Nickel-Chromium-Molybdenum Superalloys: The Solution to Corrosion Problems in Wet Limestone FGD Air Pollution Control Systems

Lewis E. Shoemaker and James R. Crum
Special Metals Corporation, Huntington, WV USA

Introduction

Changing attitudes towards how we address the environment has resulted in international efforts to restrict the emission of sulfur dioxide into the atmosphere. Efforts to curb damage to the environment by acid rain has necessitated the construction of flue gas desulfurization (FGD) systems at coal-fired electric power stations around the world. The environments inside these huge chemical processing systems are very corrosive. Thus, corrosion-resistant nickel-chromium-molybdenum alloys are often required for general construction of the components and for protective lining of the system.

When FGD scrubber construction began in the 1970's, no one had a good understanding of the corrosion mechanisms taking place within the systems. Consequently, problems attributable to corrosion were common. In their attempts to use low cost materials, designers inevitably used lower grade alloys than were needed resulting in the premature failure and replacement of many FGD components and linings. However, by studying this process over a period of thirty years, the present generation of FGD scrubbing systems use advanced corrosion-resistant alloys which should result in long, reliable service.

Early Failures and Successes

Type 316 stainless steel wet I.D. fans failed at the Arizona Public Service - Four Corners Power Plant in 1972. Alloy 625 was chosen for replacement because of its excellent corrosion resistance, high strength, and excellent fatigue properties. This usage is generally regarded as the first significant application of a nickel alloy for FGD equipment. The first sheet alloy liner was installed in a FGD system at Pennsylvania Power Company's Bruce Mansfield Station in 1977. INCOLOY® alloy 825 sheets were used to repair carbon steel fan housings when rubber linings failed. In 1979, the first application of alloy C-276 was reported for precooler rings at Central Illinois Public Service Newton Plant. In the same year, a complete scrubber system was fabricated from alloy 625 for an incinerator located in Cleveland, Ohio.

During the early 1970's, most of the components of FGD equipment were designed with materials having the lowest initial cost (i.e. unlined steel or structural steel covered with organic linings). It was generally assumed that the FGD environments would not be excessively corrosive. This perception was, unfortunately, proved to be far from accurate when FGD equipment began to show premature failure, poor reliability, high maintenance costs, and forced shutdowns for repair of corroded components. Corrosion, erosion, and poor lining installation, particularly in outlet ducting and stack liners, caused significant problems for utilities (Figure 1).

Initial Use of High Alloy Materials

FGD designers, fabricators, and operators learned many valuable lessons when in 1980 alloy 904L in the quencher and sump of a double-loop scrubber at Basin Electric Cooperative - Laramie River Unit failed by pitting corrosion. Most of the failures occurred in alloy 904L matching composition welds, in weld heat-affected-zones, under heat tint resulting from welding, at scratches introduced during fabrication, and under paint markings. Alloy 625 welding products were used to repair the alloy 904L equipment. It became obvious that improved fabrication procedures were essential in achieving acceptable FGD service life. It was also concluded that molybdenum-containing stainless steel alloys required overalloyed welding products containing 9 to 16% molybdenum for optimum weld metal corrosion resistance. The necessity of removing heat tint, embedded iron, and paint marks from stainless steels was also defined.

FGD material technology took another giant step forward that same year when a glass-flake polyester lining failed in the mixing chamber of the direct-bypass reheat outlet duct at the South Mississippi Electric Power Association - R.D. Morrow FGD Unit. A replacement lining of alloy G (installed with alloy C-276 weldments) failed within 6 months of its installation. However, it was observed that the alloy C-276 welds were not attacked. The corroded alloy G was covered with thin, 0.062" (1.6 mm) sheets of alloy C-276. This repair proved to be quite successful and alloy C-276 became recognized as the solution to FGD problems. The technique of overlaying a steel structure with thin alloy sheet proved to be a very effective and economical method for the repair of corroded FGD components as well as for the construction of new alloy linings. This lining technique is still popular and generally referred to as "wallpapering".

Corrosion Testing Programs

Because of the corrosion problems encountered in numerous FGD systems, field corrosion tests are performed to evaluate materials for FGD service. A popular test technique is the corrosion test spool rack (Figure 2). Test spools offer the advantage of testing a variety of materials simultaneously in the same location. A comprehensive summary of spool corrosion test data developed in FGD and other scrubber systems is currently available from the Nickel Development Institute (NiDI) as Publication No. 1300. This document was originally published by the International Nickel Company in 1980 as a Corrosion Engineering Bulletin.

Other types of field tests have been used to evaluate the performance of alloys in various sections of FGD systems. One obvious method is to simply attach samples of sheet to the scrubber or duct wall. Some of the more complex test samples contain multiple alloys, weldments deposited by different welding products and welding procedures (Figure 3). Data generated from such exposures are considered the most reliable since tests conducted in this manner expose materials to essentially the identical environment conditions which resulted in failure of the original material. Corrosion testing in simulated FGD environments has also been conducted in laboratory simulations. Laboratory testing permits better control of environmental parameters and variables being investigated than field testing. Perhaps more important is the fact that such tests can be easily scheduled and data developed in relatively short periods of time. Other environments utilized included the infamous "Green Death", sulfur dioxide saturated salt solutions, and many mixtures deemed to approximate the FGD environment.

While these laboratory simulations are useful when rapid data development is a necessity, the reliability of such information is often marginal. Data developed in in-situ field tests are much more dependable.

Also, caution must be exercised in selecting laboratory test procedures. For example, material acceptance testing procedures such as ASTM G-28, methods A and B have been erroneously used compare alloys. Corrosion rates in these tests are alloy specific and, in reality, tell one nothing about the relative resistance of alloys to the FGD environment. These tests are designed to ensure that materials have been properly heat treated during production and fabrication. They are quality control tools and nothing more.

To combine the testing ease and short duration of laboratory tests with the reliability of field tests, a pilot plant which simulated FGD conditions was developed at the LaQue Center for Corrosion Technology in Wrightsville Beach, North Carolina, USA. With this system, corrosion data could be obtained under dynamic operating conditions nearly identical to those encountered in full-scale FGD scrubbers, but with much greater control of FGD environmental conditions (e.g., pH, halide concentration, and temperature). Throughout the 1980's, this scrubber system was used to determine the effect of numerous FGD conditions on various types of materials. The corrosion test results of the model scrubber have been published at NACE annual conferences since 1983, and all AIRPOL seminars held since 1984. The testing program was a milestone in providing guidance on the use of stainless steels and nickel-base alloys for FGD service. Highlights of the results showed the effects of chlorides on alloys up to 100,000 ppm chlorides, simulating closed-loop FGD operation and the beneficial effect of alloy molybdenum content in enhancing localized corrosion resistance, especially in the outlet duct area. The trends of test results in the model scrubber showed excellent agreement with experience from actual full-scale, field-operated utility FGD equipment.

