

Flue Gas Desulfurization Materials Guidelines Update

Coatings and High Alloys

Technical Report

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Coatings and High Alloys

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REPORT SUMMARY

Materials reliability problems plagued early flue gas desulfurization (FGD) systems. Thirty years of research has developed new materials with much greater corrosion resistance, though materials issues persist. This report discusses advances and innovations during the 90s in materials of construction for wet lime/limestone FGD systems.

Background

In the 1970s, EPRI initiated a systematic on-going program of technical support to utilities operating FGD systems to comply with environmental regulations limiting emissions of sulfur oxides from fossil-fired power generation stations. EPRI research has been a major factor in propelling FGD technology from infancy to maturity over the last 30 years. The first-generation FGD systems were so fraught with equipment reliability issues that the systems were multi-redundant and most were capable of operating at full capacity with one absorber off line at all times for maintenance. EPRI-sponsored research has raised utility confidence in the technology to the point that advanced design plants now being planned have no redundant absorbers and the anticipated outage interval has been doubled from 12 to 24 months. This report, part of EPRI's *FGD Equipment Issues Guidelines*, discusses developments and innovations in FGD materials technologies in the 1990s.

Objective

To describe advances and innovations during the 1990s in the materials of construction for wet lime/limestone FGD systems.

Approach

The project team reviewed EPRI *FGD Equipment Issues Guidelines* that deal with specific components of wet lime/limestone FGD systems to identify the materials issues that have become the bottlenecks for FGD operation in the 1990s. The team reviewed recent literature and conducted informal interviews with the major vendors of FGD materials of construction as well as with selected utilities to assess their experience and concerns.

Results

By the end of the 1980s, alloys had been identified that would provide adequate corrosion resistance under most FGD operating conditions at chloride levels up to 100,000 ppm. The 1990s saw the issuance of two industry consensus standards reducing the cost of high-performance alloy construction through the use of clad material. Much more sophisticated algorithms were developed to assist material selection, and a number of intermediate-cost alloys were “migrated” from other technologies for FGD service in the 20,000 to 50,000 ppm chloride range. These

intermediate alloys have not accumulated enough service time for a meaningful assessment of their long-term performance.

There were no significant developments of organic linings for FGD applications during the 1990's, though some 20-year successes with organic coatings are documented in the report. Many of the coating products of the 1970s and 1980s have been reformulated. The long-term performance of these reformulated products has not been demonstrated.

Two components—slurry agitators and the inlet chute and drum lining of ball mills have become materials performance bottlenecks as the duration between outages has increased.

C-class agitators in high chloride service have required weld build-up repairs at 3-month intervals, but a cobalt-based corrosion and wear alloy that can be applied as a weld overlay has been identified. This weld-overlay is expected to far exceed the corrosion and erosion resistance of the C-class alloys, but more experience will be required before the benefits can be determined.

Most FGD materials selection discussions have focused on long-term durability. This report identifies several products that may be useful for intermediate repairs intended to last just until the next scheduled outage.

EPRI Perspective

This report continues EPRI's longstanding commitment to research in FGD systems by summarizing a decade of work in the development of corrosion resistant materials for FGD applications. Increasing pressure to maintain high unit availability will continue to challenge the construction materials used in FGD systems. EPRI plans further work in this area as utilities bring additional FGDs on line to meet the increasingly stringent standards of the Clean Air Act Amendments

Keywords

Flue gas desulfurization

Corrosion

SO₂

Ball mills

ABSTRACT

Continuing development of corrosion-resistant materials has improved the performance and cost effectiveness of flue gas desulfurization (FGD) systems at power generating plants. This report discusses advances and innovations during the 90s in materials of construction for wet lime/limestone FGD systems. Developments in FGD alloys and organic FGD materials are described and assessed along with innovative materials for extended cycle operation of agitators and ball mills. Temporary repair products are identified that may be useful for intermediate repairs intended to last until the next scheduled outage.

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1

INTRODUCTION

The first generation (1970's) FGD construction was characterized by a general underestimation of the corrosive severity of the FGD process environment. This led to the inclusion of design features such as direct-bypass reheat outlet ducts that were discovered to create extraordinarily corrosive environments. Much of the first generation construction relied heavily upon carbon steel lined with rubber or reinforced organic resin coatings. Since the mid-1970's there has been a steady trend in the utility FGD industry toward the use of corrosion resistant alloys to withstand the hostile FGD environment.

By 1990, the selection of materials for FGD applications was approaching maturity. The industry had determined that certain design concepts—notably direct bypass reheat outlet ducts—were to be avoided because they frequently result in intractable corrosion problems.

In 1980, there was one commercial C-Class alloy (Alloy C-276) that could be used in confidence against the most corrosive of FGD environments. By the late 1990's, at least five new "C-Class" alloys, including the first alloy specifically engineered for FGD applications, were commercially available.

Materials innovation in FGD applications during the 1990's have been characterized primarily by development of standards, refinements of existing technology, and improvements of the materials engineering selection process. A few new materials have been introduced.

At the same time, there has been a fundamental change in the operational concept of FGD systems. Figure 1-1 illustrates the concept of the systems of the 1970's and 1980's. These systems were highly redundant; able to operate at full capacity with one or more absorber towers off-line. Likewise, the support systems for each absorber were typically redundant so that, for example, pump seals could be maintained "on the fly," each absorber and its support equipment were typically thoroughly overhauled at least once per year.

Figure 1-2 illustrates the advanced technology concept for future wet lime/limestone FGD systems. Conceptually, these systems may serve multiple generation units. They are characterized by a single mammoth scrubber module integrated into the base of the stack, eliminating the need for an outlet duct. The advanced technology system also has a design outage interval of two years with a minimum of redundancy.

While the advanced system *per se* has not been built at this time, a number of utilities are driving their current systems to longer and longer intervals between maintenance. One consequence is that components that were not priority problems ten years ago are becoming priority items today. Examples include agitators and certain components of ball mills.

Additionally, the change in operating philosophy is likely to spur more interest in "temporary" repair materials—materials that are expected to remain serviceable for relatively short times until the next major scheduled outage comes around.

Section 2 of this report addressed innovations and developments in alloy construction techniques and materials selection practices, as well as alloys introduced into FGD technology from other technologies.

Section 3 addresses developments in the understanding of the limitations of organic materials—reinforced organic resins and sheet elastomers used in FGD construction.

Section 4 discusses possible materials innovations to extend the maintenance cycles of slurry agitators and ball mills.

Section 5 addresses materials innovations in miscellaneous FGD system components not addressed in the previous sections.

Section 6 discusses innovative use of materials for temporary repairs—repairs intended to last just until the next major scheduled outage.

