EXPERIENCE IN EFFECTIVE APPLICATION OF METALLIC MATERIALS FOR CONSTRUCTION OF FGD SYSTEMS

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ABSTRACT

Since the inception of coal fired power plant flue gas desulfurization (FGD), the industry has experienced many difficulties and accomplishments. Early failures of coated carbon steel, stainless steels and even titanium demonstrated the unexpected severity of the various environments found in FGD systems. Both normal operation and excursions or unintentional slurry additions were found to provide severe pitting and crevice corrosion promoting environments. Nickel alloys containing high levels of molybdenum were found to resist attack, but were relatively expensive. Innovative construction techniques such as nickel alloy clad steel plate and "wall paper" lining for both new and retrofit applications were devised for economical use of nickel alloys. Effective welding techniques were developed for each application. The various sections of FGD systems are examined with close attention to local environmental conditions and possible failure mechanisms, as well as optimum construction materials and fabrication techniques. An overall diagram is presented in which different FGD zones of varying corrosivity are clearly outlined.

KEY WORDS

Flue Gas Desulfurization, FGD, Corrosion, Nickel Alloys, Welding, Stainless Steels, Austenitic, Duplex, Alloy C-276, Alloy 22, Alloy 686, Super-austenitic, Molybdenum, Pitting, Crevice Corrosion, Chloride, Clad Steel Plate, Wallpaper, Over-Matching, Filler Metal, Pollution Control, Halide, Acid

INTRODUCTION

Pollution control systems for modern coal-fired power plants must be reliable, efficient, and cost effective. To control costs, designers must take advantage of a new generation of reduced cost, corrosion-resistant alloys. In the 1970's when construction of wet FGD systems began, it was determined that very resistant material were required to prevent equipment failure due to corrosion [1, 2] (Figure 1). High nickel, super-resistant materials such as INCONEL® alloys C-276 (UNS N10276), 22 (UNS N06022), and 686 (UNS N06686) are still needed for construction of components for service in the most aggressive areas of FGD systems [3].

However, super-austenitic stainless steels such as INCOLOY® alloys 25-6MO (UNS NO8926) and 27-7MO (UNS S31277) are seeing increased use. The properties of these iron-nickel-chromium-molybdenum alloys are enhanced by additions of nitrogen and copper. If the corrosive conditions encountered within the FGD system are fully defined and the operation of the system is fully understood, engineers can take advantage of the cost-savings possible with these new alloys and build a FGD system that will give many years of dependable service [4, 5].

DEFINING CORROSIVE CONDITIONS

To confidently specify the use of lesser alloys in a FGD system, limits to the use of the alloys must be defined. Many conditions contribute to the aggressive conditions to which a particular component in a FGD system is exposed. Dew point, acidity (pH), temperature, halide concentration (chlorides and fluorides), wet / dry and crevice conditions, and gas velocity all must be considered in defining the corrosivity of the environment.

Dew Point

The conditions inside the scrubber (e.g., acid concentration) determine the temperature at which acids condense. Condensation of acids normally accounts for most of the corrosion encountered in FGD systems.

Acidity

The severity of the acidity within the various components in a FGD system can vary greatly. When the flue gases entering the system are initially quenched, acids (e.g., sulfuric and sulfurous acids) are formed and can be very aggressive. The pH of the acidic media in the entry duct can be 1 or less. Conditions are quite variable. With the great volume of slurry flowing into the absorber vessel, conditions rapidly reach equilibrium and the pH is significantly increased. Depending on design, the acidity in the absorber will typically range from 4.0 to 5.5. The scrubbed gas leaving the vessel still contains some amount of acid. Cooling of the gases in the outlet duct and cold duct walls result in condensation of acidic media. This condensate is very acidic and, consequently, very corrosive. Condensation also occurs on the chimney flue walls, again resulting in very aggressive conditions. The flue gas can also mix with the moist atmosphere as it leaves the chimney to form droplets of acid which can fall back into the chimney and cause corrosion on the chimney walls.

Temperature

The temperatures to which metallic components are exposed greatly influence the rate at which they corrode. In general, increasing the temperature will increase the corrosion rate.

Halides

The addition of halides, principally chlorides and fluorides, to acidic media can greatly increase their corrosivity. Halides can enter FGD systems via limestone and coal. In closed loop systems regeneration of the spent slurry can concentrate the halides. Halide levels over 100,000 ppm have been encountered in FGD systems. The effects of fluorides are normally found to be more detrimental than chlorides. The corrosive effects of chlorides in sulfuric acid is seen in Table 1.

Wet/ Dry Conditions

Areas where the conditions fluctuate between wet and dry (e.g., entry ducts) experience some of the worst corrosive attack encountered in FGD systems. The metallic surfaces become wet with acids. The temperature then increases, effectively boiling the acidic media resulting severe attack of the material.

Crevice Conditions

Tightly adhering deposits or films on the surface of metals can induce crevice corrosion. Under some conditions, mineral deposits (e.g., limestone, flyash, and gypsum) can build up on the walls of the ducts and absorbers to create crevice conditions. The presence of the crevice creates a micro-environment that can result in conditions much more aggressive than those in the macro-environment. Accelerated corrosion under crevices can quickly lead to perforation. Crevice corrosion is best avoided by washing the walls of the absorber vessels, constant operation of electrostatic precipitators, and maintaining conditions in the absorber (e.g, pH) to avoid precipitation.

CONDITIONS ENCOUNTERED IN FGD SYSTEMS

The conditions inside the operating FGD systems vary greatly depending upon the part of the system or component of interest. Thus, some parts of the FGD system require more aggressive corrosion protection than others.

Entry Duct and Quencher

The flues gases coming from the boiler and electrostatic precipitator are hot (typically, 350 to 500°F/ 177 to 260 °C) and dry and, thus, not particularly corrosive. However, when the gases mix with water either in the quench area (if the system is so designed) or in the entry duct where the gases encounter moisture from the absorber vessel, acids are formed and the environment becomes quite aggressive. Because of the high temperature of the environment, corrosion rates can be quite high if insufficient material are specified. Wet / dry conditions are often encountered in the entry duct which can further in crease the severity of the conditions to which alloy components are exposed.

Absorber Vessel Walls and Floor

As stated earlier, the conditions inside the absorber vessel (Figure 2) tend to reach equilibrium as the flue gases mix with the limestone slurry. The conditions are cooler (typically 130 to 160°F/ 54°C to 71°C) and the pH is higher (typically 4.0 to 5.5). Newer absorbers are often designed so that the walls are continuously washed by the slurry to avoid formation of deposits which can induce crevice corrosion.

Spray Headers and Mist Eliminators

The piping which carries the slurry to the spray nozzles are exposed to high flow rates and, sometimes, condensate from the top of the absorber vessel. The mist eliminators are exposed to similar conditions.