Significant Findings

The results of numerous testing programs helped define the conditions within the FGD system which were most responsible for causing corrosion. The temperature and acidity of the system naturally were found to be significant variables. The concentration of halides also proved to be significant especially when the use of stainless steels such as 316 or 317 was in question.

The physical condition of the system was determined to be an important factor in the resistance of the system to crevice corrosion. Because flyash and minerals from the scrubbing process are present in the system, there is a propensity for mineral deposits to build up on the walls of the scrubber. Corrosive media tend to collect and concentrate under these deposits leading to crevice corrosion. Smooth metal surfaces and low profile weldments are important factors in avoiding this problem.

The quench areas of scrubbers are particularly prone to corrosion because of the presence of a wet / dry interface. The hot, dry flue gases upstream from the quench chamber are subjected to varying amounts of mist from back flow of the quench spray. Thus, these gases tended to cool and condense creating a wet / dry interface in the duct. Furthermore, this interface was found to move forward and backward within the duct. In these sections of the entry duct, gases condensed and, alternately, liquids boiled creating severely corrosive conditions. Since these sections of the entry duct were expected to be exposed only to hot, dry flue gas, they were generally constructed of unprotected carbon steel. Thus, severe corrosion has been encountered in such portions of the entry duct. This problem is normally addressed by lining the steel duct with a corrosion-resistant alloy (e.g; alloy C-276).

Outlet ducts are prone to attack in low areas where pools of acid tend to collect, stand, and concentrate. Proper drainage to the ducts helps address this problem. However, elimination of all low spots is impractical. Thus, lining of the duct with a corrosion-resistant alloy is a more practical solution.

Construction Options

Three types of construction are used for construction of FGD systems: thin sheet lining or “wallpaper”, solid alloy plate, and alloy clad steel plate or “roll clad”. Depending on the component to be fabricated and the requirements for service, any of these construction scenarios may be preferred.

Wallpaper cladding is accomplished by welding thin alloy sheet, usually 1/16 in. (1.6 mm) or 1/8 in. (3.2 mm) in thickness, to a structural steel substrate (Figure 4). The sheet is attached by means of intermittent welds between the alloy sheet and the structural steel (Figure 5). Thus, the attachment welds are diluted with iron from the steel structure. A second sheet overlaps the edge of the previous sheet to protect the diluted structural welds. A solid weldment is then used to join the two sheets. Thus, the weldment which will be exposed to the service media is not diluted with iron but is fully resistant. Capped plug welds are used to stiffen the sheet cladding (Figure 6).

Because of the thinness of the alloy sheets they are readily formed (Figure 7). Thus, wallpapering is preferred for cladding complex shapes. Wallpapering is particularly applicable to repair or upgrade of existing structures (Figure 8). A disadvantage of wallpapering is that the alloy cladding is not integrally bonded to the steel backing. Thus, leaks can quickly cause extensive damage.

Perhaps the most straight forward type of construction is to simply fabricate the vessel, duct or flue from alloy plate. Thus, the plate acts as both a structural member and a barrier against corrosion. Nickel alloy plates offer high strength along with excellent ductility so they are readily formed by conventional equipment and procedures. The use of alloy plate is particularly effective for components exposed to severely corrosive conditions or abrasion. Solid plate is commonly used for scrubber vessel and duct walls (Figure 9), floors, turning vanes, chimney breeching, chimney flues (Figure 10) and storm caps.

Alloy clad steel plate offers the economy of wallpaper with most of the advantages of solid alloy plate construction. Alloy clad steel structures can be built for about half the cost of an equivalent solid alloy structure.

Alloy clad steel plate is manufactured by rolling an alloy / steel packet at high temperature and pressure such that a metallurgical bond forms between the alloy and the steel plates (Figure 11). The plates are rolled to size and heat treated by procedures similar to those used in the production of solid alloy plates. Fabrication procedures are essentially identical to those employed for solid alloy plates as well. For FGD construction, alloy clad steel plates are joined with alloy weldments. Since there may be some iron dilution from the steel substrate into the alloy weld deposit, the use of overmatching composition welding products is recommended.

Common applications for alloy clad steel plate construction are absorber vessel and duct walls, chimney flues, and rolled and welded piping.

Alloy Performance

Operating experience and compilation of the data generated from corrosion testing programs have allowed corrosion scientists to set general limits on the conditions under which various alloys can be used. By monitoring the conditions within a section of the FGD system, it is possible to specify alloys economically and confidently.

Nickel-chromium and iron-nickel-chromium alloys have been found to provide the required resistance to corrosion for long term service of FGD components. Molybdenum has been identified as the metallic element most responsible for imparting resistance to corrosion to alloys in FGD service. Niobium (columbium) and tungsten also contribute.

For general comparison, molybdenum content can be used as a gauge of the resistance of nickel-chromium-base alloys to corrosion in the FGD environment. This comparison and these guidelines are very general and are not meant to be by any means a recommendation for the application of these materials. They are only a report of past experience and some general conclusions.

The molybdenum-bearing austenitic stainless steels, grades 316 and 317, contain 3 and 4 1/2% molybdenum, respectively, and are used in the least aggressive section of the system (e.g; slurry piping). These materials are generally found to be marginal to unacceptable in any section of the vessel or ducting. Conditions for these materials are normally limited to about 5,000 ppm chlorides and pH 5 or higher. The newer grades of 6% molybdenum, nitrogen bearing stainless steel (sometimes referred to as "super-austenitic stainless" steels) are used in slightly more aggressive environments. The general limit for usage of these materials is 10,000 to 20,000 ppm chlorides though some report successful use up to 40,000 ppm. Acidity limits for such materials should be pH 4 or higher. These materials are used in essentially the same range as the alloy G family of 6% molybdenum materials, but are lower in cost because of their lower nickel content. The addition of nitrogen to these alloys maintains a fully austenitic structure while also enhancing strength and corrosion resistance.

INCONEL® alloy 625 (UNS N06625), a 21% chromium, 9% molybdenum, 4% niobium nickel-base alloy, is in a family by itself. While it has been used in many FGD applications, it has been replaced in most lining applications by the higher molybdenum alloys such as INCONEL alloys 622, C-276, and 686. However, alloy 625 exhibits strength and fatigue resistance superior to any of these alloys. Thus, it is particularly well suited for pollution control fans (Figure 12) and rotating pump parts. A newly introduced variation of this material, INCONEL alloy 625LCF, optimizes the alloy's fatigue resistance. INCONEL Filler metal 625 and INCONEL Welding Electrode 112 are also widely used as over-matching composition welding products for joining the austenitic grades 316 and 317 and super-austenitic grades of stainless steels and the 'G' family of alloys for FGD service.