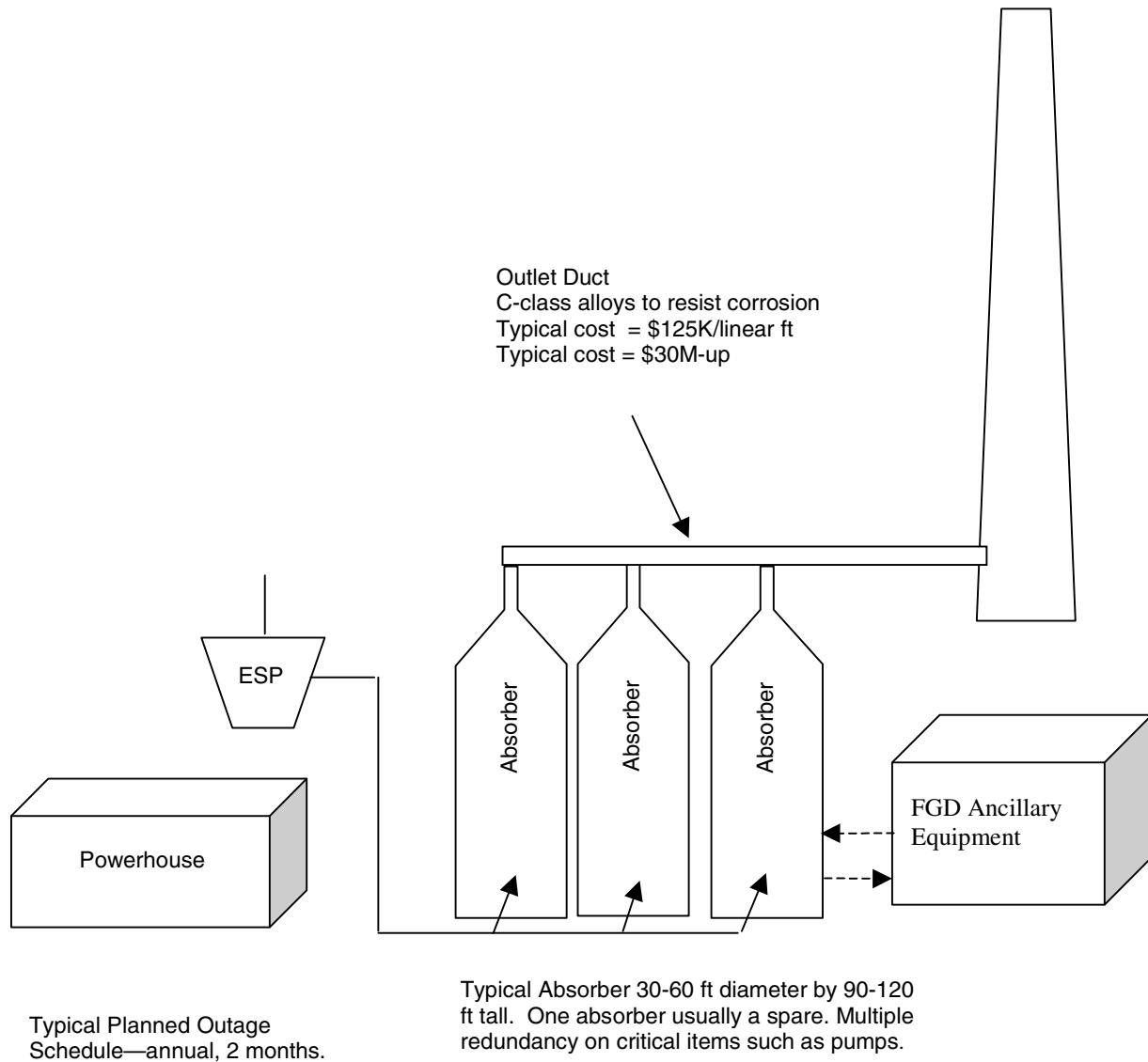


Figure 1-1
Conventional Wet Lime/Limestone FGD System, circa 1970-1990

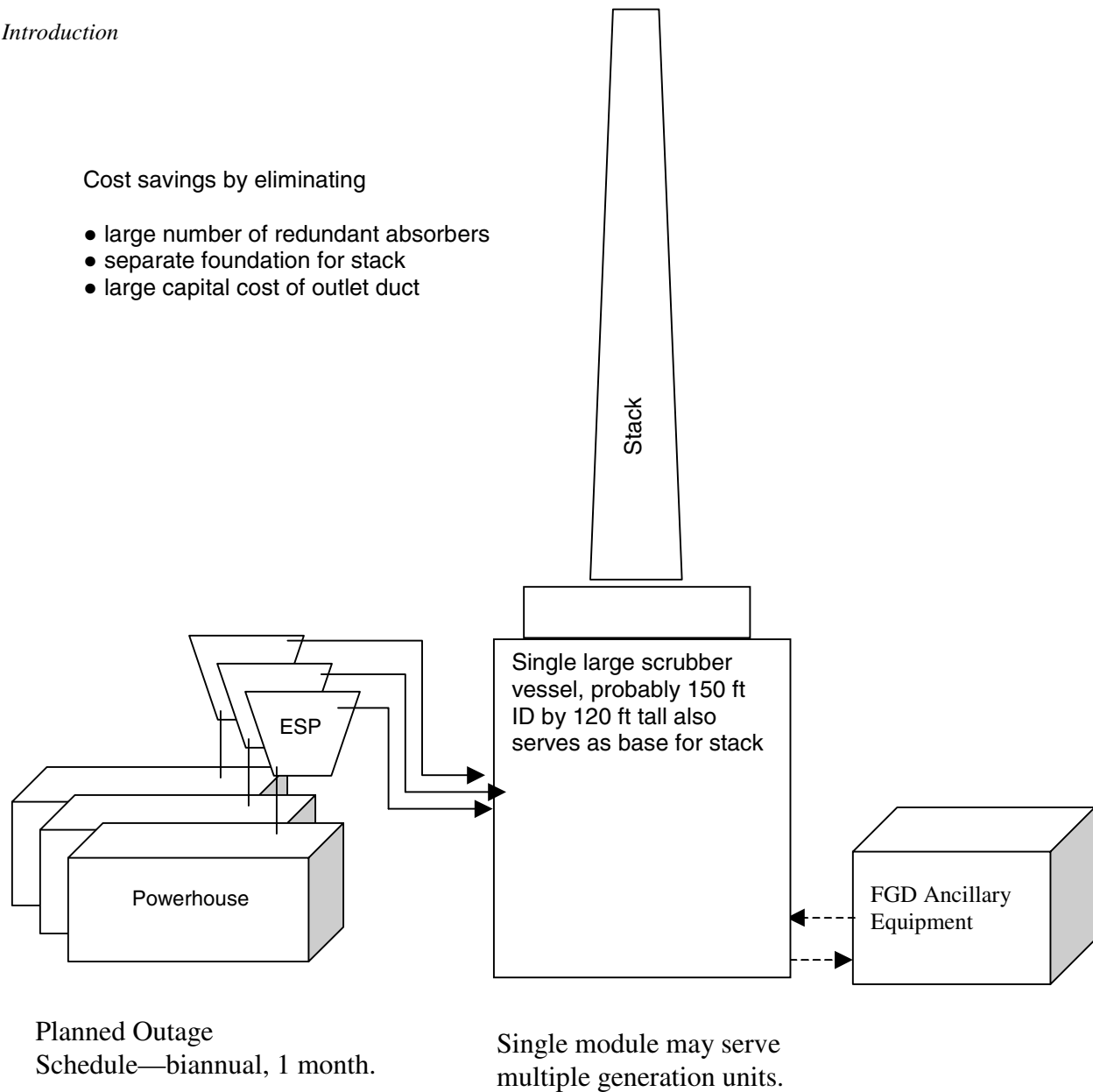


Figure 1-2
Advanced Technology Wet Lime/Limestone FGD System, circa 2001-2020

2

ADVANCES AND INNOVATIONS IN FGD ALLOY

The significant advances and innovations in FGD alloy technology during the last decade of the 20th Century were in the areas of:

- Consensus industry standards that significantly reduced the cost of construction using highly corrosion resistant alloys,
- Development of improved guidelines for alloy selection; and
- Transfer of alloy technology from non-FGD applications

2.1 Reduced Alloy Construction Cost through Consensus Industry Standards

During the 1990's, the National Association of Corrosion Engineers International (NACE-I) issued two consensus recommended practices, each of which had the result of reducing construction cost with C-Class alloys by 20 to 40% compared to conventional construction using solid alloy plate.

NACE-International Standard RP0292-98, "Installation of Thin Metallic Wallpaper Lining in Air Pollution Control and Other Process Equipment," was originally issued in 1992 and re-issued in 1998. This standard governs the application of thin (typically 0.062 inch, 1.6 mm) sheets of corrosion-resistant sheet to a carbon steel substrate to obtain the corrosion resistance of the alloy while relying on the carbon steel substrate for strength.

While some new constructions have been made using wallpapering, the technique has primarily been used to retrofit high performance alloy liners into existing FGD equipment.

NACE-International Standard RP0199-99, "Installation of Stainless Chromium-Nickel Steel and Nickel-Alloy Roll-Bonded and Explosion-Bonded Clad Plate in Air Pollution Control Equipment," was issued for the first time in 1999, and applies to the construction of FGD equipment from continuous clad plate created by hot roll-bonding or explosion-bonding¹.

"Continuous clad" means that the bond between the corrosion resistant alloy and the carbon steel substrate is effectively continuous, i.e., that the two components act as a single inseparable unit. Continuous clad plate has the advantages that structural attachments can be made to the alloy

¹ Roll-bonded clad plate is formed by pressing hot carbon steel and corrosion resistant alloy plates together between high pressure rollers so that an effectively continuous metallic fusion bond forms between the plates creating a single inseparable unit. The same fusion is achieved in explosion-bonded clad plate via the shock wave of an explosive detonation.

clad, and that there is no void space that can be flooded with corrosive condensate should one of the welds be less than perfect. On the other hand, while continuous clad plate is well suited to new construction, it cannot be easily retrofitted into existing vessels or ducts.

2.2 Innovative Guidelines for Alloy Selection for FGD Absorber Service

One of the most significant recent developments in FGD alloy technology has been the development of a mathematically quantitative criterion for FGD alloy selection based on alloy composition, the FGD process pH, and the slurry chloride concentration. This FGD Materials Selection Algorithm clarifies the behavior of the alloys traditionally used in FGD construction, eliminates much of the guesswork of alloy selection, and allows estimation of the behavior of alloys based on their compositions. The evolution of the algorithm is reviewed in Appendix A, while the results are presented in a series of figures below.

Table 2-1 lists the common names and UNS designations of 24 alloys discussed in this report. By far the largest group contains the austenitic stainless steels and nickel-base alloys. All of the alloys in this group have 100% austenitic (face-centered cubic) microstructures and contain a minimum of 12% chromium and 8% nickel. Most contain molybdenum, and all but a few contain iron. The division between austenitic stainless steels and nickel-base alloys is vague and controversial to the extent that the AMS expects to reclassify as stainless steels, a number of alloys currently classified as nickel-based. All of these alloys have the same basic microstructure and all derive their corrosion resistance from their chromium, molybdenum, and nitrogen contents. They are in fact a homogenous series with no clear functional division between the “stainless steels” and the “nickel-base alloys.” In this report, the entire group is designated as Cr-Ni Austenitic Alloys.

Table 2-1 also shows three alloys designated as Cr-Ni Duplex Stainless Steels. Like the austenitic stainless steels, these alloys all contain a minimum of 12% chromium by definition, and the actual chromium contents range from 22 to 25% (nominal). These alloys all contain between 4 and 8% nickel, which is not sufficient to produce a stable austenitic microstructure at room temperature. As a result, the microstructure consists of a mixture of ferrite (body-centered cubic) and austenite (face-centered cubic). This mixed or “duplex” microstructure enhances both the strength and corrosion resistance of the duplex stainless steels.

2.3 FGD Alloy Selection Diagrams

Figures 2-2 and 2-3 are alloy selection charts for Single-Loop and Dual-Loop wet lime/limestone FGD absorbers, reaction tanks, and recycle slurry piping for slurry supernatant (or filtrate) chloride concentrations from 100 to 100,000 ppm. Figure 2-4 presents alloy selection charts for chloride concentrations above 100,000-mg/kg chloride in the slurry supernatant or filtrate.

These charts relate the empirical threshold conditions for severe localized corrosion to the chloride resistance factor (CRF) parameter of the alloy. The CRF is a function of alloy composition and microstructure. For austenitic stainless steels and the chromium-bearing nickel-base alloys,

$$\text{CRF}_{\text{AUS}} = \text{Austenitic chloride resistance factor} \quad 2.1$$

$$= \text{Cr}_{\text{min}} + 3.3(\text{Mo}_{\text{min}} + \frac{1}{2}\text{W}_{\text{min}} + \frac{1}{2}\text{Nb}_{\text{min}}) + 16\text{N}$$

while for duplex alloys,

$$\text{CRF}_{\text{DUP}} = \text{Duplex chloride resistance factor} \quad 2.2$$

$$= 1.2[\text{Cr}_{\text{min}} + 3.3(\text{Mo}_{\text{min}} + \frac{1}{2}\text{W}_{\text{min}} + \frac{1}{2}\text{Nb}_{\text{min}}) + 16\text{N}] - 3.1$$

The “very conservative” curves in these diagrams were generated using the alloy minimum values for CRF. These curves are very conservative because actual alloy CRF’s should always exceed the hypothetical grade minimums. Indeed, typical commercial runs of stainless steels used in FGD construction average approximately 2 CRF points higher than their respective grade minimums, based on the comparison of a sizeable number of alloy heat analyses with their respective grade minimum CRF’s. The “conservative” curves in Figures 2-2 and 2-3 reflect this average 2-point difference in CRF.

The dashed vertical bars in these figures are the grade minimum CRF’s of the indicated alloys. Reading chloride from the intersection of one of these bars and the “very conservative” chloride curve gives the very conservative threshold chloride concentration for probable severe localized corrosion. Reading the intersection of the same bar with the “conservative” curve gives the conservative threshold chloride concentration for probable severe localized corrosion.

Table 2-1
Alloy Designations and Classifications

Alloy Common Name	UNS Designation	Current UNS Classification	Common Vernacular Classification	Designation In This Report
316L	S31603	Austenitic Stainless Steel	Austenitic Stainless Steel	Ni-Cr Austenitic Alloys
316LN	S31653	Austenitic Stainless Steel	Austenitic Stainless Steel	
317	S31703	Austenitic Stainless Steel	Austenitic Stainless Steel	
317LN	S31753	Austenitic Stainless Steel	Austenitic Stainless Steel	
317LM	S31725	Austenitic Stainless Steel	4Mo Austenitic Stainless Steel	
317LMN	S31726	Austenitic Stainless Steel	4Mo Austenitic Stainless Steel	
904L	N08904	Nickel-base Alloy	4Mo Austenitic Stainless Steel	
Alloy 33	R20033	Chromium-base Alloy		
Alloy G	N06007	Nickel-base Alloy	6Mo Nickel-base Alloy	
1925hMo	N08926	Nickel-base Alloy	6Mo Superaustenitic Stainless Steel	
6XN	N08367	Nickel-base Alloy	6Mo Superaustenitic Stainless Steel	
254 SMO	S31254	Austenitic Stainless Steel	6Mo Superaustenitic Stainless Steel	
Alloy 31	N08031	Nickel-base Alloy	6Mo Superaustenitic Stainless Steel	
Alloy 625	N06625	Nickel-base Alloy	9Mo Nickel-base Alloy	
654 SMO	S32654	Austenitic Stainless Steel	9Mo Ultra-Austenitic Stainless Steel	
Alloy C-22	N06022	Nickel-base Alloy	C-class Nickel-base Alloy	
Alloy 622	N06022	Nickel-base Alloy	C-class Nickel-base Alloy	
Alloy C-276	N10276	Nickel-base Alloy	C-class Nickel-base Alloy	
Alloy 59	N06059	Nickel-base Alloy	C-class Nickel-base Alloy	
AlloyC-2000	N06200	Nickel-base Alloy	C-class Nickel-base Alloy	
Alloy 686	N06686	Nickel-base Alloy	C-class Nickel-base Alloy	
255	S32550	Duplex Stainless Steel	Duplex Stainless Steel	
2705	S32750	Duplex Stainless Steel	Duplex Stainless Steel	
Zeron 100	S39276	Duplex Stainless Steel	Duplex Stainless Steel	Duplex Alloys

