens are present and there is a lack of water. For example, if water is added to alcohol solutions with halide impurities, zirconium's susceptibility to SCC will be suppressed. Table Z.8 provides corrosion rates of zirconium in selected organic solutions.

## ZYMAXX

Zymaxx is the registered trademark for DuPont's carbon fiber–reinforced Teflon. This composite material has outstanding mechanical and corrosion resistant properties. It has an operating temperature range of –350°F to 550°F. At 550°F Zymaxx has four times the flexural strength of filled PTFE at 400°F and with less deflection. Its compressive creep is less than 1% after 100 hours at 500°F and 6000 psi as compared with other polymeric materials that soften and "cold flow." In addition, it offers low friction, low wear resistance, a coefficient of thermal expansion less than that of steel, and virtually no water absorption. Listed in the table (see page 673) is a comparison of the major properties of Zymaxx, filled PTFE, and reinforced PEEK.

**Table Z.8** Corrosion Rates for Zirconium in Organic Solutions

| Environment | Concentration (wt%) | Temperature (°C) | Corrosion rate (mpy) |
|---|---|---|---|
| Acetic acid | 5–99.5 | 35 to boiling | <0.07 |
| Acetic anhydride | 99.5 | Boiling | 0.03 |
| Aniline hydrochloride | 5, 20 | 35–100 | <0.01 |
| Chloroacetic acid | 100 | Boiling | <0.01 |
| Citric acid | 10–50 | 35–100 | <0.2 |
| Dichloroacetic acid | 100 | Boiling | <20 |
| Formic acid | 10–90 | 35 to boiling | <0.2 |
| Lactic acid | 10–85 | 35 to boiling | <0.1 |
| Oxalic acid | 0.5–25 | 35–100 | <0.5 |
| Tartaric acid | 10–50 | 35–100 | <0.05 |
| Tannic acid | 25 | 35–100 | <0.1 |
| Trichloroacetic acid | 100 | Boiling | >50 |
| Urea reactor | 58% urea, 17% $NH_3$, 15% $CO_2$, 10% $H_2O$ | 193 | <0.1 |

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| Property | Zymaxx | Filled PTFE | Reinforced PEEK |
|---|---|---|---|
| Chemical resistance | E | E | G |
| Intrinsic mech. properties | G+ | P | G+ |
| Impact resistance | E | G | P |
| Wear performance | G | F | F |
| Low coeff. of thermal exp. | E | P | G+ |
| Low water absorption | E | E | G+ |

E = excellent; G = good; F = fair; P = poor.

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