Materials offering the greatest resistance to FGD corrosion are the nickel-chromium alloys containing 14 to 16% molybdenum: INCONEL alloys 622 (UNS N06022) and C-276 (UNS N10276). These products are used worldwide in the most corrosive segments of FGD systems including entry and outlet ducting, reheat components, chimney liners, and the scrubber vessel and its internal components. These alloys resist corrosion at pH levels as low as 1 and at chloride levels up to 100,000 ppm. In general, when a corrosion problem is encountered in a FGD application, these alloys provide the solution.

Development of a New Alloy with Improved Corrosion-Resistance

While the conventional, highly corrosion-resistant nickel-base alloys such as INCONEL alloys 622 and C-276 perform satisfactorily in most FGD service, systems requiring improved operating reliability, long periods of operation without maintenance, or operation under upset conditions demand an alloy with even greater resistance to corrosion. Technological advances in alloy production techniques have made possible the addition of even greater levels of alloying elements to nickel-base material while still maintaining metallurgical stability. This has made possible the development of more corrosion-resistant alloys for use in FGD systems. INCONEL alloy 686 (UNS

N06686) was introduced to the FGD market in the mid 1990's. The alloy is nickel-base with 22% chromium, 16% molybdenum, and 4% tungsten. Iron is controlled to less than 1%. Alloy 686 is the most highly alloyed (40.7%) wrought corrosion-resistant alloy available.

With such a high alloy content, special process controls are required to prevent formation of secondary phases (e.g; mu and sigma). Alloy 686 ingots receive a proprietary high temperature homogenization prior to hot rolling. The high temperature homogenization treatment allows the alloying elements to diffuse away from areas of local segregation which develop during solidification of the ingot. The homogeneous state of the ingot avoids the subsequent formation of embrittling phases.

Reducing the iron content in these highly alloyed compositions is also helpful in two respects. First, lowering the iron from about 5% to about 1% allows the addition of about 4% more nickel. This can have a significant effect on stability. Secondly, iron and titanium content have been found to effect the alloy's resistance to intergranular attack (IGA) after exposure to temperatures between 1400°F to 1800°F (760°C to 982°C).

Though the carbon content of alloy 686 is controlled to less than 0.008%, the effect of carbide precipitation can be reduced by the addition of titanium at a level resulting in a Ti/C ratio greater than about 3.

INCONEL alloy 686 is vacuum induction melted and electroslag remelted to control the chemical composition and maintain the desired microstructure.

INCONEL alloy 686

INCONEL alloy 686 (UNS N06686) is a single-phase, austenitic, nickel-chromium-molybdenum-tungsten alloy. It is designed for outstanding corrosion-resistance in a wide range of severe environments. The chemical composition of the alloy is in Table 1. The high nickel and molybdenum contents provide good corrosion-resistance in reducing environments while the high chromium level imparts resistance to oxidizing media. The molybdenum and tungsten also aid resistance to localized corrosion (pitting and crevice corrosion). The low carbon content and other composition controls help minimize grain boundary precipitation to maintain resistance to corrosion in heat-affected zones of welded joints.

Alloy 686 is used in the most severe environments encountered in FGD systems including stack liners, ducts, dampers, scrubbers, stack-gas reheaters, fans, and fan housings. Alloy 686 components are used in the pollution control, chemical processing, petrochemical, oil and gas, pulp and paper, marine, and power industries. Applications for chemical and petrochemical processing include heat exchangers, reaction vessels, evaporators, and transfer piping. Heavily cold worked alloy 686 fasteners offer high strength along with resistance to seawater attack and hydrogen embrittlement

With its high alloy content, alloy 686 offers high mechanical strength. While the alloy is most often used in the annealed condition, it may be cold worked to even higher strength levels. The alloy matrix is a stable, solid solution. It cannot be strengthened by heat treatment. Typical room temperature tensile properties of various product forms in the annealed temper are given in Table 2.

Outstanding corrosion resistance is the major attribute of alloy 686. The alloy's composition provides resistance to general corrosion, stress-corrosion cracking, and localized corrosion (pitting and crevice corrosion) in a broad range of aggressive environments. A particularly desirable feature of the alloy is its resistance to intergranular precipitation during welding. Thus, fabricated components maintain their corrosion resistance in the heat-affected zones of welded joints. Alloy 686 has excellent resistance to both reducing and oxidizing acids as well as to mixed acid solutions. The alloy is especially suited to handling mixed acids containing high concentration of halides. It has shown good resistance to mixed acid media with pH levels of 1 or less, and chloride levels of over 100,000 ppm. Table 3 compares the general corrosion-resistance of INCONEL alloy 686 to other nickel-base alloys in acidic solutions. Since alloy 686 is nickel-based, it resists stress corrosion cracking and attack by highly alkaline solutions, even those saturated with salt.

INCONEL alloy 686 is readily fabricated. Alloy 686 components are formed using conventional equipment and techniques. Equipment and procedures employed to form similar alloys such as INCONEL alloys 622, 625, and C-276 can likely be used for fabricating alloy 686. Work hardening during cold forming may make intermediate annealing necessary. Hot forming should be done at temperatures between 1600 and 2250°F (870 and 1230°C), with all heavy forming above 2000°F (1090°C). The alloy is normally annealed at 2150-2200°F (1180-1200°C), followed by rapid cooling.

Alloy 686 exhibits excellent weldability and needs no post-weld treatment to restore corrosion resistance. Recommended welding products are INCO-WELD® Welding Electrode 686CPT® for shielded metal-arc welding (SMAW) and INCO-WELD Filler Metal 686CPT for gas-metal-arc welding (GMAW), gas tungsten-arc welding (GTAW), and submerged arc-welding (SAW). Alloy 686 weldments exhibit excellent resistance to corrosion. INCO-WELD 686CPT Welding Electrode and INCO-WELD Filler Metal 686CPT are recommended for use as more highly alloyed, "overmatching", welding products for joining other nickel-chromium-molybdenum alloys, such as INCONEL alloys 622, 625, and C-276 for aggressive corrosive environments.

INCONEL alloy 686 Proves its Value In FGD Service

Shortly after its commercial introduction, INCONEL alloy 686 was employed to solve a major corrosion problem at the Seminole Electric Cooperative Power station in Palatka, Florida, USA. The alloy C-276 lining in a by-pass duct was being rapidly attacked by a corrosive media that was condensing on the walls and standing on the floor. Alloy C-276 plate was corroding at the excessively high rate of 40 mpy. However, alloy C-276 weldments had been essentially corroded away due to the effects of elemental segregation (Figure 13). These welds were replaced by deposits of INCO-WELD Filler Metal 686CPT. After 6 months service the 686CPT weldments showed no corrosion (Figure 14). Based on these results, the duct was completely lined with alloy 686 plate. After five years service there is no measurable corrosion.