Outlet Ducting

Though the flue gases that flow into the outlet duct have been scrubbed to remove sulfur dioxide and processed through a demister system to remove moisture, they are still wet and have some acidic character. Moisture condenses on the cold walls of the duct. Evaporation resulting from the high flow concentrates the acidic condensate resulting in corrosive conditions. Thus, alloys for the floor and lower portions of the wall may need to be more resistant than those on the ceiling and the tops of the wall. Ducts should be designed so that the condensate can be continually drained. This is accomplished with floor drains and the use of round ducts or ducts with slanted floors.

Chimney Breeching

Transition from the outlet ducting into the chimney flue requires ducting and turning vanes to direct the gases through the chimney wall into the flue. These components are normally constructed of solid alloy plate for strength requirements and corrosion integrity.

Chimney Flue

The chimney flues (Figures 3 and 4) carry the moist, scrubbed gases from the system and emit it into the atmosphere. The chimneys are necessarily tall in order to achieve sufficient draft to carry the gases from the system and emit them into the atmosphere where they will be dispersed from the immediate area surrounding the power plant. While the exterior of the chimney is normally concrete, the flue is often metallic. Alloy clad steel flues are quite popular and have given long, reliable service. The storm cap (the top of the chimney flue that prevents atmospheric moisture from getting into the flue) is normally alloy plate. The flue drainage system (normally gutters which collect condensate that forms on the chimney flue walls) is often fabricated from light alloy plate and sheet.

Heat Recovery and Reheat Systems

Some systems utilize a heat exchanger in the entry duct to capture heat from the hot flue gases. This recovered heat may then be used to reheat the scrubbed gas to increase its buoyancy and ability to rise through the chimney into the atmosphere or for some external purpose.

The heat recovery heat exchanger is exposed to very aggressive conditions, as sulfuric acid tends to form and concentrate on the tubes. The most corrosion-resistant materials such as alloy 686 are used for this application. Even with the most resistant alloys, polymer sheathing is sometimes required to increase the life of the components.

The conditions at the reheat heat exchanger are not as aggressive as those in the heat recovery exchanger. The temperature is somewhat less and the acids that form are not as concentrated. However, conditions can still be very corrosive such that a very resistant alloy is required. Alloy C-276 has been successfully used for construction of components in this part of the system

ALLOYS TO PREVENT FGD CORROSION

Several alloys have been used for prevention of corrosion in wet limestone FGD systems with varying degrees of success. As stated earlier, conditions within various parts of the system are quite different. Thus, the corrosivity varies greatly in the various areas of the FGD system. An alloy that functions well in one area may not be at all suitable for service in another.

Nickel-chromium and iron-nickel-chromium alloys that contain some amount of molybdenum have been found most effective at resisting the aggressive conditions in the scrubbing system (Table 2). Alloys with higher contents of molybdenum are normally found to be the most resistant. Alloys are best compared by their Pitting Resistance Equivalency Number (PREN). While several equations (depending upon the types of alloys to be compared) are used to calculate the PREN, that shown in Table 3 has proven to be effective for the complete line of nickel-chromium-molybdenum FGD alloys. The PREN of each alloy is related to its corrosion resistance as evidenced by the Critical Crevice Corrosion Temperature and Critical Pitting Temperature determined by ASTM G48, methods C and D.

Austenitic Stainless Steels

Several grades of the 300 series iron-chromium-nickel austenitic stainless steels have been used in FGD service. In general, only the molybdenum-bearing grades have offered any acceptable resistance. Grade 316 with nominally 2.5% molybdenum offers only marginal resistance to the mildest of FGD environments. Attempts in early FGD systems to use grade 316 were mostly unsuccessful so the alloy is seldom considered for FGD service. Grade 317 (with nominally 3.75% molybdenum) and 317LMN (with nominally 4.25% molybdenum) have enjoyed some success in the milder areas of FGD systems. However, pH and chlorides must be limited and closely controlled and crevice conditions must absolutely be avoided.

Duplex Alloys

Duplex alloys derive their corrosion resistance and strength from their duplex microstructure which exhibits both austenite and ferrite phases. The use of such material in FGD construction is relatively new so there is little experience. Fabrication techniques for these alloys are very demanding and control is imperative to maintain alloy properties and corrosion resistance.

A study was conducted at Huntington Alloys to determine the relative resistance of several alloys to corrosion in FGD environments. Pitting tests in a chloride / sulfate environment showed the duplex alloys tested (grade 2205 – UNS S31803 and grade 2507 – UNS 32750) to offer better resistance than grade 316 austenitic stainless steel but less than that of the super-austenitic and nickel-base corrosion-resistant alloys (Table 4).

In addition general corrosion tests were conducted in two more highly acidified environments (Table 5). As above, the super-austenitic and nickel-base corrosion-resistant alloys offered significantly superior resistance in both environments. In the more oxidizing environment containing nitric acid, grade 316 offered significantly better resistance than the duplex alloys (Figure 5). However, in the more reducing test medium (without nitric acid), the duplex alloys performed somewhat better than 316 stainless steel.

A study sponsored by the Nickel Development Institute [6] compared several alloys in FGD service. In this study (Figure 6), duplex alloy 2205 (UNS S31803) was found to be more resistant than the 300 series stainless steels but not nearly as resistant as the 6% molybdenum super-austenitic stainless steel (UNS N08926) or the higher nickel alloy C-276 (UNS N10276). These results correlate well with laboratory tests in which duplex stainless steels are shown to be less resistant to localized corrosion than 6 or 7 % molybdenum and higher nickel alloys (Figure 7).

Thus, duplex alloys are best limited to the mildly corrosive areas of the FGD system.

Super-Austenitic Stainless Steels

The development of technology for the addition of nitrogen to conventional alloys has resulted in a new family of products with properties well suited for FGD service. The addition of nitrogen results in both improved strength and corrosion resistance. And by substituting nitrogen for some portion of the nickel in the alloys, cost is reduced. The most common 6% molybdenum grades such as alloy 25-6MO (UNS N08926) have been widely used for construction of FGD vessel walls and general construction.

The most recently developed super-austenitic material is alloy 27-7MO (UNS S31277). While only slightly more highly alloyed than the more conventional 6% molybdenum grade, alloy 27-7MO offers significant improvements in strength and corrosion resistance. In fact the corrosion resistance of alloy 27-7MO in FGD environments is nearly that of the higher nickel grades such as alloy C-276. To control costs, alloy 27-7MO may be evaluated as a replacement for alloy 22 and C-276.

High-Nickel, Corrosion-Resistant Alloys

Likely the most widely used alloy in FGD corrosion-resistant material in FGD construction is alloy C-276 (N10276). With nominally 16% molybdenum and 16% chromium, alloy C-276 offers resistance to all but the most aggressive conditions experienced in FGD systems. Alloy C-276 FGD components have been in service since the mid 1980's and are still offering reliable, low maintenance service. The FGD chimney flue seen in Figure 4 was fabricated from alloy C-276 roll-bonded clad steel at the Louisville Gas and Electric Company Cane Run Station in 1984 and is still in service today. No significant corrosion has been found.