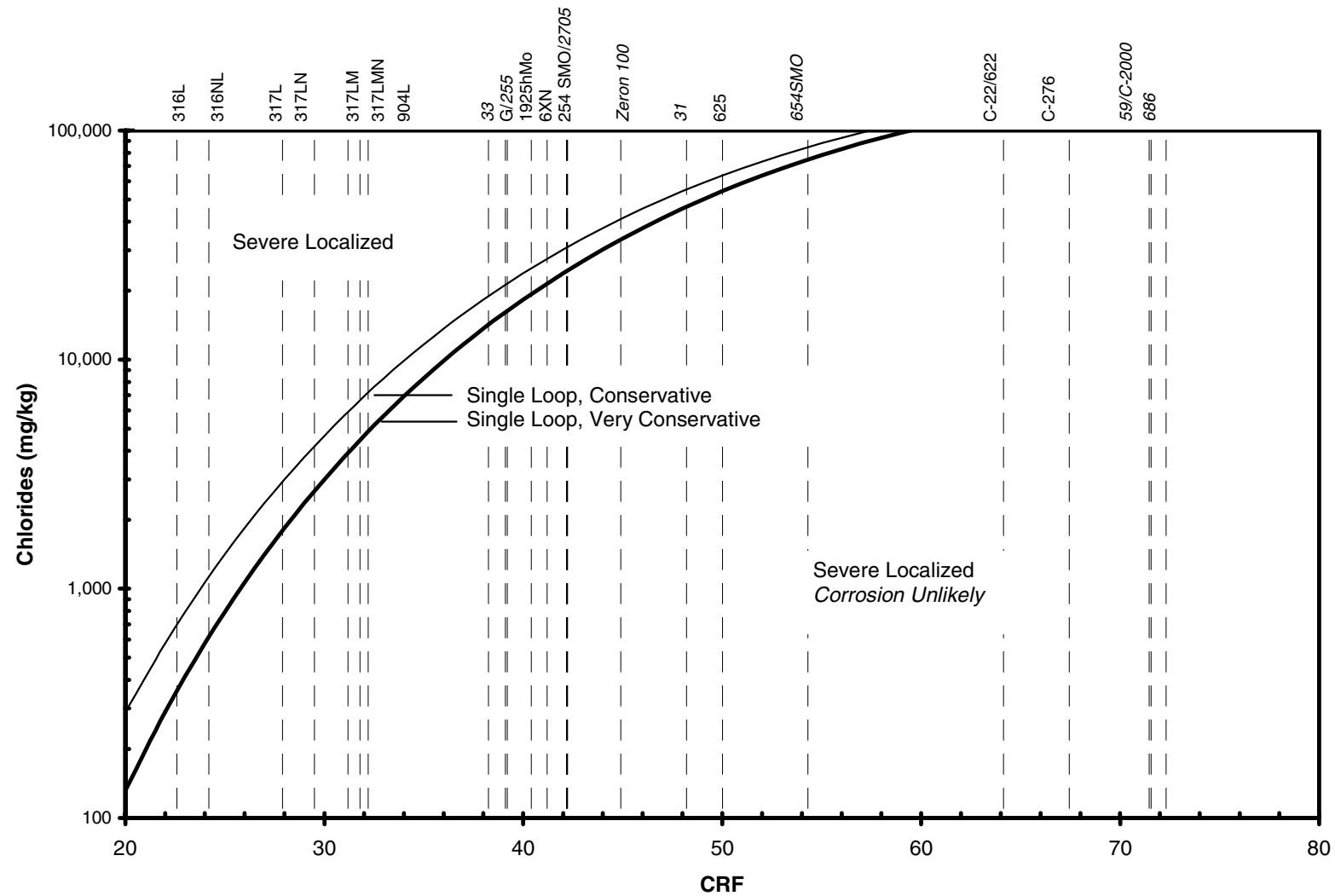


Figure 2-1

Alloy Selection Chart for Single-Loop Wet Lime/Limestone FGD Absorbers, Reaction Tanks, and Recycle Slurry Lines.
 See text for definition of CRF. *Italicized alloy designations represent recent or under-utilized alloy entries to the FGD Arena.*
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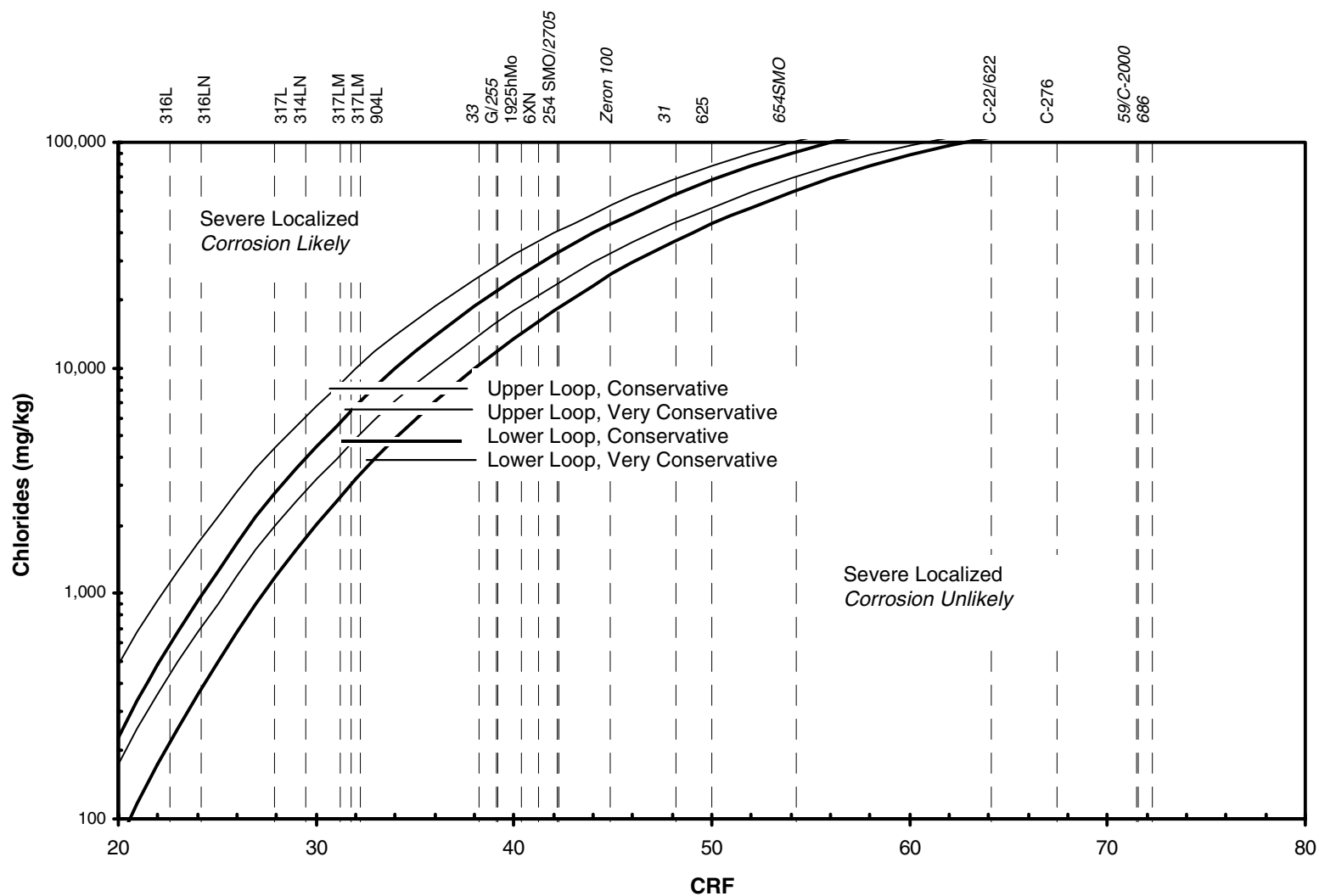


Figure 2-2
Alloy Selection Chart for Dual-Loop Wet Lime/Limestone FGD Absorbers, Reaction Tanks, and Recycle Slurry Lines.
 See text for definition of CRF. *Italicized alloy designations represent recent or under-utilized alloy entries to the FGD Arena.*
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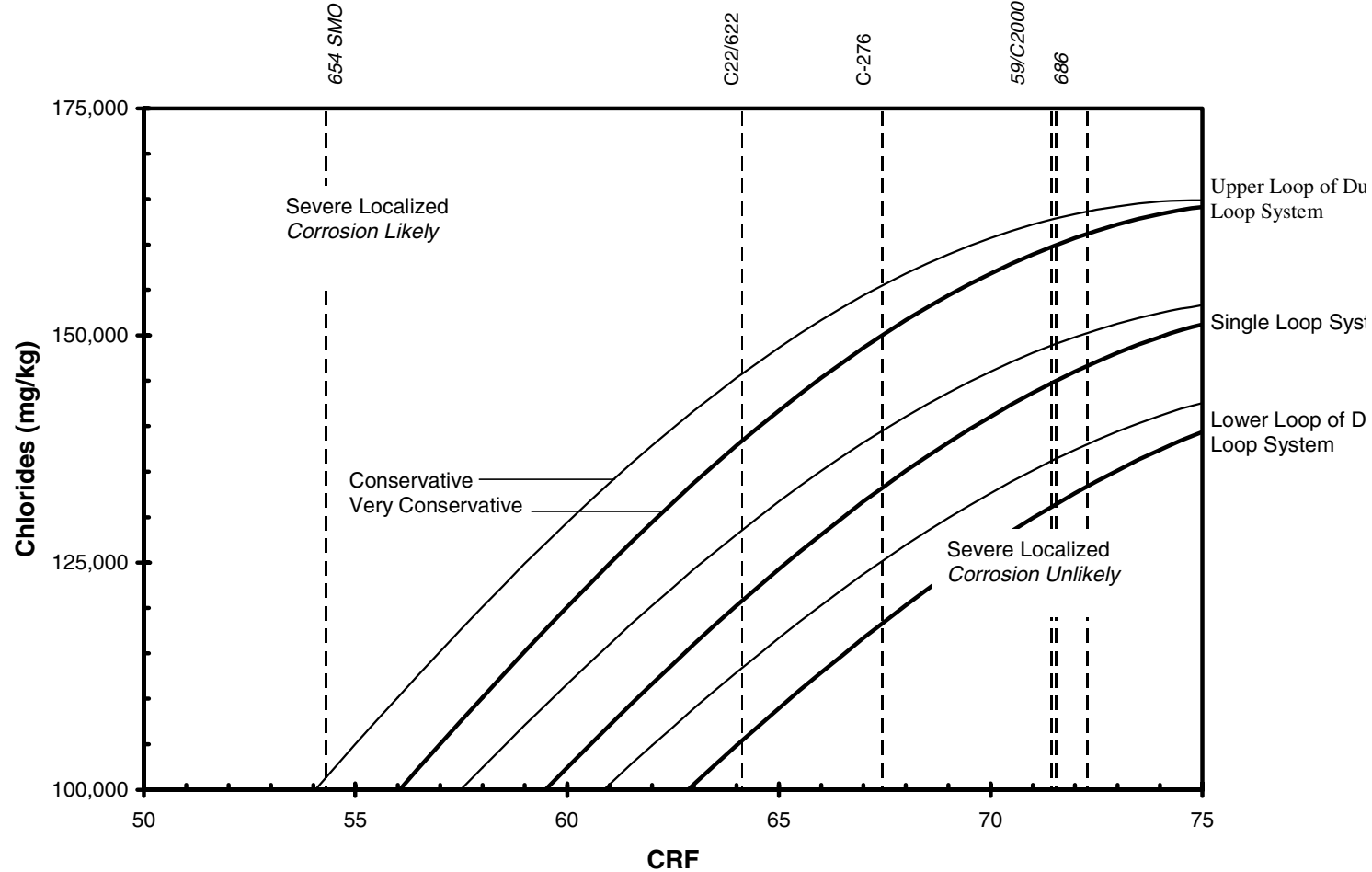


Figure 2-3
Alloy Selection Chart for Chlorides in Excess of 100,000 mg/kg.
 See text for definition of CRF. *Italicized alloy designations* represent recent or under-utilized alloy entries to the FGD Arena.
 M&M Engineering

2.4 Recent FGD Alloy Developments

2.4.1 Tier 1 Alloys

The Tier 1 alloys have CRF values of 22 – 28 and include Type 316L and 317L, plus a recent introduction to the FGD industry, Type 316LN. Type 316LN contains a controlled addition of nitrogen, which improves chloride resistance slightly. The addition of nitrogen to austenitic stainless steels is very inexpensive, and there is a general industry trend to upgrade traditional grades by nitrogen addition. It is possible, but unlikely, that Type 316LN could displace Type 316L in mill production, making Type 316L obsolete.