To determine why the alloy C-276 lining was corroding at such a high rate, the condensate inside the duct was analyzed . It was found to contain 127,000 ppm chlorides, 2,900 ppm fluorides, and 180,200 ppm sulfates at a pH of 0.8 ! Thus, it is not surprising that alloy C-276 corroded under these conditions. What is most important, however, is that alloy 686 products, even segregated weldments, were able to resist this environment.

Further testing was conducted by exposing a 4-alloy panel in the duct. Four pieces of ¼" plate 12 inches square each were welded together with Filler Metal 686CPT to form a 2 foot square panel which was welded to the floor of the by-pass duct. The alloys making up the panel were INCONEL alloy 622, C-276, and 686 and INCOLOY alloy 25-6MO, a 6% molybdenum super-austenitic stainless steel. After a six month exposure the panel was examined. The alloy 686 was unattacked, there was slight corrosion of the alloy 622 and C-276, but the alloy 25-6MO plate had totally corroded away (Figure 15).

The results of the panel test emphasize the importance and economy of the use of highly resistant nickel-base alloys. Under the conditions in the by-pass duct at the Seminole Plant, a duct constructed of ¼" stainless steel plate would have lasted less than 6 months while a duct lined with only 1/16" of alloy 686 would have exhibited an indefinite life.

FGD – the Future

Over the past thirty years, we have learned a great deal about the performance of the various materials in FGD service. There were numerous premature corrosion-related failures of non-metallic and low alloy linings in the early days of the industry. However, materials engineers now have a much better understanding of the corrosivity of the system and the alloys necessary to meet the requirements of FGD service. Nickel-chromium-molybdenum alloys provide corrosion resistance for the various components found in FGD systems. Conventional alloys such as INCONEL alloys 622 and C-276 provide adequate corrosion resistance for most components of the system. For the most corrosive sections, INCONEL alloy 686, a new superalloy with vastly improved resistance to the conditions that cause FGD corrosion, is available. A better knowledge of system conditions in combination with the use of a new, highly corrosion-resistant superalloy will result in FGD systems, which offer many years of reliable, corrosion-free service. This will ultimately lead to a cleaner environment free of the problems associated with sulfur dioxide and acid rain.

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References

Dr. George T. Paul and Ralph W. Ross, Jr., "Corrosion Performance in FGD Systems at Laramie River and Dallman Stations", Paper No. 194, Corrosion'83, NACE, Houston, TX, 1983

Stephen L. Morse and Lewis E. Shoemaker, "INCONEL alloy 625 Clad Steel Plate for Applications in Wet Scrubber Systems", Paper No. 310, Corrosion'84, NACE, Houston, TX, 1984

T.S. Lee and B.S. Phull, "Use of a Model Limestone SO_2 Scrubber to Evaluate Slurry Chloride Level Effects on Corrosion Behavior", *Proceedings of the 1984 Air Pollution Seminar*, NACE, Orlando, FL, December 5-7, 1984

Ralph W. Ross, Jr., "The Performance of Corrosion-Resistant Nickel Alloys in Utility Lime / Limestone Flue Gas Desulfurization Systems", *Proceedings of the 1984 Air Pollution Seminar*, NACE, Orlando, FL, December 5-7, 1984

Edward L. Hibner, Lewis E. Shoemaker, Ralph W. Ross, Jr., and Stephen l. Morse, "Effect of Welding Procedure on Corrosion Resistance of Welded INCONEL alloy 625 Clad Steel Plate in a Flue Gas Desulfurization Environment", Paper No. 53, Corrosion'85, NACE, Houston, TX, 1985

Edward L. Hibner and Ralph W. Ross, Jr., "Localized Corrosion Behavior of Nickel Alloys in Model SO_2 Scrubber Environments", Paper No. 251, Corrosion'87, NACE, Houston, TX, 1987

Carl E. Stevens, Edward L. Hibner, Ralph W. Ross, Jr., "Nickel Alloy Clad Steel Plate for Flue Gas Desulfurization Applications", Paper No. 253, Corrosion'87, NACE, Houston, TX, 1987

Edward L. Hibner & Carl E. Stevens, "Nickel Alloy Clad Steel Plate for Application in the Chemical Process Industries", Paper No. 324, Corrosion'88, NACE, Houston, TX, 1988

James R. Crum and Lewis E. Shoemaker, "Laboratory testing and Field Experience with Advanced Corrosion Resistant Alloys", AIRPOL'90, Louisville, KY, October 17-19, 1990

James R. Crum, Thomas O. Bates, and Lewis E. Shoemaker, (Effect of Welding Procedure on the Localized Corrosion Resistance of Some Ni-Cr-Mo Alloys", Paper No. 263, Corrosion'91, NACE, Houston, TX, 1991

Ralph W. Ross, Jr., "The Evolution of FGD Technology", Paper No. 414, Corrosion'93, NACE, Houston, TX, 1993

James R. Crum and Lewis E. Shoemaker, "Advances in Molybdenum Bearing, Corrosion Resistant Alloys for FGD Service", Paper No. 423, Corrosion'93, NACE, Houston, TX, 1993

Richard E. Avery, “Fabrication Options for Nickel-Containing Alloys in FGD Service: Guidelines for Users”, *Materials Performance*, December, 1993, NiDI Reprint Series No. 14 029

Thomas J. Wess, James R. Crum, and Lewis E. Shoemaker, “Corrosion Environments Experienced in FGD Applications”, Paper No. 414, Corrosion’94, NACE, Houston, TX, 1994

Thomas J. Wess, James R. Crum, and Lewis E. Shoemaker, “Seminole Electric FGD Study Reveals Corrosion Mechanisms, Duct Material Performance”, *Power Engineering*, December, 1994

Lewis E. Shoemaker & Heinz Zickler, “The Evolution of Ni-Cr-Mo Alloys for FGD Construction”, *Stainless Steel Europe*, May, 1995

Evan B. Hinshaw & James R. Crum, “Effects of Fabrication Practices and Techniques on the Corrosion and Mechanical Properties of Ni-Cr-Mo Nickel Based Alloys N10276, N06622, N06686, and N06625”, Paper No. 434, Corrosion’96, NACE, Houston, TX, 1996

James R. Crum and Lewis E. Shoemaker, “The Role of Nickel Alloys in Fighting Corrosion in Wet Limestone FGD Systems”, Paper No. 454, Corrosion’96, NACE, Houston, TX, 1996