Alloy C-276 is considered the "workhorse" alloy of the FGD industry. This product is widely used in the more corrosive areas of FGD systems. In the form of wallpaper or alloy clad steel plate, alloy C-276 is used for absorber vessel wall construction and construction of outlet ducts. Because of the mechanical rigors of their environment, floors are normally solid alloy plate. Alloy C-276 clad steel plate is commonly used for construction of FGD chimney flues. The alloy has offered excellent performance in all these applications.

Alloy 22 (UNS N06022) has also been used in FGD construction. It is very similar to alloy C-276 exhibiting slightly higher chromium but slightly reduced molybdenum content. As a result its resistance to crevice corrosion and environments with an oxidizing character is somewhat improved. However, its resistance to general corrosion is slightly diminished. Thus, alloy 22 is best used when crevice conditions are anticipated (e.g, when flyash / mineral deposits may form on components or walls) or when oxidizing species such as oxidizing salts (e.g, ferric or cupric chloride) are present.

Advanced Corrosion-Resistant Alloy

By use of the latest metallurgical technologies, an advanced grade of high-nickel, corrosion-resistant alloy was developed. Alloy 686 (N06686) offers the high molybdenum content of alloy C-276 along with the high chromium content of alloy 22. The content of tungsten is increased to 4% (from 3% in alloys 22 and C-276) and the iron content is limited to less than 2%. To maintain the high level of alloying elements in solid solution, special thermal / mechanical processing is required. This increased effort however, is well justified as alloy 686 offers the greatest corrosion resistance to the FGD environments available today.

The superiority of the corrosion resistance of alloy 686 to alloy C-276 is demonstrated in Figures 8 and 9. The alloy C-276 by-pass duct at Seminole Electric Cooperative's Palatka Station was corroding rapidly to the point that the weld had lost essentially all structural integrity (Figure 8). The filler metal C-276 weldment was replaced with one deposited with filler metal 686CPT®, the alloy 686 welding product (AWS A5.14 ERNiCrMo-14). After 6 more months of service, the alloy 686 weldment showed full resistance to the environment while the alloy C-276 ducting continues to corrode (Figure 9). To better understand this environment, a test panel made up of plate samples of alloys 25-6MO, C-276, 22, and 686 was installed on the floor of the duct beneath the level of the corrosive condensate. After 6 months of exposure, the alloy 686 panel was untouched, incipient corrosion was found on the alloy 22 and C-276 samples, while the alloy 25-6MO sample was completely corroded away (Figure 10). Eventually, the alloy C-276 duct walls and floor were replaced with alloy 686 and the corrosion stopped.

Alloy 686 should be considered for the most aggressive components of FGD systems. It is an excellent candidate for entry ducts, especially those in which wet / dry conditions exist. The hot gases mix with moisture from the scrubber vessel in the entry ducts resulting in hot, acidic conditions. Alloy 686 should also be considered for duct floors, especially those lacking proper drainage. If acidic puddles are to be allowed to concentrate, the most resistant alloy is required for resistance. Alloy 686 should also be considered for areas where crevice conditions exist.

Alloy 686 welding products offer over-matching chemical composition for all FGD alloys (except alloy 686 itself) and, thus, are recommended for this purpose (Figure 11). They are also recommended for joining alloy clad steel plate.

Alloy Selection

Selection of the most cost effective alloy for particular application is essential in today's competitive FGD and power markets. While a conservative approach might be to construct the entire system from a high-nickel, corrosion-resistant alloy, the financial constraints of today's market simply won't allow this to happen. Thus, designers must select materials that offer economy as well as performance. Tables 6 and 7 offer guidelines for assistance in the selection of corrosion-resistant alloys for various combinations of conditions found within the FGD system.

LESSONS LEARNED ABOUT FGD DESIGN

High Alloy versus Low Alloy

In attempting to cut costs, designers sometimes are tempted to use a heavier section of a low alloy as opposed to a higher, more resistant alloy. The experience learned from the test sample at the Palatka Station demonstrates why this is not a good idea. In this case a ¼" (6.2mm) section of a lesser alloy (a super-austenitic stainless steel, alloy 25-6MO) corroded away in 6 months while the higher alloyed 686 sample was not corroded at all. Thus, a thin section (1/16" / 1.6mm) of alloy 686 would have a long life while a heavier section of a lower alloyed material would fail in 6 months or less. And when one compares the cost of 1/16" (1.6mm) alloy 686 lining with that of ¼" (6.2mm) alloy 25-6MO plate, the alloy 686 construction is actually lower in total (material + construction) cost. So, it is recommended that alloy clad steel plate construction or "wallpaper" lining with thin alloy sheet be considered for FGD construction when very aggressive environments are anticipated.

Overmatching Composition Welding Products

It is a well known fact that nickel-chromium-molybdenum weldments are subject to elemental segregation during solidification. High melting elements solidify more quickly than those with lower melting temperatures so some parts of the weld cell are enriched with elements while the other end is depleted. This phenomenon results in weldments that despite the fact that they exhibit the same bulk chemical composition as the wrought base metal are found to be less resistant to corrosion. To offset this effect, welding products that are more highly alloyed than the base metal are preferred. This again is demonstrated by the experience at the Palatka utility. The alloy C-276 weldment was corroding at a greater rate than the wrought alloy C-276 base metal to the extent that the weld integrity was compromised while the alloy plate duct was still serviceable. The alloy 686 replacement weldments, however, offered full resistance to the environment. Figure 11 provides further evidence of this. Matching composition welds tested in the Green Death solution exhibit severe corrosion while over-matching composition filler metal 686CPT welds are not attacked.

Alloy Cladding - Clad Steel Plate & Wallpaper

The chimney flues seen in Figures 3 and 4 were fabricated from roll-bonded alloy clad steel plate. This mode of construction is accomplished at about half the cost of solid alloy plate construction. Low cost carbon steel provides the structural strength requirements while a thin cladding of alloy provides corrosion protection.

Alloy cladding with thin sheet ("wallpaper") can accomplish similar results. A steel structure is clad using an overlapping technique such that iron-diluted welds are not exposed to the service environment.

Alloy clad steel plate offers the advantage of full bond integrity while the wallpaper cladding is only bonded to the plate substrate at the weldments. Wallpaper, however, is usually found to be slightly lower in cost.

The use of over-matching composition welding product is particularly important for joining clad steel plates when the welds may be somewhat diluted with iron from the steel substrate.

Drainage

Vessel floors and ducts should be designed such that standing puddles of condensate are avoided. As previously noted, standing condensate can concentrate and become very aggressive. Ducts, floors, and flues should be designed such that condensate is naturally drained from the system by ducts, gutters, and drains.

SUMMARY

All the components discussed are shown in the schematic diagram of an FGD system in Figure 12. Areas of varying corrosivity are color coded to represent mild (white), moderate (gray) and aggressive (black) conditions. In general, material selection for the mild conditions would be austenitic stainless steel and duplex alloys, the moderate conditions would best be handled by 6 or 7 % molybdenum super austenitic stainless steels and the aggressive conditions would require much more highly alloyed Ni-Cr-Mo-W materials.