2.4.2 Tier 2 Alloys, “the 4Mo-austenitic Stainless Steels”

The Tier 2 alloys have CRF values of 28 – 33 and include the traditional FGD alloys 317LM and 904L. Types 317LN and 317LMN were introduced in the 1990’s in accord with the trend of alloy upgrade by nitrogen addition. Type 317L is still in production, but 317LMN has totally displaced its predecessor grade in manufacture. Type 317LM is now effectively obsolete.

2.4.3 Tier 3 Alloys, “6-Mo Superaustenitic Stainless Steels”

Some of the Tier 3 alloys are not austenitic stainless steels and not all contain 6% (nominal) molybdenum. All of these alloys, however, have CRF values between 38 and 45, and have somewhat similar resistance to chloride attack. The archetypal alloy in this group was Alloy G, now obsolete in FGD applications. When Alloy G was introduced, steel-making art was such that it was not possible to produce a 6Mo austenitic stainless steel with acceptable mechanical properties. The so-called 6Mo superaustenitic stainless steels, such as 1925hMo, 6XN, and UR SB8, were introduced as lower-cost alternative to Alloy G as the art of steel making improved. Alloy 33 is a new entry into the FGD industry from marine applications. It is apparently being tested as an absorber wallpaper alloy in Europe.

This group also contains three duplex stainless steels, Alloy 255, Alloy 2705, and Zeron 100. Alloy 255 has been successfully but not widely used in U.S. FGD applications since the 1980’s. Alloy 2705 is migrating into the FGD arena from oil production brine service applications. Zeron 100 has primarily been a European alloy. All three of these grades offer chloride resistance comparable to the 6Mo-superaustenitic grades at a fraction of the cost.

2.4.4 Tier 4—“The 9Mo Alloys”

Tier 4 has CRF values from 48 to 56. Until recently, the sole member of this group was Alloy 625, originally developed as an aerospace alloy, but subsequently found to have very high resistance to chloride attack. Both Alloys 31 and 654 SMO are recently introduced austenitic stainless steels containing nominally 8 – 9 % molybdenum. These alloys offer the corrosion resistance of Alloy 625 at a fraction of its cost.

2.4.5 Tier 5—“The C-Class Alloys”

Tier 5 alloys have CRF values of 64 or higher. The archetypal alloy of this group is Alloy C-276. Alloy C-276 was also the sole member of this group until its patent expired in the 1980's. Since then, five variants have appeared in the FGD market. These are:

- Alloy C-22
- Alloy 622
- Alloy 59
- Alloy C-2000
- Alloy 686

As shown by Figures 2-4 through 2-6, all of these alloys have chloride thresholds for probable severe localized corrosion in excess of 100,000 mg/kg in all FGD absorber, recycle tank and slurry piping applications.

The primary application of these alloys has been in FGD system outlet ducts, particularly those having direct-bypass reheat. During the 1980's and 1990's hundreds of thousands of square feet of C-Class alloys were “wallpapered” into FGD outlet ducts and stacks². NACE-International issued a Recommended Practice (RP0292) for *The Installation of Thin Metallic Wallpaper Lining in Air Pollution Control and Other Process Equipment* in 1992 with renewal in 1998. This recommended practice recognized that the greatest single challenge to a successful wallpaper lining installation is the necessity for 100% leak-tight integrity of hundreds to thousands of linear feet of seal welds.

Extreme difficulty in obtaining reliable leak-tight welds has been a recurrent problem with wallpaper applications. The consequences of weld failure are particularly serious when the seal welds are submerged. For example, the geometry of the direct-bypass mixing zone of the outlet duct at Indianapolis Power and Light's Petersburg Number 4 FGD system allowed the accumulation of several hundred gallons of acid condensate to pool on the floor of the outlet duct. When corrosion perforated a thin spot in one of the seal welds, the highly corrosive condensate flooded the gap between the C-22 wallpaper and the carbon steel shell of the outlet duct. The condensate then leaked onto the roof of the gas inlet duct, which was located directly below the outlet duct, and corroded holes in that duct as well [8].

The difficulties of obtaining 100% reliable seal welds spurred interest in duct construction using C-Class alloys hot-roll bonded or explosion bonded³ to carbon steel to reduce alloy cost while eliminating the seal weld and leakage problems associated with wallpapering.

² When “wall-papering” with alloy liners, thin sheets, typically 62 mils thick, are cut to fit, then skip-welded to the metal substrate. Subsequent sheets overlap the first sheets laid down and are seal welded to the overlapped alloy sheets and skip-welded to the substrate. The process is repeated until the substrate is entirely covered and all exposed welds are continuous seal welds.

³ In hot-roll bonding, a corrosion resistant alloy plate is fused to a carbon steel backing plate as the two plates pass through the hot rolling mill. In explosion bonding, the pressure that produces the fusion between the two plates is supplied by the detonation of an explosive. Once bonded by either method, the clad slab is then rolled to the final

NACE-International issued a recommended practice, RP0199-99, *Installation of Stainless Chromium-Nickel Steel and Nickel-Alloy Roll-Bonded and Explosion Bonded Clad Plate in Air Pollution Control Equipment*, in 1999.

Most clad plate installations have consisted of 62 mils of C-Class alloy bonded to 188 mils of carbon steel to make a total thickness of 0.25 inch. Thicker carbon steel is used as required for structural support.

These constructions have eliminated the seal-weld problem affecting alloy wallpapering, but may ultimately give less than the desired life due to uniform corrosion of at least some of the C-Class alloys. While these C-Class alloys show remarkable resistance to pitting and crevice corrosion under direct-bypass reheat conditions, Alloy C-22 and C-276 have exhibited significant uniform corrosion in the wet-dry mixing zones of direct bypass reheated outlet ducts. For example, wallpaper linings of Alloy C-22 and C-276 on the vertical wall of the direct bypass zone of the Petersburg Number 4 FGD system exhibited uniform corrosion rates of 4.5 ± 0.7 mil/yr. and 4.1 ± 0.7 mil/yr. respectively. The rates were not statistically different. The average corrosion rate of Alloy C-22 in an acid puddle on the duct floor was 10.1 ± 0.5 mil/yr. Approximately 50% of the thickness of the wallpaper lining on the floor had corroded away in just less than 3 years [8]. Despite the 20% reduction in thickness on the walls and 50% reduction in thickness on the floor, the severity of the corrosion was not apparent because it was uniform. Most inspections of wallpaper linings are strictly for pitting, and significant uniform corrosion may go undetected.

The newer C-Class alloys, Alloy 59, Alloy C-2000, and Alloy 686 are even more highly alloyed than C-22 and C-276. Their chloride resistance is greater in laboratory tests and is projected to be greater in FGD service as well. Their higher chromium contents, compared to C-276, may enhance their resistance to uniform corrosion in acid condensate as well, and Haynes International, the developer in Alloy C-2000, note that this alloy contains a small addition of copper, specifically to enhance resistance to uniform corrosion by concentrated acid condensates. The effects of these alloying additions on uniform corrosion of C-Class alloys in FGD outlet duct service have not been demonstrated at this time.

2.5 Relative Alloy Costs

The market price of nickel, a major constituent of many of the alloys used in FGD construction, historically exhibits large cyclic variation. Thus, the dollar costs of alloys, particularly those containing large concentrations of nickel, tend to be volatile. However, comparisons of relative alloy costs made over the years tend to show relatively minor fluctuation.

Alloy cost comparisons based on weight tend to be misleading for two reasons. Firstly, construction is on a square foot basis, and a realistic cost comparison must include the cost of turning billet into plate. Secondly, each square foot of plate has an associated forming and erection cost that varies little from alloy to alloy and tends to dilute the effect of material cost.

desired thickness. From an engineering standpoint, the bond of the corrosion-resistant alloy to the carbon steel is continuous.

Table 2-2 compares the relative cost of alloys and erected construction for late 1999. The dilution of material cost difference by fixed erection costs is evident. The significant cost advantages of some of the recent alloy entries into the FGD market place are also apparent.

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3

RECENT DEVELOPMENTS IN ORGANIC FGD MATERIALS OF CONSTRUCTION

3.1 Linings and Coatings on Steel Absorber and Duct Shells

3.1.1 Introduction

FGD construction in the 1970's relied heavily on sheet elastomeric and reinforced thermoset resin linings applied to carbon steel. The materials used fall into the following broad categories:

- Reinforced Thermoset Resins
 - Vinylesters
 - Novolac epoxies
 - Bisphenol-A-epoxies
 - Bisphenol-A-fumarate polyesters

Reinforced with mica (not recommended for FGD applications), glass flake, or chopped glass fiber for strength. The resins may also be filled (mixed) with silicon carbide grit, alumina grit, or alumina spheres for abrasion resistance.

These products are normally applied by spraying or trowelling, and were widely applied in absorbers, reaction tanks, and outlet ducts.

- Sheet Elastomeric Linings
 - Compounded⁴ natural rubber
 - Compounded chlorobutyl-natural rubber blends
 - Compounded neoprene
 - Fluoropolymer sheet

Compounded natural rubber with a hardness of approximately 40A (Shore) was the elastomeric lining of choice during the 1970's, when abrasion resistance was perceived as the life-determining property of the lining.

⁴ "Compounded" or "compounding" are rubber-making terms that denote a mixture of polymer, carbon black, curing agents, fillers, plasticizers, etc., that produce the desired properties in the cured product.

By the early-1980's, compounded chlorobutyl (actually a blend of natural rubber and chlorobutyl polymers containing 15-20% natural rubber) with a hardness of approximately 60A (Shore) had become the industry standard [1].

Use of neoprene has been limited almost exclusively to situations where building codes required that the lining not support combustion.

3.1.2 Development 1-Understanding of the Fundamental Failure Mechanism of Thermoset Resin and Sheet Elastomeric Linings

One of the significant developments of the late 1980's and early 1990's was the recognition that the life of both reinforced thermoset resin and sheet elastomer coatings and linings are inherently limited by the semipermeable properties of the barrier material through a phenomenon called the "cold wall effect." The cold wall effect occurs whenever the process side of the barrier material is both wet and warmer than the substrate side of the barrier material.