Richard E. Avery, William L. Mathay, & William H.D. Plant, “Utilization of Nickel-Containing Alloys for FGD Systems in North America and Europe”, Paper No. 455, Corrosion’96, NACE, Houston, TX, 1996

James R. Crum and Michael J. Shaw, “The Use of INCO-WELD Filler Metal 686CPT as an Overmatching Filler Metal for Chemical Process Industry Applications”, EUROCORR’99, Eurogress Aachen, Germany, August 30 – September 2, 1999

James R. Crum, Lewis E. Shoemaker, and Samuel D. Kiser, P.E., “Special Alloys and Overmatching Welding Products Solve FGD Corrosion Problems”, Corrosion’2000, NACE, Houston, TX, 2000

“Inco Alloys International: INCONEL alloy 622”, Publication No. IAI-144, Special Metals Corporation, Huntington, WV, 1995

“Special Metals: INCONEL alloy C-276”, Publication No. SMC-019, Special Metals Corporation, Huntington, WV, USA, 1999

“Special Metals: INCONEL alloy 686”, Publication No. SMC-024, Special Metals Corporation, Huntington, WV, USA, 2000

“Lukens Roll-Bonded Clad Steels: High Alloy Performance at Lower Cost”, Bethlehem Lukens Plate, Coatesville, PA, USA, August, 1996

Table 1 – Limiting Chemical Composition, %

Chromium	19.0 – 23.0	Manganese	0.75 max.
Molybdenum	15.0 – 17.0	Sulfur	0.02 max.
Tungsten	3.0 - 4.4	Silicon	0.08 max.
Titanium	0.02 – 0.25	Phosphorus	0.04 max.
Iron	1.0 max.	Nickel	Balance
Carbon	0.008 max.		

Table 2 – Room-Temperature Tensile Properties of Annealed Material

Product Form	Thickness or Diameter		Tensile Strength		Yield Strength (0.2% offset)		Elongation
	in	mm	ksi	MPa	ksi	MPa	%
Plate	0.500	12.7	104.7	722	52.8	364	71
Plate	0.250	6.35	106.3	733	57.9	399	68
Sheet	0.125	3.18	116.5	803	61.1	421	59
Sheet	0.062	1.57	123.0	848	59.2	408	59
Rod	1.50	38.1	117.5	810	52.1	359	56

Table 3 – General corrosion-resistance of nickel base alloys in acid solutions Corrosion rate in mm/yr - 168 hour test

Alloy	80% H_2SO_4 80°C	2% HCl Boiling	10% H_2SO_4 + 5% HCl at 80°C
UNS N06455 W. Nr. 2.4610	0.80	1.82	1.20
UNS N10276 W. Nr. 2.4819	0.58	1.09	1.01
UNS N06022 W. Nr. 2.4602	1.29	1.40	2.77
INCONEL alloy 622	1.32	1.32	2.08
UNS N06059 W. Nr. 2.4605	0.62	0.70	1.29
INCONEL alloy 686	0.11	0.15	0.85

Figure 1

Failure of an organic coating led to perforation of a steel vessel by corrosion after only 6 months of operation at the Louisville Gas & Electric Company Cane Run Station in Louisville, KY. The use of corrosion-resistant superalloys has essentially eliminated such failures in modern FGD systems.

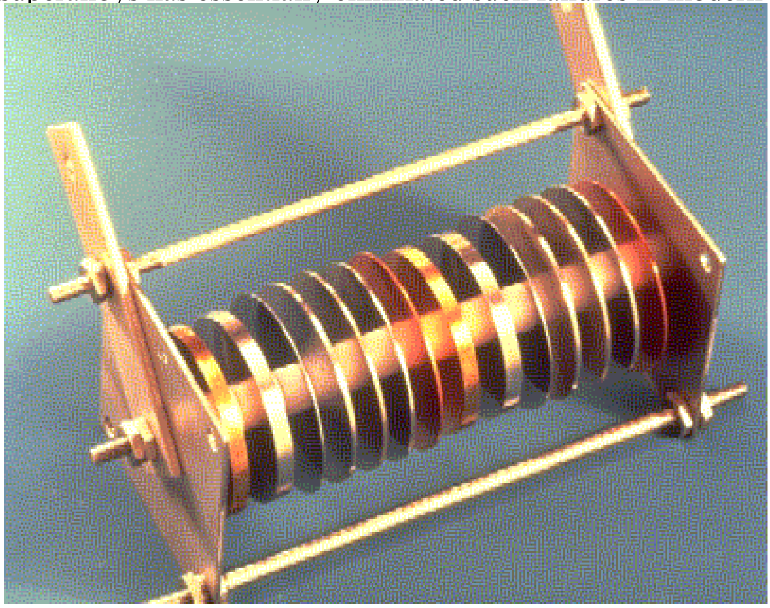

Figure 2

A multiple sample test spool for installation in an operating system to evaluate alloys for service in the corrosive environment. Each sample is electrically isolated from the other to avoid galvanic effects.

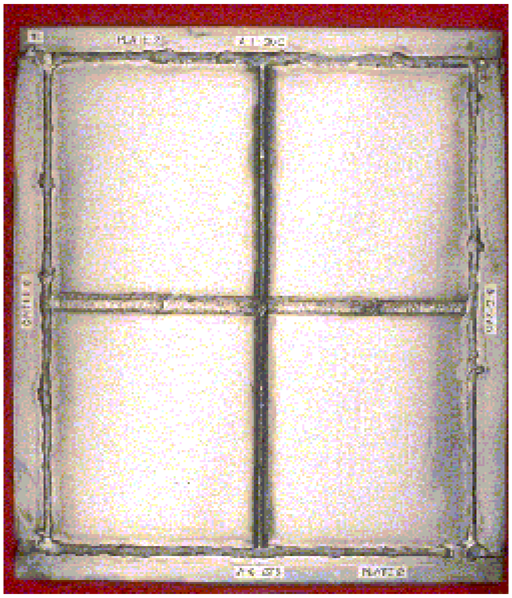

Figure 3
A four alloy test panel used to evaluate alloys and welding products and procedures for service in FGD systems.