CONCLUSIONS

The current flurry of activity in the U.S. FGD industry will require the construction of many wet limestone FGD SO_2 scrubbing systems. Experience gained over the past 25 years demonstrates that corrosion-resistant alloys offer good resistance to the aggressive conditions encountered in FGD systems. By exercising proper care in design and selection of corrosion-resistant alloys and utilization of proper fabrication techniques, the resulting FGD systems offer long, reliable, low maintenance service and are capable of meeting the demanding pollutant removal levels mandated by state, provincial, and federal government legislation.

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TABLE 1
EFFECT OF CHLORIDE CONTAMINATION ON CORROSION IN SULFURIC ACID

Alloy	40% H_2SO_4 at 75°C Plus Chloride Concentration as Indicated	
	ppm Chloride (as NaCl)	Corrosion Rate, mpy (mm/y)
25-6MO (N08926)	0	20.0 (0.51)
C-276 (N10276)	0	4.5 (0.11)
686 (N06686)	0	1.5 (0.04)
25-6MO (N08926)	1,000	41.5 (1.05)
C-276 (N10276)	1,000	6.5 (0.16)
686 (N06686)	1,000	1.0 (0.02)

TABLE 2
CHEMICAL COMPOSITION (%)
OF CORROSION -RESISTANT ALLOYS

	Ni	Cr	Mo	Fe	W	Others
Stainless Steel 316 L (UNS S31603)	12	17	2.2	68	–	Cu 1.0, N 0.25
alloy 25-6 MO (UNS N08926)	25	20	6.5	47	–	Cu 1.0, N 0.35
alloy 27-7 MO (UNS S31277)	27	22	7.2	42	–	Nb 3.6
alloy 625 (UNS N06625)	61	21	9	2.5	–	–
alloy 22 (UNS N06022)	59	22	14	2.3	3.2	–
alloy C-276 (UNS N10276)	57	16	16	5.5	3.8	–
alloy 686 (UNS N06686)	58	21	16	1	3.8	–

TABLE 3
LOCALIZED CORROSION RESISTANCE OF CORROSION-RESISTANT ALLOYS COMPARED TO THEIR PITTING RESISTANCE EQUIVALENCY NUMBER (PREN)

Alloy	CPT (°C)	CCT (°C)	PREN*
316 Stainless Steel	20	<0	25
alloy 25-6MO	70	35	49
alloy 625	>85	35	52
alloy 27-7MO	>85	45	57
alloy C-276	>85	50	69
alloy 686	>85	>85	74

*** PREN = Cr + 3.3MO + 30N**

TABLE 4
PITTING TEST RESULTS OF FGD ALLOYS

Alloy	Pitting Attack *
C-276 (N10276)	No
27-7MO (S31277)	No
25-6MO (N08926)	No
2507 (S32750)	Edge Pitting
2205 (S31803)	Edge and Surface Pitting
316L (S31603)	Deep Edge Pitting

* Samples exposed one week at 60°C in test solution with 6,000 ppm chloride + 3,000 ppm sulfate at pH 3.5 and 60°C

TABLE 5
CORROSION RATES OF ALLOYS UNDER LABORATORY-SIMULATED FGD CONDITIONS

Alloy	Corrosion Rate (MPY)	
	Test 1	Test 2
C-276 (N10276)	5	3
27-7MO (S31277)	2	7
25-6MO (N08926)	5	8
2507 (S32750)	1999	64
2205 (S31803)	1864	129
316L (S31603)	37	1465
Condition for test 1: 60% H_2SO_4 + 0.5% HCl + 0.1 % HF + 0.1 HNO_3 at 70°C for 1 week		
Condition for test 2: 60% H_2SO_4 + 2.5% HCl + 0.2% HF at 60°C for 1 week		

TABLE 6
ALLOY USAGE

		Mild		Moderate	
		Chlorides (ppm)		Chlorides (ppm)	
	pH	100	500	1,000	5,000
Mild	6.5	SS	SS	alloy 25-6MO	alloy 25-6MO
Moderate	4.5	SS	alloy 25-6MO	alloy 25-6MO	alloy 25-6MO
Severe	2.0	alloy 25-6MO	alloy 25-6MO	alloy 25-6MO	alloy 27-7Mo
Very Severe	1.0	alloy 25-6MO	alloy 25-6MO	alloy 27-7Mo	alloy 27-7Mo

TABLE 7
ALLOY USAGE

		Severe		Very Severe	
		Chlorides (ppm)		Chlorides (ppm)	
	pH	10,000	50,000	100,000	200,000
Mild	6.5	alloy 27-7Mo	alloy 27-7Mo	HNA	alloy 686
Moderate	4.5	alloy 27-7Mo	HNA	alloy 686	alloy 686
Severe	2.0	HNA	HNA	alloy 686	alloy 686
Very Severe	1.0	HNA	alloy 686	alloy 686	alloy 686

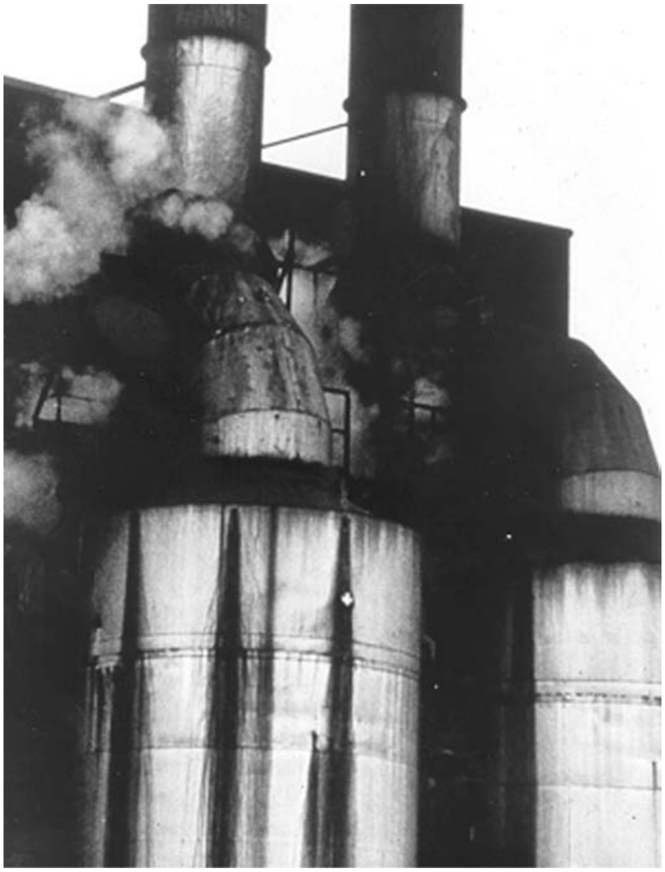


FIGURE 1 – FGD absorber vessel leaking due to non-metallic lining

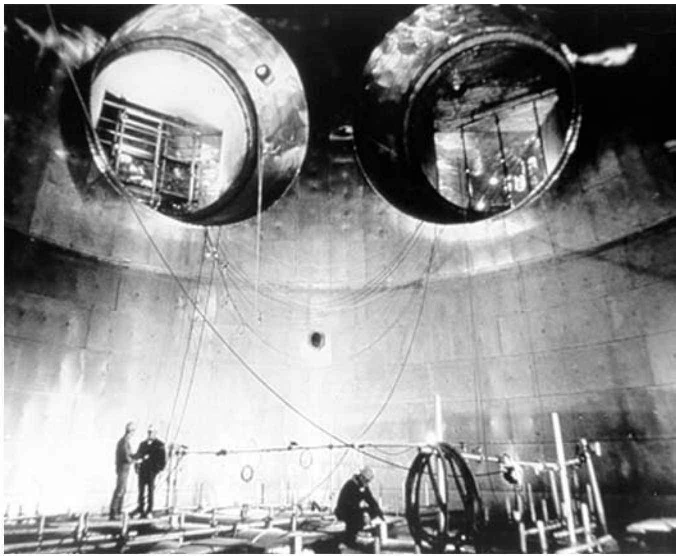


FIGURE 2 – Alloy C-276 sheet lined absorber vessel using the “wallpaper’ technique