Moisture permeates through the lining or coating in a vapor-like state. The process side of the lining is in contact with slurry at approximately 120 to 140°F in the absorber or reaction tank, or with carry-over moisture and condensate in the outlet duct. The lining-substrate interface is essentially at atmospheric temperature, resulting in a water vapor pressure differential on the order of 1–3 psi through the lining or coating, resulting in moisture diffusion toward the cooler substrate. When moisture arrives at the substrate, it accumulates at microvoids along the metal/lining interface until the microvoid vapor pressure reaches the dew point, at which time the vapor condenses as liquid water. This liquid water leaches ions from the barrier material and from any contamination on the substrate surface. Diffusion of moisture through the barrier material is now driven by osmosis⁵, with typical osmotic pressures of 2 – 3 atmospheres⁶. Long before the infusing water can develop such pressure, the continued infusion of water to the barrier-substrate results in blisters that eventually rupture, allowing the corrosive FGD liquids to attack the substrate.

This mechanism explains why successful coating or lining application requires such exacting surface preparation. One of the essential functions of the surface preparation is to reduce the concentration of ionic contaminants along the barrier-substrate interface to the absolute minimum so that the ionic strength of moisture at the metal/coating interface will be as low as possible, slowing blister growth by osmosis. This mechanism also accounts for the common observation that both reinforced thermoset resins and sheet elastomeric linings tend to deteriorate more rapidly downstream of the mist eliminators than upstream, even in the absence of reheat. Upstream of the mist eliminators, the barrier material is wetted with slurry, while downstream the barrier material is wetted mostly by condensation. The difference in ionic strength between the slurry and blister liquid is less than the difference between the ionic strength of the

⁵ When two solutions having different ionic strengths (i.e., different concentrations of dissolved ions) are separated by a semipermeable membrane, water molecules will diffuse through the membrane from the less concentrated solution into the more concentrated solution until the ionic strengths are equal.

⁶ The osmotic pressure is the pressure that must be applied to the more concentrated solution to halt the diffusion of water through the semipermeable membrane.

condensate and the blister liquid. Therefore, the osmotic driving force for blister growth is less on the slurry-wetted lining than on the condensate-wetted lining [2].

3.1.3 Development 2-Recent Trends

A steady move away from the use of reinforced thermoset resins and sheet elastomeric linings in absorbers and outlet ducts began in the 1980's and continued through the 1990's. By the early 1990's it had become apparent that the mean life expectancy without major repair/replacement of both reinforced thermoset resin coatings and sheet elastomer linings in absorbers was approximately 8 years upstream of the mist eliminators and 6 years downstream of the mist eliminators [2]

3.1.4 Development 3—Some Noteworthy Successes

There are some noteworthy exceptions. In 1988, 90,000 ft² of the steam-reheated outlet duct of the LaCyne Power Station (Kansas City Power and Light Company) was lined with Trowelon 325SL⁷, a “plastalloyed” system of phenolic, epoxy, and melamine copolymers reinforced with an inert filler. The material was applied to a thickness of 1/8-inch and cured at 180°F for 16 hours. The area lined with 325SL had previously been lined with a trowelled flake glass polyester and with a 40-mil sprayed vinylester. Each of these prior coatings had failed in less than four years. As of March 2000, the 325SL was reported to be in “good condition without blistering or cracking [3-5].”

The second noteworthy success demonstrates the absolute criticality of correct application to the success of a reinforced thermoset resin lining. Monongahela Power's Pleasants Station Unit 1 has a 1,000-ft reinforced concrete stack with a 900-ft carbon steel liner, the outlet duct breaching being approximately 100 feet above grade [6-8]. In 1979, the 900-ft tall by 20-ft diameter carbon steel liner was coated with Plasite 4005⁸. Plasite 4005 was a three-part heavy-duty vinylester resin combined with special curing agents and inert flake pigment/reinforcement, capable of continuous dry exposure at 380°F with dry excursions to 460°F.

The application specifications for Plasite 4005 required a 4-mil anchor profile and a SSPC-SP5 white metal blast, as well as that the Plasite 4005 be applied in three spray applications to a total dry film thickness (dft) of 35 –45 mils. The surface was incorrectly prepared in some areas, and the coating was applied in excess of 50 mils dft. The areas where the coating thickness exceeded 50 mils spalled off during the first plant startup and spewed out of the stack. The areas where the coating was applied to the correct thickness remained intact.

Under warranty, the applicator blasted off the failed lining, correctly prepared the steel surface, and reapplied the Plasite 4005 to the prescribed 35 –45 mils under close supervision and inspection. Plant start-up occurred without incident. Close visual inspection in 1998 showed no

⁷ Neither the mention of a particular vendor nor product is to be construed as an endorsement or to imply that the vendor or product cited is superior to comparable alternatives.

⁸ Plasite 4005 was subsequently reformulated to replace asbestos reinforcing fibers with a non-hazardous inert reinforcing material. The reformulated product is designated as Plasite 4300.

significant damage. The stack was again inspected in 1999, with the conclusion that the bottom 18-ft of the 900-ft stack (2% of the coated area) was degraded enough to warrant replacement after 20 years of service [8].

The carbon steel stack liner of the Cholla Power Station was lined with Plasite 4005 in 1978 [9]. According to Plasite, this lining has required only occasional spot repairs as of 1999 [8].

3.1.5 Development 4—The Reformulation Problem

From the discussion of the cold wall effect, it is clear that—factors such as substrate surface preparation and through-wall thermal gradient being equal—the life expectancy of a reinforced thermoset resin or sheet elastomer lining is a function of its thickness, moisture permeation resistance, and the strength of its bond to the substrate.

The moisture permeation resistance and substrate bond strength are the result of the total formulation of the barrier material, the specific polymers used as well as the fillers, catalysts, curing agents and, in the case of reinforced thermoset resins, the solvents used.

Unlike the specifications for alloys, which are open records, the formulations of reinforced thermoset resin and sheet elastomer products are closely held trade secrets, leaving the purchaser no recourse by which to verify that the product offered today is truly comparable to the one with promising service experience that serves as the basis for the current selection.

Virtually all of the reinforced thermoset resin lining products on the market today have been reformulated within the last ten years to meet requirements for low volatile organic carbon (VOC) emissions. These reformulations drastically altered the solvent systems and frequently required changes in catalysts and curing agents as well. Based on results of accelerated laboratory tests, the manufacturers offer these reformulated products as equivalent to the high VOC products that they replaced. However, the long-term properties of these reformulated products may not be comparable. These low-VOC reformulations are in fact new products that have not been demonstrated in long-term FGD service.

The new low-VOC reformulations are at least designated as new products. A more subtle form of reformulation also occurs as manufacturers change sources of the ingredients of their coating or lining products. The bisphenol-A fumarate and associated catalysts purchased from Source A may not yield exactly the same properties as the bisphenol-A fumarate purchased from Source B for example. Similar “source reformulations” also occur within the rubber lining industry as manufacturers shop for more economical sources of ingredients. The subtle differences in behavior may not be significant in less hostile conditions, but can be significant under FGD conditions. In 1983, EPRI identified such product variation as one of the major contributory factors in the failure of rubber linings in FGD applications [1].

3.2 Rubber-Lined Steel (RLS) and Rubber-Lined Rubber Covered Steel (RCLS) Pipe

While there has been a steady trend away from the use of rubber linings in absorbers and outlet ducts, the popularity of rubber lined steel (RLS) pipe for external recycle piping, and of rubber-lined, rubber-covered steel (RCLS) for slurry spray headers does not appear to have decreased significantly. Piping within the absorber does not experience a significant through-wall thermal gradient, so there is no cold wall effect to cause moisture permeation through the lining or coating in the first place. The rubber-lined pipe external to the absorbers does experience thermal gradients comparable to linings within the absorber, but the lining is also exposed to operating pressures of 2-3 atmospheres. This is sufficient to counterbalance the osmotic pressure of moisture at the rubber-substrate interface, suppressing blister formation inside the pipe. The result is that RLS recycle piping and RCRLS slurry piping can give many more years of service than the same elastomeric lining applied to the vessel wall [10].

Several investigations of failure of RLS FGD slurry piping demonstrated the critical importance of proper and adequate curing of the rubber once the lining was installed. RLS and RCLS pipe is normally cured in autoclaves using 15-30 psi steam. This procedure results in the optimal cure of the rubber lining. Failures have resulted from inadequate curing of the flanges of large diameter pipe when the sections were too large to autoclave. The ends of the pipe were blinded off with plywood and atmospheric steam was injected to cure the rubber. Small spacers were inserted between the plywood and gasket face allowing steam to flow across the gasket face. While the cure time was adequate for the rubber lining in the pipe, it was not adequate for the flange faces [11].

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4

INNOVATIVE MATERIALS FOR EXTENDED-CYCLE OPERATIONS OF AGITATORS AND BALL MILLS

Historically, agitators and ball mills have been accepted as necessarily high maintenance items. The leading edges of agitator blades undergo erosion or erosion corrosion as they slice through the slurry. Abrasive wear is the limiting damage mode for ball mills.

4.1 Innovative Materials for Extended-Cycle Agitator Operations

The current trend toward construction of large capacity FGD systems with very limited redundancy coupled with the outage cycle extension to 18 to 24 months can be expected to result in a refocus of attention on the slurry agitators of the reaction tank. These agitators may be either vertical or side-mounted, with radial, axial, or mixed flow. Open blade designs (which appear similar to marine propellers in many cases) are more common than closed or shrouded designs. In general, the reliabilities of side-mounted and vertical agitators appear to be approximately equal, as do the reliabilities of open and shrouded blade designs [1].

4.1.1 *Materials Selection*

The majority of first-generation agitators had carbon steel armatures covered with natural or chlorobutyl rubber. Rubber-covered steel impellers are still popular today, but require approximately annual repair of the rubber.

More efficient impeller designs are possible with all-alloy blade construction. Alloy mechanical properties and resistance to corrosion, erosion, and corrosion govern materials selection. Superaustenitic stainless steels appear to be reliable at chloride concentrations up to between 20,000 and 30,000-ppm chloride, as does Ferralium 255.

Cast Alloy C-276 was selected for the agitator blades of a hypersaline (greater than 20,000-ppm chloride) FGD system burning high-sulfur eastern coal. While C-276 has demonstrated resistance to chlorides at very high levels under FGD service conditions, the C-Class alloys as a family are not noteworthy for their resistance to erosion and erosion corrosion. One utility with cast Alloy C-276 agitator impellers found it necessary to weld repair the blades every three months [1].

To Mechanical & Materials (M&M) Engineering's knowledge, cobalt alloys have not been used in this application, but M&M Engineering believes that one cobalt based alloy, UNS R31233, applied as a weld overlay hard-facing, may greatly extend agitator blade life whenever excessive wear encountered. UNS R31233 is available as Haynes Ultimet®.

Ultimet® and Alloy C-276 show virtually identical corrosion behavior in accelerated laboratory tests, for example 11.5% sulfuric acid plus 1.2% hydrochloric acid plus 1% ferric chloride plus 1% cuprous chloride solution as well as 10% ferric chloride solution, used to compare resistance to localized corrosion [2]. Alloy C-276 and Ultimet® were exposed side by side to acid condensate in the bypass reheat zone of an FGD outlet duct. The Ultimet® showed no visible corrosion while the Alloy C-276 corroded at a rate of 4-mpy [3].