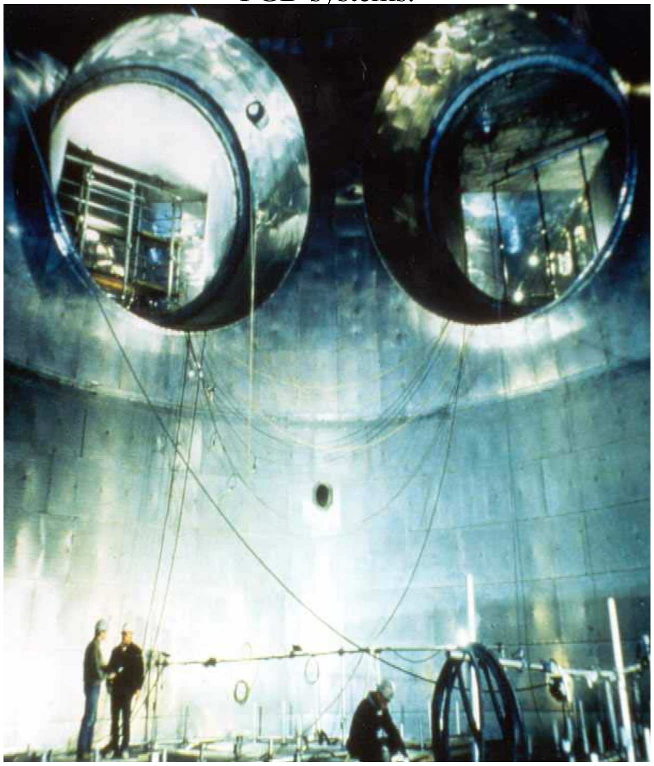

Figure 4
A wet limestone FGD vessel lined with 1/16” (1.6 mm) INCONEL alloy C-276 sheet by the wallpaper technique at the Ontario Hydro Lambton Station in Sarnia, Ontario. Note that plug welds are used to reinforce the sheet lining.

Figure 5

Installation of 1/8” (3.2 mm) INCONEL alloy 622 sheet by the wallpaper technique at the Virginia Electric Power Company Mt. Storm Station in Davis, WV. Intermittent (“skip”) weldments are used to attach the alloy sheets to the steel substrate. The next sheet to be installed will overlap this sheet by 1 to 2 inches. Thus, the seal weld which will be exposed to the service environment will not be diluted with iron from the steel structure.

Figure 6

A close-up view of a section of INCONEL alloy 622 wallpaper at the Virginia Electric Power Company Mt. Storm Station. Note that the plug welds are covered with protective caps of the same alloy. Here as above the service welds are full alloy with no iron dilution.

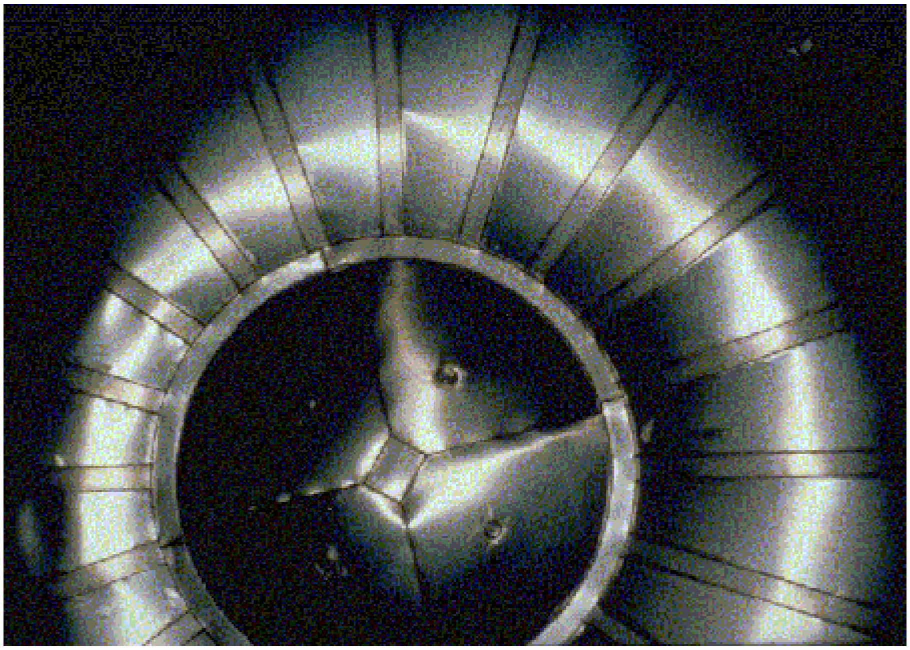

Figure 7

Alloy lining of the top of a FGD vessel showing the complex shapes that can be clad by the wallpaper technique.

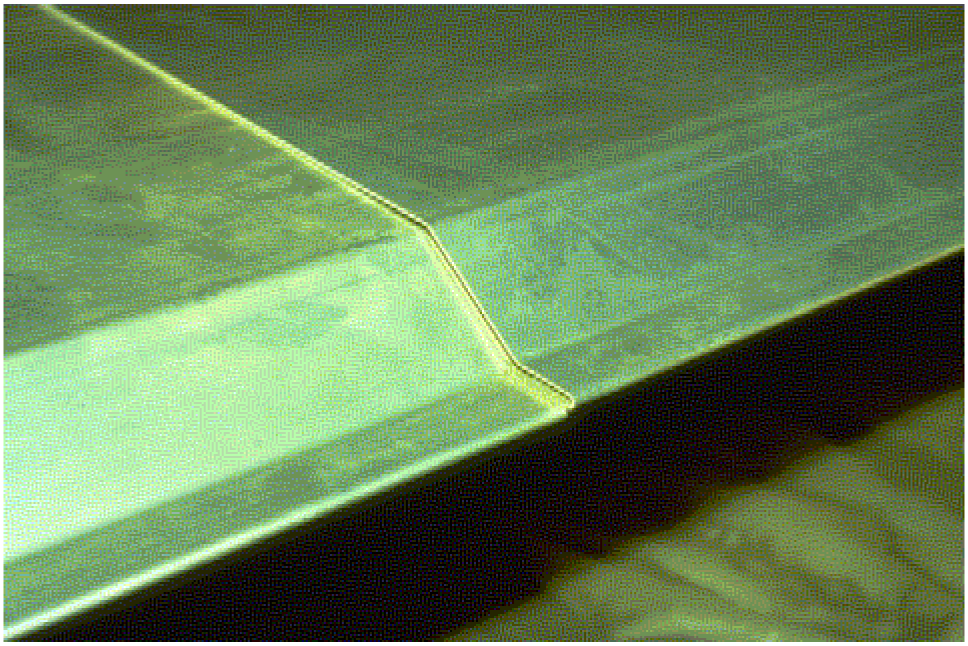

Figure 8

Repair of a corroded INCOLOY alloy 825 louver damper blade with INCONEL alloy C-276 sheet by the wallpaper technique at the Tampa Electric Company Big Bend Station in Apollo Beach, FL.