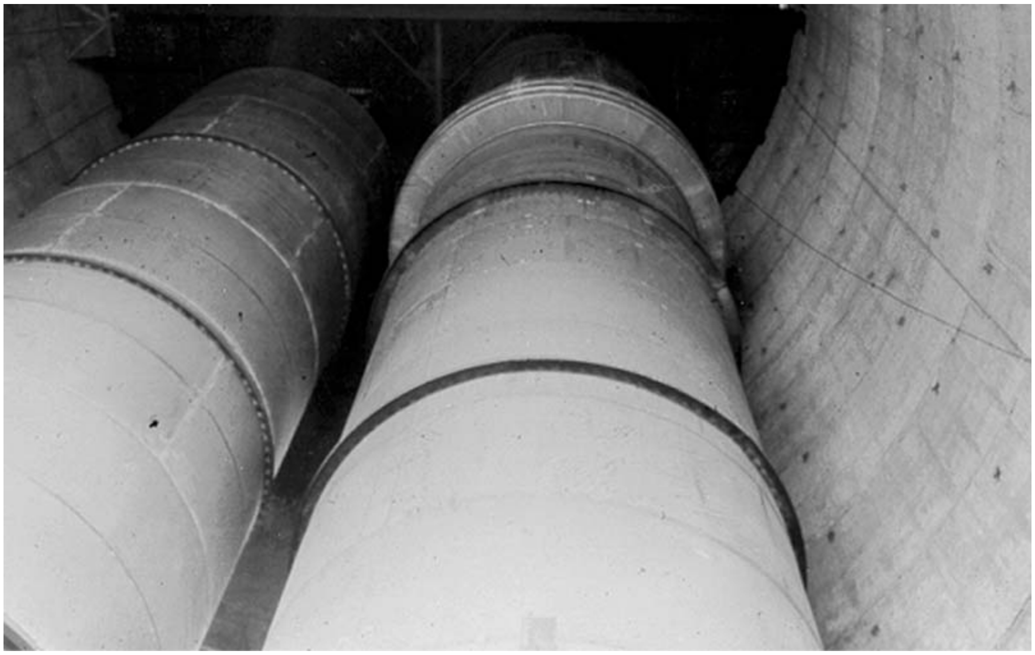


FIGURE 3 - Chimney flues fabricated from solid alloy 625 plate

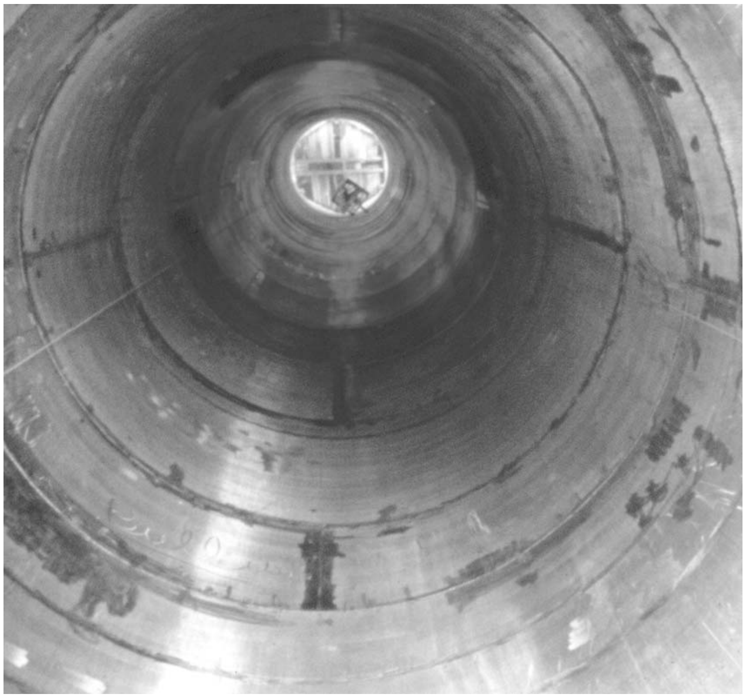


FIGURE 4 – FGD chimney flue fabricated from alloy C-276 clad steel plate

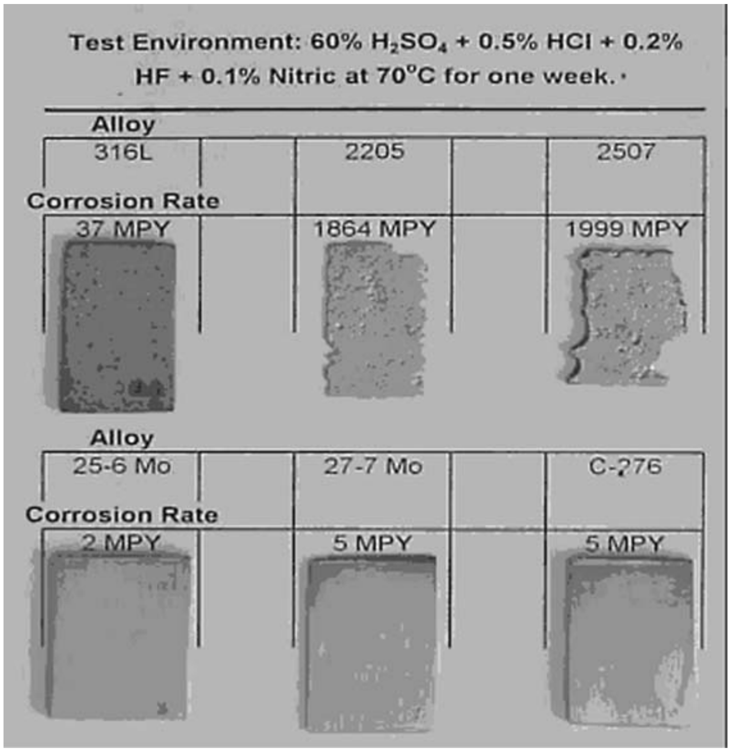
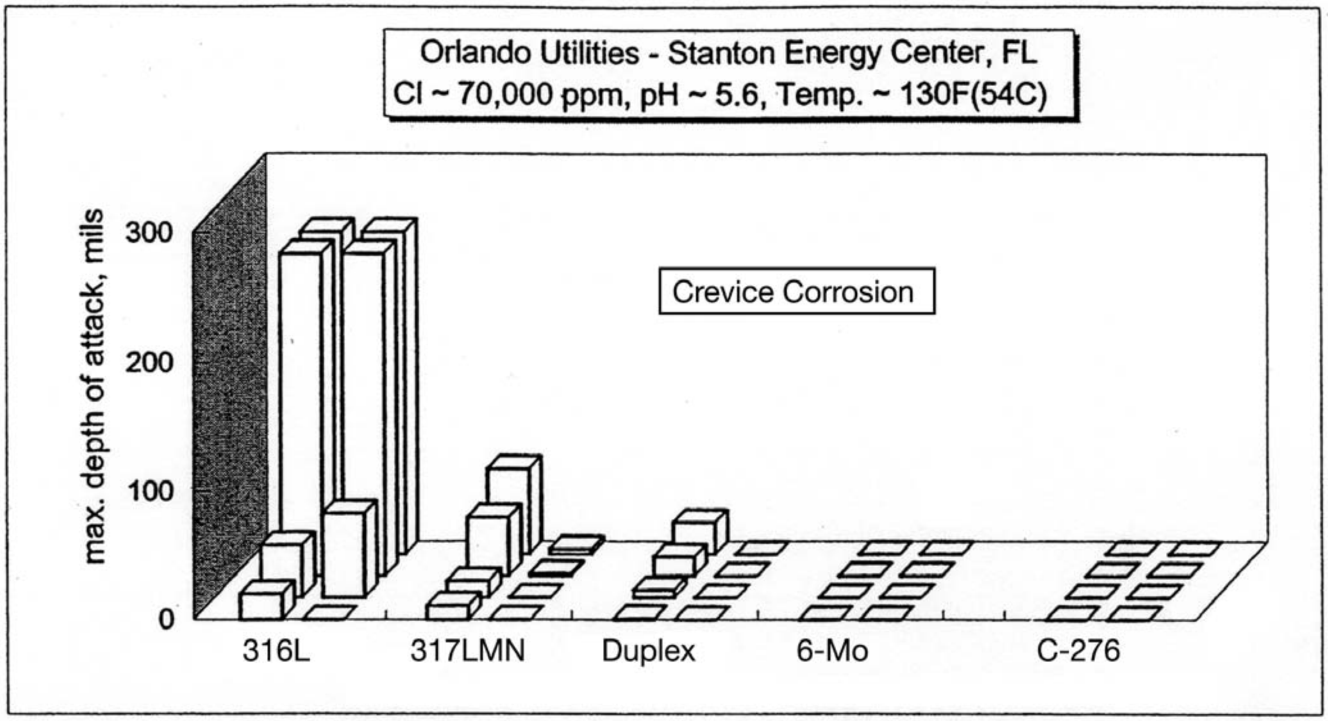


FIGURE 5 – Corrosion of various alloys in a simulated FGD environment.



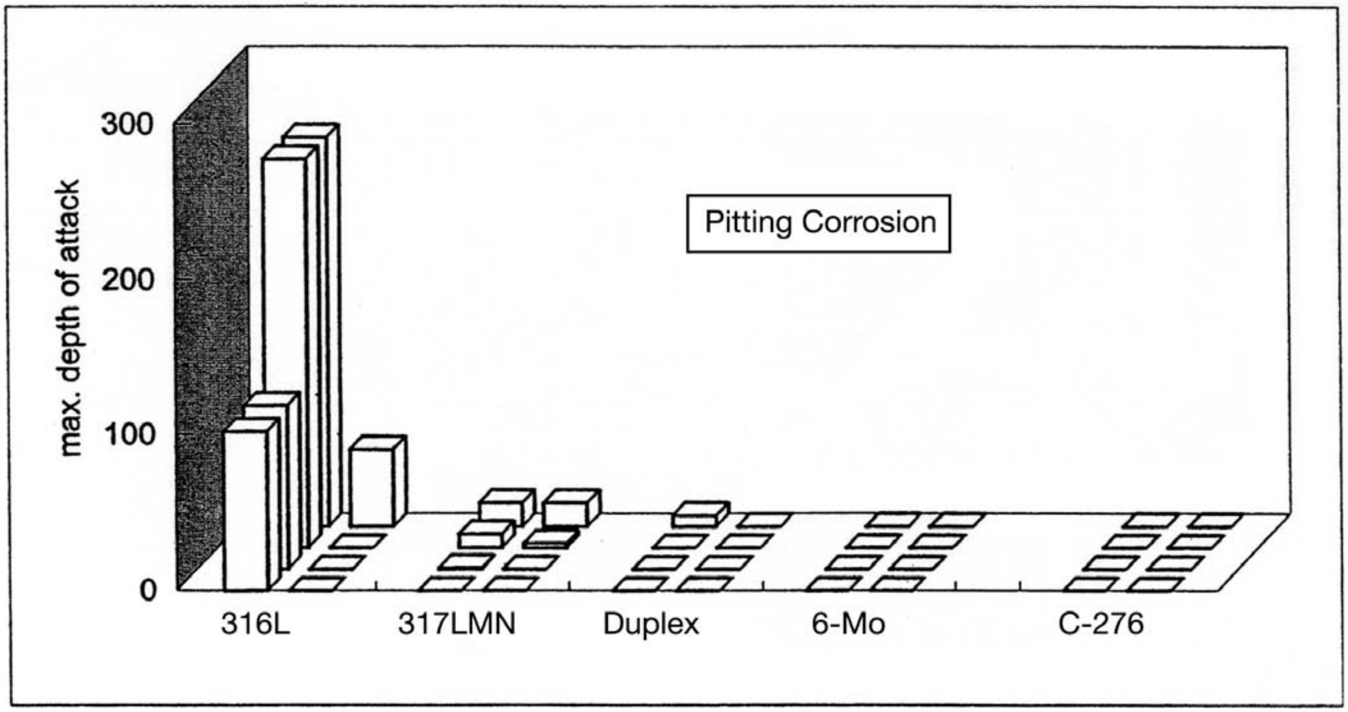


FIGURE 6 – Maximum depth of crevice corrosion and bold surface pitting. For each alloy, the 1st set of columns (going from front to back) represent data for replicate specimens with tight crevice formers and the 2nd set for those with loose crevice formers. The exposure duration for all specimens in this scrubber was 270 days. The tallest 4 bars for crevice corrosion and the tallest 2 for pitting correspond to specimen perforation by corrosion. (1mil = 0.0254 mm).