Haynes International represents that Ultimet® can be applied as a weld overlay on carbon steel, austenitic stainless steels, and the chromium-containing nickel-base alloys using GTA, GMA, SMA, SMAW, and SAW. Haynes recommends a single-layer deposit of 0.125 to 0.188 inch (3.0 to 4.8 mm). Haynes estimates that the overlay would cost \$300 to \$450 per square foot. It is likely, however, that only critical areas along the leading edges of the agitator blades may require Ultimet® hard facing to extend time between repair by at least a factor of six relative to Alloy C-276 [2].

Ultimet® is not to be confused with the various Stellite cobalt wear alloys, widely used in FGD applications for "pigtail" slurry nozzles. Stellites contain approximately 1% carbon and owe their wear properties to the formation of extremely hard islands of chromium carbide within a cobalt matrix. Because the majority of the chromium is bound to carbon and not available to form a protective passivation film, alloys of the Stellite family do not have high resistance to chlorides. When exposed to slurry in reaction tanks, Stellite 6B has less resistance to chloride pitting than Type 316L stainless steel. Ultimet, on the other hand, is a low carbon alloy with high chromium and molybdenum contents.

4.1.2 Operational Considerations

Agitators are susceptible to a variety of system-specific operational problems with the result at a particular design may perform well at one site and poorly at another. One major concern, regardless of material of construction is resonance and harmonic interaction with the slurry. Resonance occurs if the natural frequency of the agitator is close to its operating speed, resulting in heavy vibration and fatigue failure of the shafts. Harmonic interaction refers to the influence of one agitator upon another transmitted through the slurry.

Care must be exercised to review the dynamic damping properties when considering alternative materials for agitators. For example, one utility specified that replacement agitators would be fabricated from Alloy C-276 rather than the previously used material—an obvious upgrade in corrosion resistance. However, the damping properties of Alloy C-276 were significantly different with the result that the shaft frequency was at the critical frequency of the agitator. The "improved" agitators suffered rapid fatigue failure of the shafts. The problem was resolved by shortening the shaft and changing the impeller rotation speed [1].

4.2 Innovative Materials for Extended-Cycle Ball Mill Operations

Most limestone FGD systems grind the reagent limestone in closed circuit, horizontal wet ball mills. Two components of the ball mill limit time-between-outages as a result of severe wear. These two components are the reagent feed chute and the lining/lifter bars of the mill itself.

4.2.1 Feed Chute

Figure 4-1 is a schematic diagram of the feed chute of a horizontal ball mill. The primary wear zone, indicated in this figure, results from the impact and abrasion of limestone reagent chips or chunks being dropped into the chute.

Many materials, such as ceramic tile, that would provide excellent protection against sliding wear from the reagents being introduced to the mill, but would be immediately destroyed by the impact of chunk stone and mill balls dropping into the chute.

Up until recently, the chutes have been made of either very hard steel or carbon steel lined with hard rubber (ebonite). Service life may vary from a few months for mills faced with high demand and poor quality rock to a few years for low-demand units receiving premium quality limestone.

One utility has recently (in 2000) begun experimenting with flame-sprayed powder metallurgy “chromium carbide” as a wear protection surface [1]. Time will tell if this wear coating has sufficient impact strength to be an improvement. Weld-overlayed chromium carbide on carbon steel would have significantly greater impact strength. A 0.25-inch (6.4-mm) overlay on 0.5-inch (12.5-mm) carbon steel would cost approximately \$50/ft² [4].

Note that chromium carbide overlays can be used in this application but not for agitators because significant corrosion resistance is not required. While chromium carbide coatings are high in chromium, most of the chromium is bound to carbon and does not contribute to corrosion resistance.

The coatings traditionally used for FGD applications would be of no benefit in the ball mill feed chute because they would be shattered by the impacting rock and balls. However, there are some wear coating systems, notably Trowellon 117CL® and Duomar Ultra-Build®, used to line rock chutes in mining operations, suggesting that they may be tough enough for this service. Each of these products is an epoxy matrix filled with silicon carbide grit for wear resistance against small particles and alumina spheres for wear resistance against large particles. These coatings are estimated to have up to eight times the wear resistance of hardened nickel-iron [5,6]

4.2.2 Mill Liner and Ball Lifters

Figure 4-2 shows the traditional mill liner and ball-lifter arrangement. The liner and lifter bars are hard rubber panels bolted into place (the bolts are not shown in Figure 4-1). As the drum rotates, balls lodge on the rising shelf of the lifter bar, then roll off and fall on the rock chips below as the drum rotates. Sliding abrasive wear gradually grinds away the rubber lining and rapid damage to the shell will occur if the rubber lining wears through. Relatively frequent inspection may be required to assure that the rubber lining does not wear through.

Svedala Grinding has developed a “poly-met” lining, depicted schematically in Figure 4-3. The lifter bars are reinforced with hard steel wear bars that take the brunt of the abrasive wear of the recirculating balls. Svedala Grinding claims that the poly-met lining will last about 2.5 times longer than the conventional rubber lining shown in Figure 4-1 [1]. Time will tell.

Simply lining the mill drum with weld overlay chromium carbide would probably not be acceptable because the rubber lining provides significant sound damping in addition to providing wear protection. Figure 4-4 shows a conceptual design for a chromium carbide hardened liner that retains the damping properties of the rubber liner. The inner shell consists of pre-shaped carbon steel plate segments with integral lifter bars. The plates are overlaid with chromium carbide and are held in place by bolting just as the current rubber linings are secured. It is estimated that this hybrid lining could extend lining life by a factor of five.

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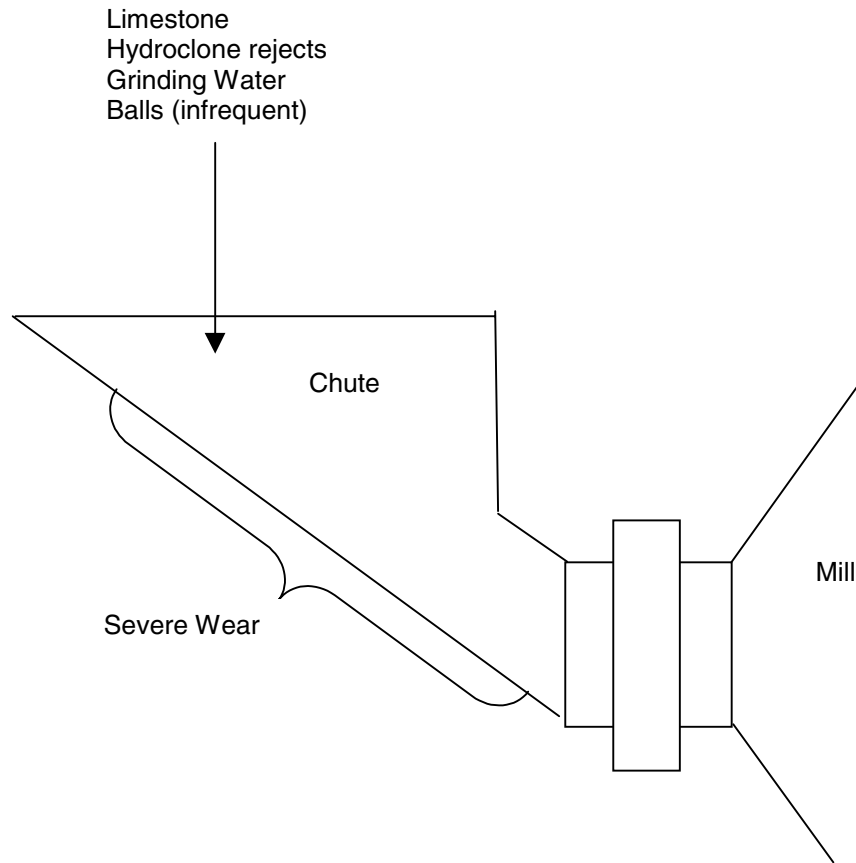