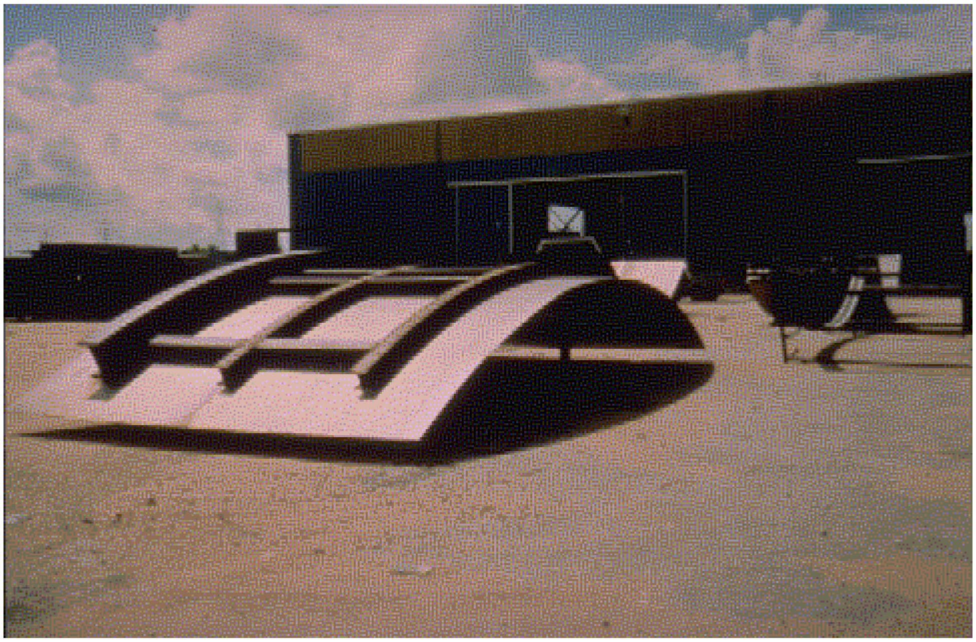

Figure 9

INCONEL alloy C-276 plate fabricated into segments of a FGD vessel wall for the Salt River Project Navajo Station in Page, AZ. Structural strength is supplied by the external steel I-beams. The fabrication was done by PSP Industries in Schertz, TX.

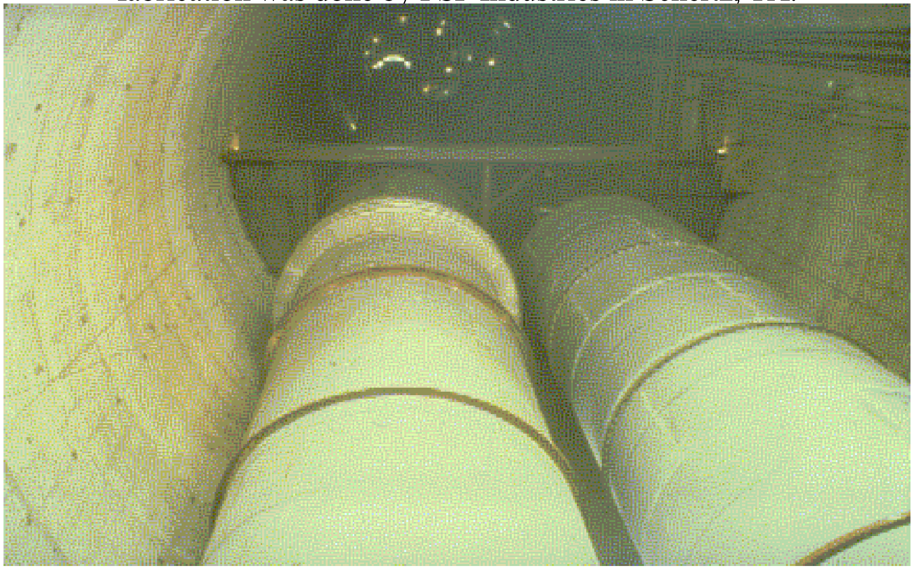

Figure 10

FGD chimney flues at the Bruce Mansfield Station of the Pennsylvania Power Company in Shippingport, PA. The flues are fabricated from ¼” (6.4 mm) INCONEL alloy 625 plate. Alloy clad steel plate could have been a product option for these components. In the years following the construction of these flues in 1980, alloy clad steel plate has indeed become the product of choice for such fabrication.

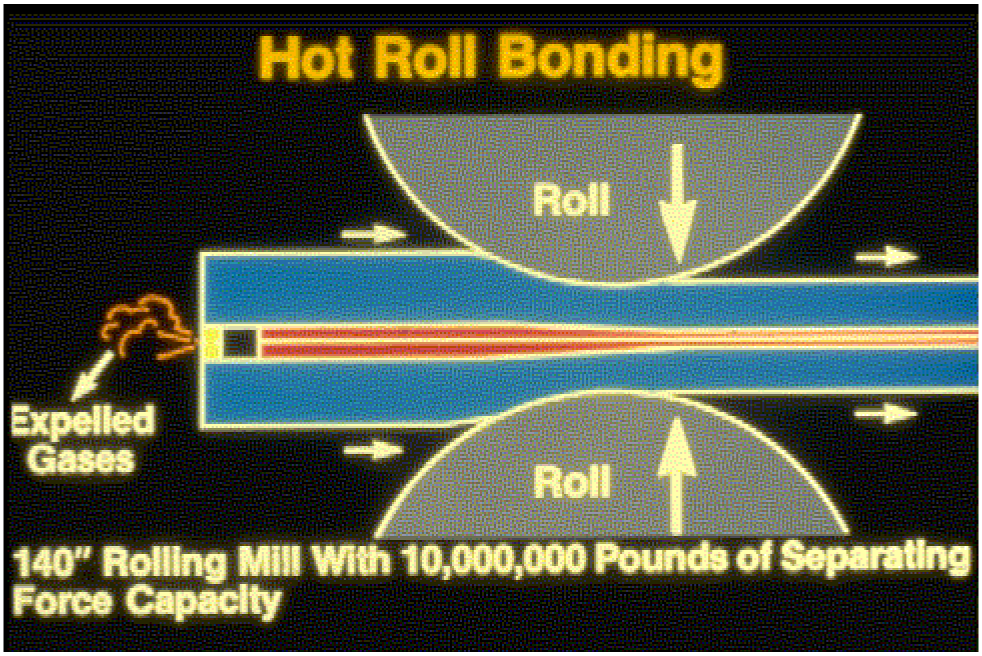

Figure 11
A schematic drawing showing the roll bonding technique for manufacture of alloy clad steel plate at Belthlehem Lukens Plate in Coatesville, PA. Most Ni-Cr-Mo and Fe-Ni-Cr-Mo corrosion-resistant alloys can be clad to steel by this process.