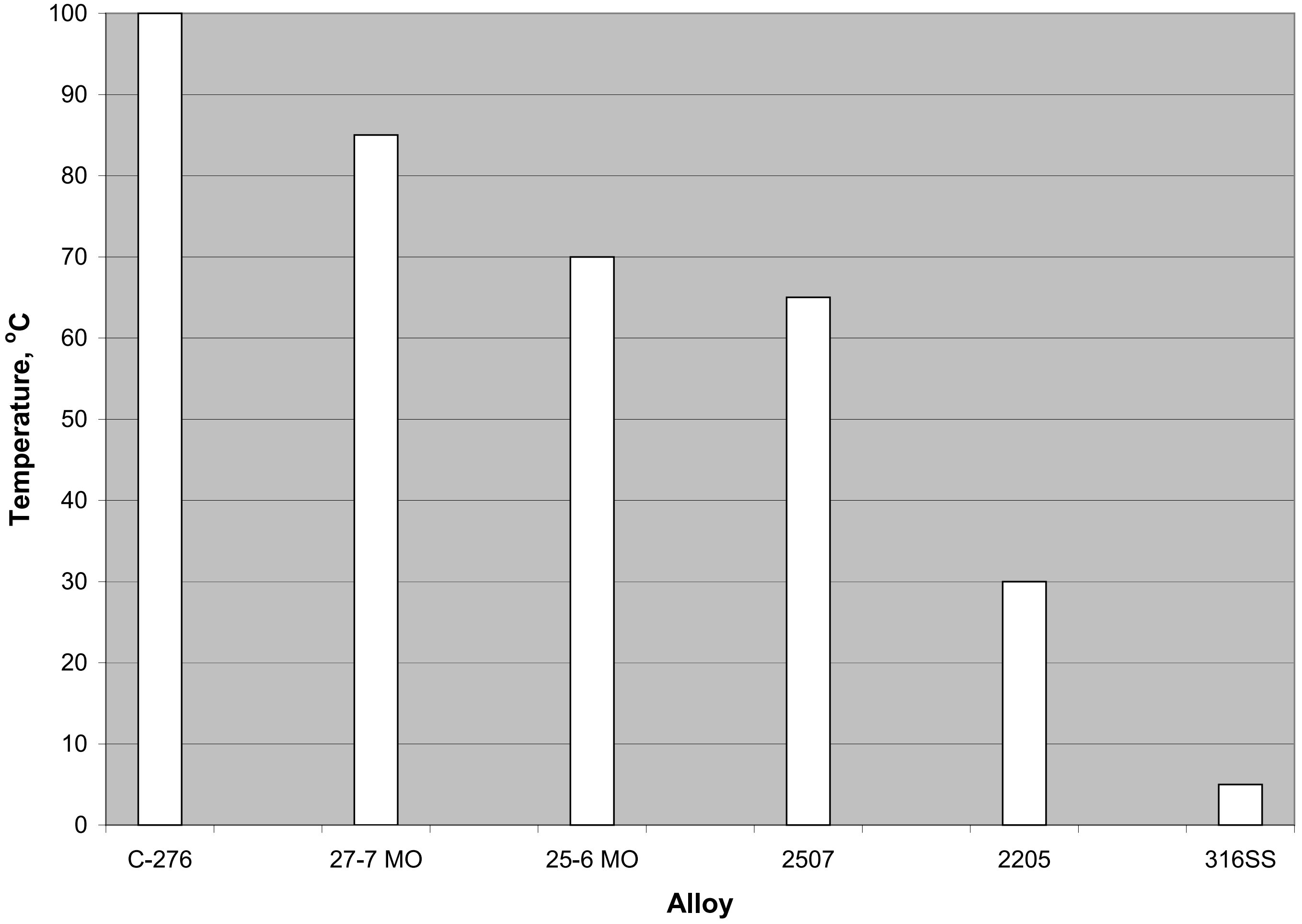


FIGURE 7 – CPT of Several FGD alloys in Green Death

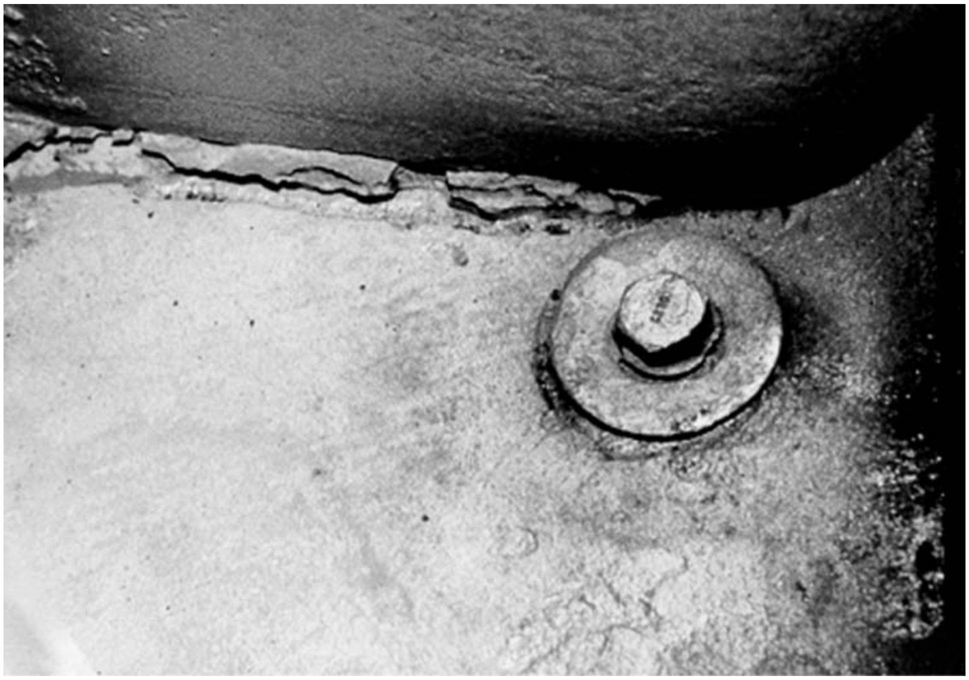


FIGURE 8 – Corroded alloy C-276 weldment in FGD bypass duct

FIGURE 9 – Alloy 686 weldment after 6 month exposure in FGD Bypass Duct

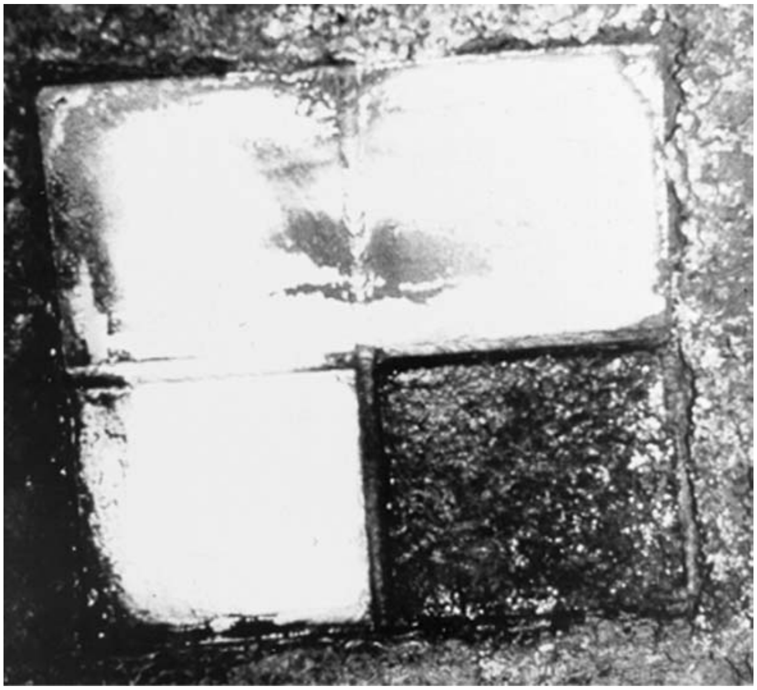


FIGURE 10 – Four alloy test panel in FGD bypass duct after 6 month exposure