Figure 4-1
Schematic of Horizontal Ball Mill Feed Chute

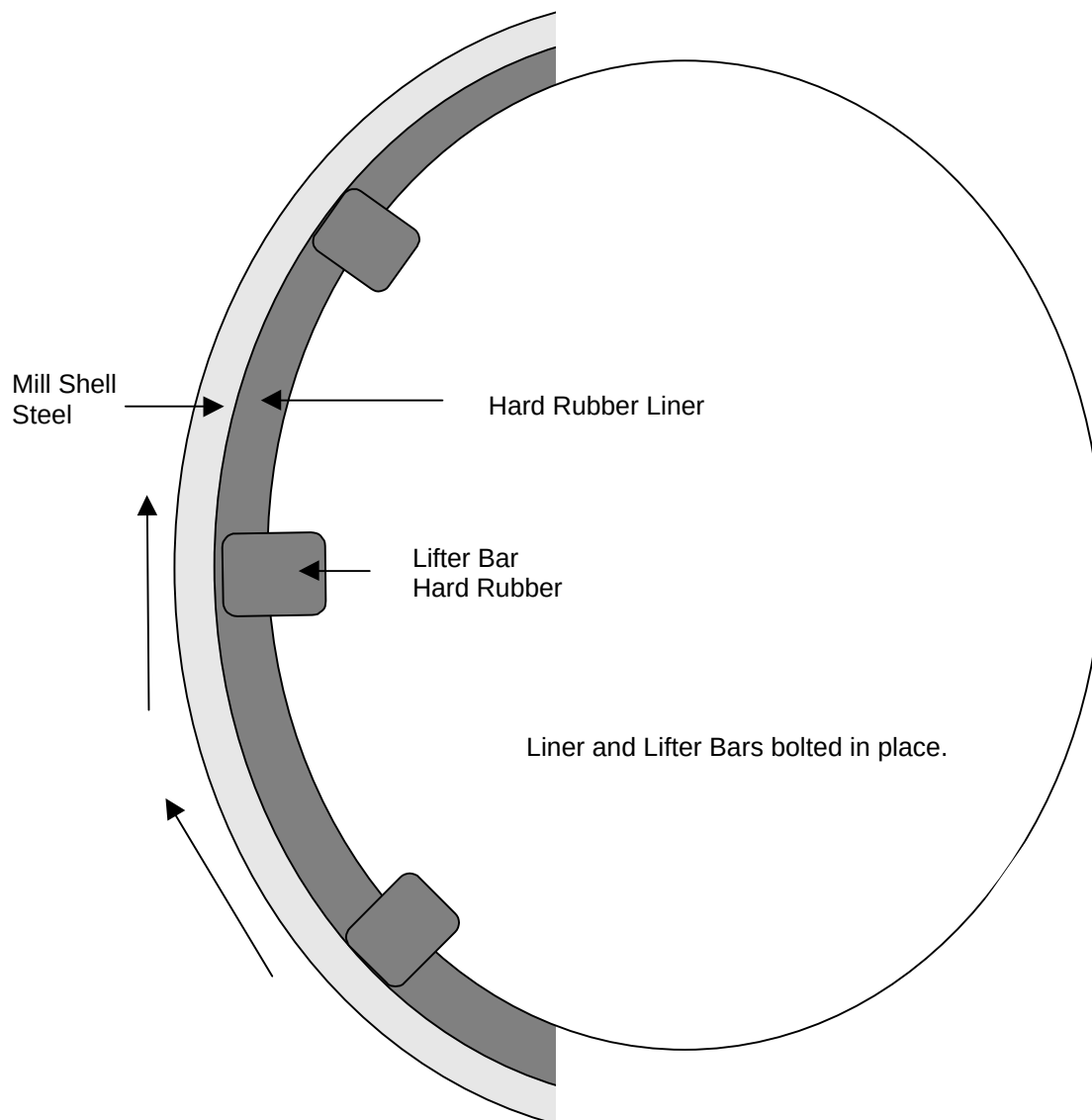


Figure 4-2
Typical Hard Rubber Ball Mill Lining and Lifter Bars

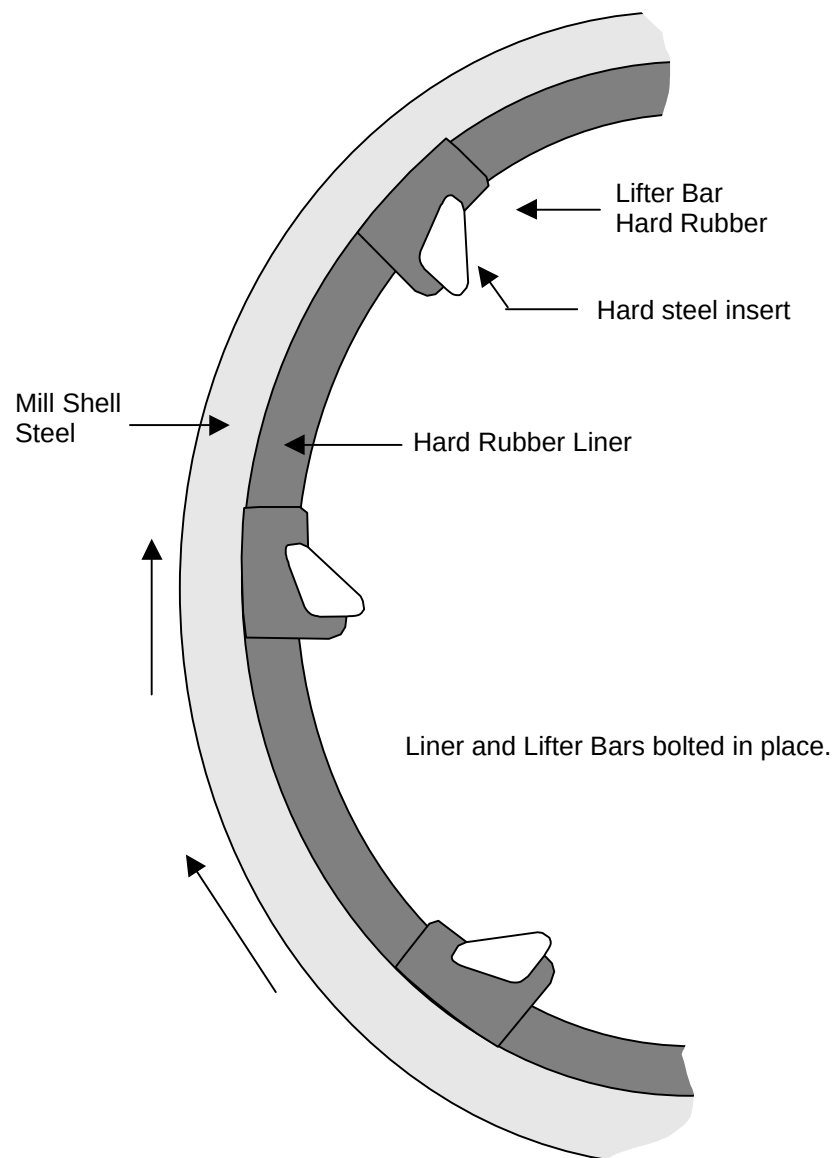


Figure 4-3
Hard Rubber Lining with Svedala Hard Steel Wear Inserts

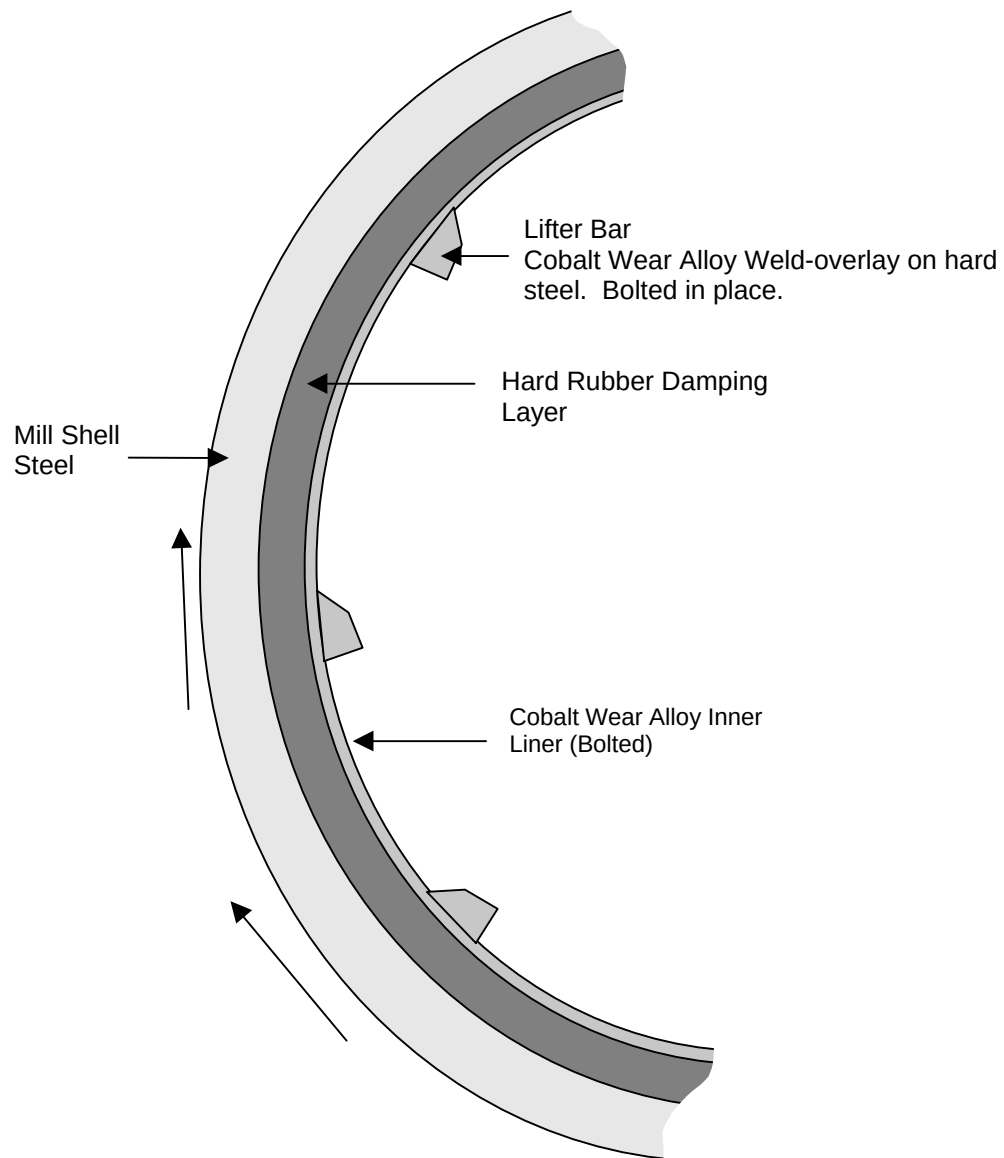


Figure 4-4
Conceptual Wear-Alloy/Rubber Ball Mill Liner

5

MISCELLANEOUS MATERIALS AND COMPONENTS

5.1 Slurry Pumps

5.1.1 *Natural Rubber Lined Pumps*

The recent development in natural rubber lined slurry pumps has been a steady migration to alternative materials. Rubber liners were once thought desirable for FGD pump applications because they are relatively impervious to high chloride levels (e.g., 50,000 ppm or greater), are suitable for the normal range of temperature and pH, and have very high abrasion resistance. However, a recent industry survey [1] showed that rubber-lined slurry pumps with rubber-covered impellers typically require annual replacement of the rubber components. Several factors likely contribute to the failures. Rubber impellers tend to lose material near the tips of the impeller with time, due to either damage by tramp material, degradation, or erosive wear due to the formation of vortex flow [2]. Once rubber loss begins, the irregularities in the linings affect slurry flow patterns in the pump, and accelerates liner wear in isolated areas. If not caught soon enough, liners can wear through, resulting in erosion damage to the cast iron casing halves.

In addition, rubber components are susceptible to damage by oversize and/or sharp objects such as scale or nozzle parts entering the pump and making cuts. Once cut, rubber has very low resistance to tearing and peeling. When large pieces break off, they can collect in slurry nozzles and block slurry flow [1].

5.1.2 *Polyurethane Liners*

Both the original equipment pump manufacturers and third party after-market vendors have been supplying polyurethane casing linings and polyurethane covered impellers as alternative to natural rubber. Townley Manufacturing Company⁹ is such a third party vendor, one that provides replacement parts for utility FGD service. Townley and others can provide urethane liners that some utilities have found to provide longer service than natural rubber liners. Depending on the manufacturer and model of pump, these can be either bolt in or bonded liners.

Not all of the utilities using urethane casing and impeller liners have experienced improved performance over natural rubber, though. One utility reported that, on average, urethane-lined impellers were lasting about the same period of time as rubber-lined impellers [2]. Furthermore, they observed that the natural rubber lining tended to wear away gradually, while the urethane

⁹ Neither the mention of a particular vendor nor product is to be construed as an endorsement or to imply that the vendor or product cited is superior to comparable alternatives.

tended to fail by having large pieces break away. The latter is undesirable because the larger pieces can plug openings in slurry nozzles. This utility is converting to high chrome impellers, with a mixture of natural rubber and urethane casing liners [1].

5.1.3 Alloy Pumps and Impellers

Warman's standard design for FGD recycle slurry service is to use high chrome cast irons for impellers and for the throatbush or suction liner insert. As a class, high-chromium are high hardness alloys with considerable corrosion resistance. Warman's standard high-chrome (nominally 27% chrome) alloy has a minimum hardness of 600/650 Brinell, compared to approximately 150 Brinell for Type 316L stainless steel, and Warman recommends its use for up to 20,000 ppm of chloride in the recycle slurry. They offer a 28% chromium cast alloy for up to 50,000 ppm of chloride.

Townley also offers alloy replacement impellers and liners for most pumps used in FGD service. Their standard "high-chrome" alloy is a 28% chromium, but they reportedly can offer other alloys as needed to account for fluoride and chloride levels, and particle abrasiveness at individual FGD systems. Other materials Townley has used include a "super chrome" alloy (>30% chromium) and a proprietary "SS400" alloy. Townley also offers complete replacement of all of the wetted parts in some pumps with high chrome or other alloys. Instead of using replaceable liners, these parts replace the original pump casing with solid alloy pieces that bolt up to the original pump pedestals [1].

Phase I plants (those started up in the 1994/1995 timeframe for compliance with Title IV of the 1990 Clean Air Act Amendments) that were originally specified with high chrome impellers and suction liner inserts have generally obtained good service out of these materials. Most of these have seen five plus years of service with all of the original wetted parts. Townley reports some alloy pump parts that have seen seven to nine years of service in FGD applications without significant wear.

Many utilities have one or more pumps in a trial application of alloy impellers and/or liner pieces, with the intent of converting all of their pumps over time if the trials prove to be effective.