Figure 12
An induced draft fan fabricated from INCONEL alloy 625 plate. Fans are used to force the wet scrubbed gases through the scrubbing system and up the chimney when natural draft is insufficient. Because of its high tensile and fatigue strength along with its excellent corrosion-resistance, alloy 625 is the material of choice for such components.

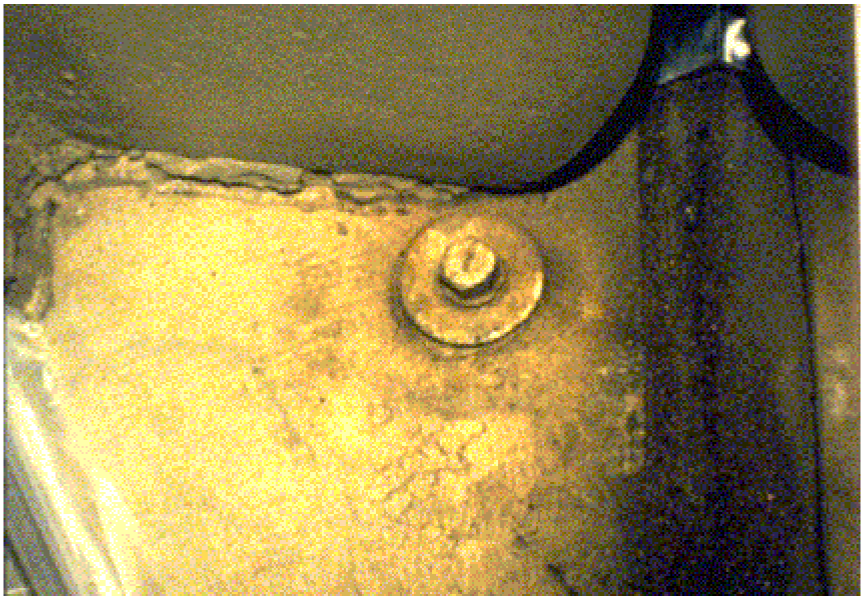

Figure 13

Severe corrosion of an alloy C-276 weldment and alloy C-276 plate in the by-pass duct at the Seminole Electric Cooperative Station in Palatka, FL. This is one of the few occurrences of rapid corrosion of alloy C-276 under FGD conditions.

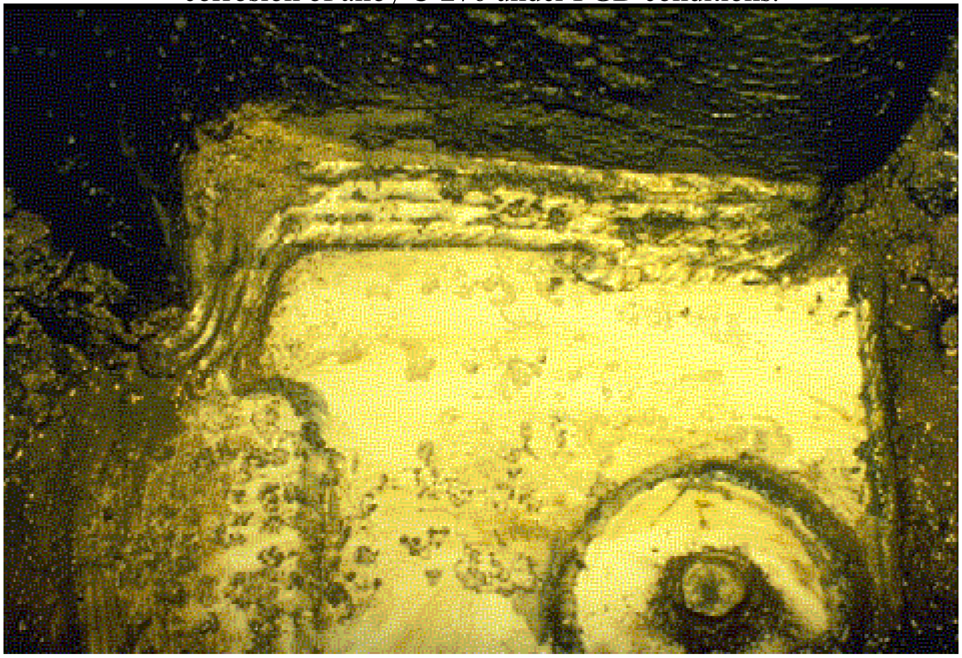

Figure 14

INCO-WELD 686CPT weldments used to replace the corroded alloy C-276 weldments seen in Figure 13. After 6 months exposure, the alloy 686 weldments exhibit no corrosive attack. During that same period, the alloy C-276 plate corroded at a rate of 40 mils per year. Eventually, alloy 686 was used to replace the alloy C-276 products in this duct.

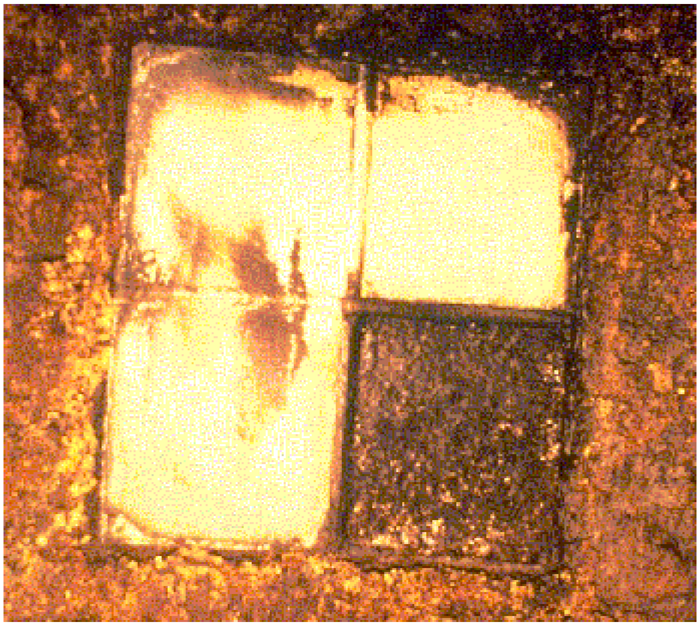

Figure 15

Results of a four-alloy test panel exposed for six months in the outlet duct seen in Figures 13 and 14. INCONEL alloy 686 (upper left corner) was not attacked. There was evidence of initiation of corrosion in INCONEL alloy C-276 (upper right corner) and INCONEL alloy 622 (lower left corner). However, a sample of INCOLOY alloy 25-6MO, a 6% molybdenum super-austenitic stainless steel (lower right corner) was completely corroded away. All test samples were initially ¼" (6.4 mm) in thickness. The value of corrosion-resistant superalloys is obvious.