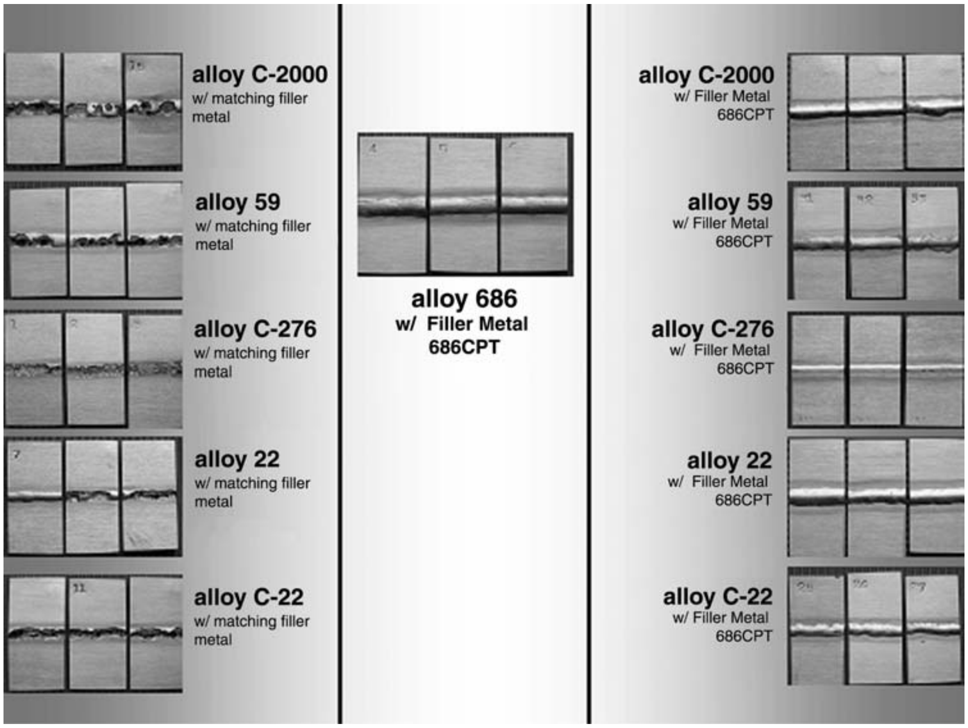


FIGURE 11 – The advantage of using overmatching over matching composition welding products for joining corrosion-resistant alloys. Samples exposed in boiling (103°C) green death solution for 72 hours.

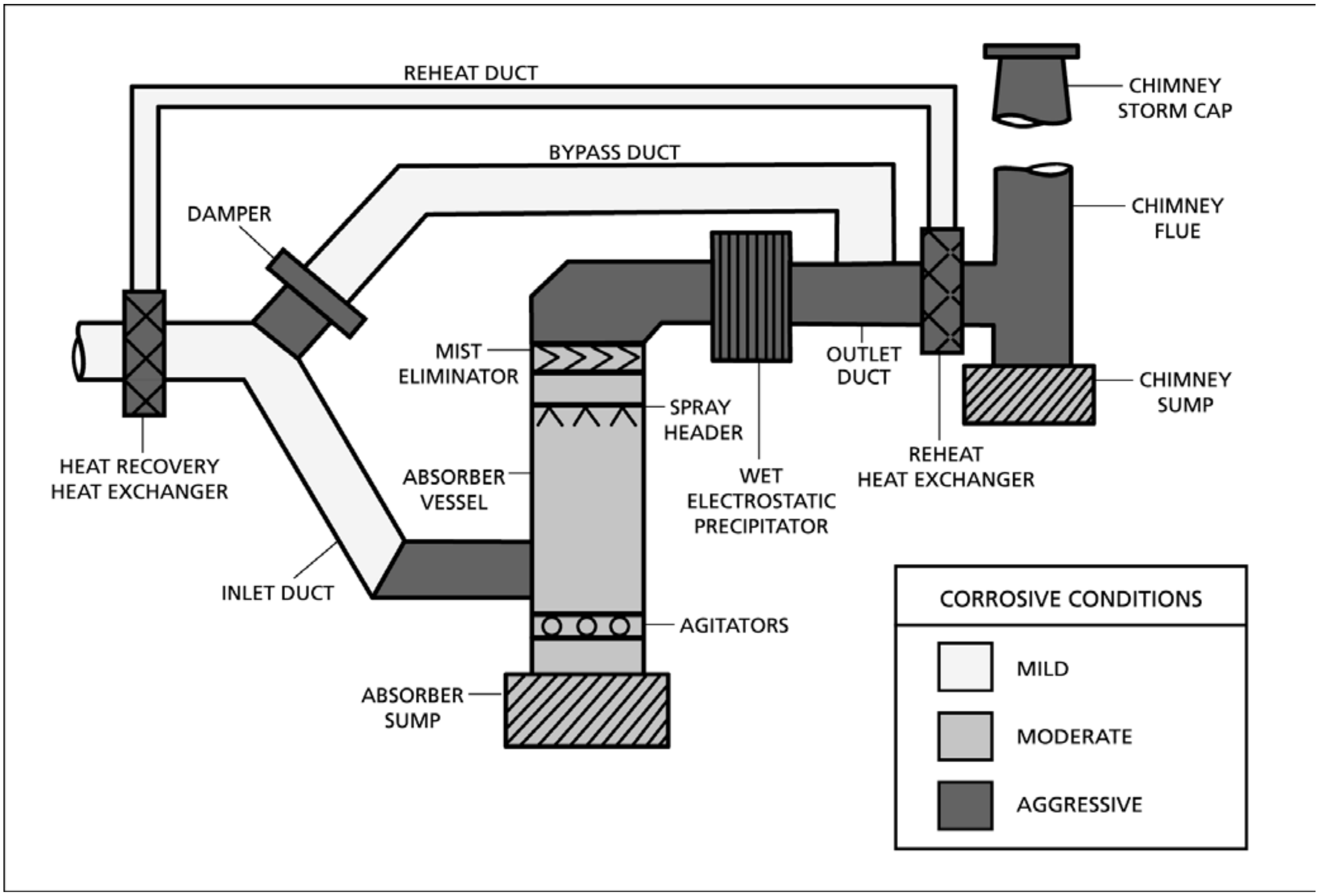


FIGURE 12 – Corrosive conditions in the wet limestone FGD system