5.1.4 Pump Shaft Seals

During the 1990's, the FGD pump industry switched from the packed gland seal designs of the 1970's and 1980's to mechanical seals. Nearly every Phase I FGD system installed in the mid-90's uses the BW/IP International (now Flowserve) RIS mechanical seal in this application. This is a flushless (does not require any seal water) seal that uses a single, flexible rubber-in-shear element rather than springs or bellows to pre-load the seal surfaces. The use of rubber rather than springs or bellows reportedly makes the seal less likely to clog. The seal faces are either tungsten carbide or silicon carbide. The seal is cooled by slurry flow on the backside of the seal.

A survey of five Phase I FGD systems included more than 50 recycle pumps in total, many of which have been in service for 5-1/2 years. Of those pumps, only one mechanical seal failure

was reported. This one failure was reportedly a result of the pump mechanic inadvertently setting the seal clearances too tight during routine pump maintenance. The remainder of these seals had run virtually untouched over this time period. One site did report that they occasionally experience minor slurry leaks from their seals, which could be eliminated with a water flush of the seal [1].

5.2 Piping

5.2.1 EHDPE Piping

The single significant recent materials development in the area of FGD piping has been the introduction of extra-high density polyethylene (EHDPE) pipe. The pipe is typically used for small diameter (4 to 6-inch) applications such as limestone feed scrubber blowdown, or thickener underflow.

One utility has been using EHDPE pipe in 24- and 36-inch diameters for recycle slurry feed and return piping for seven years without apparent difficulties. This utility also wanted to install 42-inch EHDPE pipe but 36-inch is the largest commercially available diameter rated for the temperature-pressure of FGD slurry piping [1]. The limitation arises because the strength of UHMWPE decreases rapidly with rising temperature. Thirty-six inch diameter EHDPE pipe for slurry recycle duty requires a wall thickness of 4.8 inches due to this effect. The required wall thickness for 42-inch EHDPE would be 5.6 inches (in the 4 to 6 inch diameter range, the required wall thickness is 0.5 to 0.67 inch) [3].

Despite the large wall thicknesses compared to most other materials, EHDPE is comparatively inexpensive, inert to FGD process chemicals, and highly abrasion resistant. The material is also very light, having a density less than water.

5.2.2 FRP Piping

Fiber reinforced plastic (FRP) pipe for FGD slurry applications is a multilayer laminate of bisphenol-A fumarate or bisphenol-A Novalac resin and reinforcing glass strands (fiber glass). FRP for FGD service has an inner “gel coat” composed of resin without reinforcing fibers, as well as a similar exterior gel coat. These layers protect the glass fiber laminate from degradation by the FGD slurry. A sure sign of the approaching end of the useful life of FRP pipe is the appearance of fiber bloom, a fuzzy surface appearance due to protrusion of delaminated glass fiber stubble from the surface of the pipe.

While there have not been any major product developments in FRP piping technology for FGD applications during the 1990’s, it has become apparent that some of the straight-run FRP piping is nearing the end of its service life after approximately 12 years of operation, as indicated by signs of erosion and exposure of the reinforcing glass mat.

Where the affected surfaces are accessible, it may be possible to extend the life of the pipe by resurfacing; fairly common practices in the maintenance of large FRP structures like tanks and stack linings. The damaged surface is abraded, chemically cleaned, and a new layer or layers of

gel coat are applied. In some cases, the topcoat is impregnated with silicon carbide grit to increase abrasion resistance [4].

5.3 References

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2. Conover, M., and Ellis, P., *Causes of FGD Construction Materials Failures*, Vol 3: January 1987-May 1993, Electric Power Research Institute, Palo Alto, CA, September 1994.
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6

INNOVATIVE USE OF MATERIALS FOR “TEMPORARY” REPAIRS

Virtually all published research into materials performance in FGD applications has focused on obtaining the longest possible service life. There are circumstances, however, in which long-term durability gives way to the need for a “quick fix” that need only last until the next major scheduled outage. These innovative uses are limited only by the imagination of the system operator when confronted with a problem. This section presents a few examples of innovative materials use for “temporary” repairs, some of which have lasted for many years.

6.1 Reinforced Thermoset Resins

While reinforced thermoset resin coatings have been phased out as corrosion barrier linings for absorbers and ductwork, these materials have considerable potential for maintenance and repair materials.

6.1.1 Abrasion-Resistant Thermoset Resins as Pump and Valve Repair Materials

For example, Duromar provides a series of reinforced epoxy “rebuilding putties” that have been used to rebuild the interior contours of damaged FGD slurry pumps. The putty typically used is SAR®, an epoxy putty heavily filled with alumina, capable of being built up to a thickness of an inch or more in a single application. ULTRABUILD® is a trowellable product filled with ceramic beads and other abrasion-resistant fillers, capable of being built to a thickness over 2 inches in a single coat.

Duromar reported their impression that most pump repairs made with their products were viewed as temporary by the FGD operator, who typically went ahead and ordered replacement parts for the next major outage.

6.1.2 Repair and Restoration of FRP Piping

Duromar noted a much more significant use of their rebuilding and resurfacing products in the maintenance of FRP piping. The greatest demand has been for relining of the FRP pipe immediately upstream and downstream of pumps, and SAR® has been the product most commonly used for this application, as well as being used as a topcoat for the exterior of FRP pipe where it has been eroded by falling slurry. Duromar EAC® and EAC-FE® may be useful as general-purpose gel-coat restoration materials for FRP pipe.

6.1.3 On-the-Fly Repair of Absorber Leaks

One utility has an ongoing nuisance problem with leaks due to corrosion pitting of their stainless steel absorber towers. The pitting is the result of a mandated decrease in blowdown rate and resulting increase in chlorides. The problem is a nuisance because the pits are widely separated and only a few leaks occur during each maintenance cycle.

This utility has developed a speedy on-the-fly repair. Step 1 is to drive a pointed oak peg into the leaking pit from the exterior of the tank, stopping the leak. Step 2 is to cut the protruding peg flush with the tank wall. Step 3 is to apply a “band-aid” consisting of three to five layers of glass mat saturated with bisphenol-A fumarate polyester resin to form a durable seal.

6.2 Innovative Use of Polyurethane

One utility was having difficulty obtaining replacement rubber volutes for their slurry pumps in a timely manner, the volutes were on back order. A local vendor used polyurethane to restore the contours of a damaged volute, then used that restored volute as the master for a mold. The vendor then provided cast polyurethane volutes as a “temporary” fix. The “temporary” polyurethane volutes significantly outlasted the natural rubber volutes that they had replaced.

The prize for innovative use of material for a “temporary” repair goes to a utility confronted with several thousand square feet of severely crazed or “alligatored” natural rubber lining in its scrubbers. The rubber lining had been in service for several years when inspection found reticulated cracks penetrating about one-third of the thickness of the lining. There was no indication that moisture had penetrated the lining and the utility concluded that an attempt to delay replacement of the lining was worthwhile.

Pennguard Borosilicate Glass Block® is applied with a polyurethane mastic that cures to create a tough, flexible, and highly chemical resistant membrane. Against the advice of the manufacturer, the utility trowel applied a test patch of the mastic. After six months the resulting polyurethane membrane remained tightly adherent. The utility then “temporarily” repaired several thousand square feet of rubber lining, and estimated that lining replacement had been postponed for at least seven years.

A

DEVELOPMENT OF THE CHLORIDE RESISTANCE FACTOR PARAMETER

One of the most significant recent developments in FGD alloy technology has been the development of a mathematically quantitative criterion for FGD alloy selection based on alloy composition, the FGD process pH, and the slurry chloride concentration. This FGD Materials Selection Algorithm clarifies the behavior of the alloys traditionally used in FGD construction, eliminates much of the guesswork of alloy selection, and allows estimation of the behavior of alloys based on their compositions.

The initial steps in the development of a quantitative basis for FGD materials selection were made by Hoxie and colleagues and independently by Schillmoller and colleagues in the 1970's. Both teams produced diagrams plotting the threshold chloride for serious corrosion in FGD absorbers as a function of pH for a variety of alloys [1-4].

Progress toward a condensed alloy parameter expressing the complex interaction of alloy composition as a single number evolved from ASTM G48 ferric chloride test data. The ferric chloride test was developed as a screening test of stainless steels for seawater service. Schillmoller and Rockel introduced the Pitting Resistance Equivalent or PRE concept—

$$(1) \quad \text{PRE} = \text{Cr} + 3.3\text{Mo}$$

where Cr is the percent chromium in the alloy, Mo is the percent molybdenum, etc.—based on critical pitting temperature (CPT) data in the ASTM G-48 ferric chloride test [3]. By the time nitrogen was added to the relationship, creating the so-called “Pitting Resistance Equivalent Nitrogen” or PREN, the critical crevice temperature (CCT) obtained from the ASTM G48 ferric chloride test had replaced CPT as the defining criteria, probably because there is less experimental scatter in the latter values.

In recent years, the PREN has evolved into a specification criterion, with mills guaranteeing minimum PREN values for certain products and purchasers specifying that alloys purchased must have PREN values that exceed specified minimums.

As of March 2000, there was no universally accepted standard definition of PREN, and at least 12 different versions were presented in the *Corrosion/2000* proceedings alone. The two most commonly cited versions are

$$(2a) \quad \text{PREN} = \text{Cr} + 3.3\text{Mo} + 16\text{N}$$

and

$$(2b) \quad \text{PREN} = \text{Cr} + 3.3\text{Mo} + 30\text{N}$$

Each of the dozen correlation's presented during *Corrosion/2000* was tested against a database of ASTM G48 CCT data paired to specific alloy compositions of 83 stainless steels and nickel-base alloys containing a minimum of 12%Cr [5]. The best correlation was given by

$$(3) \quad \text{PREN} = \text{Cr} + 3.3(\text{Mo} + \frac{1}{2}\text{W} + \frac{1}{2}\text{Nb}) + 16\text{N}$$

For materials selection purposes, Equation 3 has two shortcomings. First, it does not define whether the alloying element concentrations should be the grade minimums, nominals, or some other point within the allowed variation for each element, and second, it does not address the difference in chloride resistance due to alloy microstructure.

These shortcomings are overcome with the introduction of the Chloride Resistance Factor. For austenitic stainless steels,

$$(4) \quad \text{CRF}_{\text{AUS}} = \text{Austenitic chloride resistance factor} \\ = \text{Cr}_{\text{min}} + 3.3(\text{Mo}_{\text{min}} + \frac{1}{2}\text{W}_{\text{min}} + \frac{1}{2}\text{Nb}_{\text{min}}) + 16\text{N}$$

From the work of Kovach and Redmond [6], it can be shown that

$$(5) \quad \text{CRF}_{\text{DUP}} = \text{Duplex chloride resistance factor} \\ = 1.2[\text{Cr}_{\text{min}} + 3.3(\text{Mo}_{\text{min}} + \frac{1}{2}\text{W}_{\text{min}} + \frac{1}{2}\text{Nb}_{\text{min}}) + 16\text{N}] - 3.1$$

In 1998, Ellis published an algorithm with a correlation coefficient of 0.98 that accurately reflected the actual performance of austenitic and duplex stainless steels, as well as that of the C-Class alloys in FGD service between pH 5.5 and 6.5. In accord with the foundational work by Hoxie and Schillmoller, this algorithm was used with an assigned a slope of 0.30 for the relationship between pH and chloride limit to reproduce Schillmoller-Hoxie diagrams for Austenitic Cr-Ni alloys [7]. The algorithm was subsequently enhanced with a correlation between the pH coefficient and the Chloride Resistance Factor so that it accurately reflects trends of pH sensitivity vs. alloy composition published by NiDI.

Target:

SO₂ and Non-Particulate Opacity Control

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