Weld Overlay of Waterwall Tubing, Alternative Filler

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Technical Review, March 2001

EPRI Project Managers

Kent Coleman

David Gandy

EPRI-RRAC • 1300 Harris Blvd., Charlotte, North Carolina 28262• PO Box 217097, Charlotte, North Carolina 28221 • USA
800.313.3774 • 704.547.6176 • askepri@epri.com • www.epri.com

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EPRI Fossil Repair Applications Center (FRAC)
1300 W.T. Harris Boulevard
Charlotte, NC 28262

Principal Investigators
K. Coleman
D. Gandy

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REPORT SUMMARY

Background

The rate of wall thickness losses (wastage) of fireside waterwall tubing in fossil-fired utility boilers has been a concern of utility maintenance personnel for many years. Recent conversion by many utilities to low (NOx) burners for compliance with Clean Air Act requirements has increased waterwall wastage rates up to 120 mils (3 mm) a year in some boilers. To slow down this corrosion rate, utilities have been overlaying existing waterwalls with corrosion-resistant weld materials or replacing waterwall panels with new panels that have been overlaid in the factory. Though less costly than replacement panels, the field overlay process is a very expensive mitigation technology that may leave high residual stresses in the waterwall tubing. Additionally, thermal expansion differences between the base material and the weld overlay material can cause high thermal expansion stresses.

Objectives

- To investigate alternative filler materials for waterwall overlay applications that are less costly than current overlay materials and that closely match the thermal expansion characteristics of the base material.
- To analyze current welding practices and develop alternative approaches to minimize distortion and residual stresses.
- Perform field demonstration in a utility boiler
- Analyze durability of repairs in utility boiler service
- Investigate embrittlement issues with Type 312 SS
- Develop repair methods for overlayed boiler tubing

Approach

Industry technical journals were reviewed, and a material was selected that was inexpensive and had thermal expansion properties similar to the waterwall base materials. Available welding fillers were tested that contained different levels of delta ferrite to determine the relationship between delta ferrite and thermal expansion.

Welding contractors were invited to prepare mockup test panels to determine residual stresses left from currently available deposition techniques. Distortion control methods, such as varying heat input, bead sequencing, etc., were evaluated.

A field demonstration of the overlay material was performed in a utility supercritical boiler. The demonstration was subjected to a five month operating cycle at which time the unit was removed and the overlay was evaluated for wastage and serviceability. Metallurgical analysis of the demonstration overlay was performed.

Finally some repair procedures were developed to allow for replacement of damaged tubing in previously overlayed tubing.

Results

A welding filler metal was found that is less costly than currently utilized overlay fillers. Thermal expansion properties of the new filler more closely match thermal expansion characteristics of the waterwall tubing material. Welding techniques and shielding gasses were evaluated to determine optimum procedures for application of the new alloy. Alternatives to power supplies currently used by welding contractors were evaluated and found to provide superior welding characteristics.

The repair demonstration in an operating utility supercritical boiler indicated good serviceability with little wastage and only one small area of cracking. The cracking was found to be caused by poor welding and was not related to the filler metal. Very little wastage was noted after five months of operation.

Embrittlement problems with this filler metal were evaluated and shown not to be a concern for boiler operation. The filler metal was shown to be ductile at the operating temperatures of the boiler and brittle only while the unit was off line for maintenance. The embrittlement was shown to be reversible through localized heat treatment.

Initial development of repair procedures was performed to provide a complete package for alternative solution to waterwall wastage issues. This program provides utilities with another option that can be utilized to manage their steam generating assets.

EPRI Perspective

Typical waterwall corrosion overlay applications can encompass as much as 5,000 square feet (46.5 square meters) of waterwall tubing surface. The alternative material suggested by this report could typically save 25% over currently used overlay materials. The material savings alone could amount to $250,000 on one project. Distortion control and thermal expansion stress mitigation will also make the repairs performed utilizing procedures in this report more durable, allowing for longer service life of existing waterwall tubing.

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Keywords

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ABSTRACT

Boiler water wall tubing exposed to the reducing atmosphere of fireboxes designed to reduce NOx pollution is experiencing high wastage rates. Currently, these tubes are being overlaid with either Type 309 stainless steel (SS) or Inconel 625 to eliminate this problem. Type 309 SS demonstrates a considerably different thermal expansion rate than the carbon or low alloy steel from which boiler tubing is manufactured. This leads to high stresses in operation at the weld overlay interface. Inconel 625 has a closer match of thermal expansion characteristics but is a relative expensive material and in a few isolated cases has been shown to have a problem with circumferential cracking. Another problem with current repair technology is that the residual stresses from the welding process warps the waterwall tubing and creates high stresses in the tubing and attachments. This project explored alternative filler materials and welding techniques to reduce thermal expansion and residual welding stresses.

Thermal expansion properties were taken from ASME Section II D for different filler and base materials and thermal expansion curves were plotted. Comparing the expansion rates and costs of filler materials led the EPRI Fossil Repair Applications Center (FRAC) to select Type 312 SS as a possible replacement filler metal.

Commercially available Type 312 SS filler materials were obtained for testing including:

- Two Type 312 SS GMAW fillers
- Two Type 312 SS FCAW fillers
- One metal cored Type 312 SS filler

Weldability and metallurgical testing were performed utilizing each filler. Thermal expansion tests were performed on all weld metal test samples fabricated with each filler material. From these tests, one filler was selected that best matched the properties desired. Welding was then performed using the Type 312 SS filler metal selected above at different heat inputs. Again, thermal expansion tests were performed to determine the effect of heat inputs on thermal expansion.

Three welding contractors were solicited to prepare mockup waterwall panels to test for residual stresses. Distortion was measured dynamically with linear variable displacement transducers (LVDT's) during the welding process and at the macro level with a tape measure after welding. Residual stresses were measured with a blind hole technique. Different heat inputs were then used while welding with the Type 312 SS filler to explore the welding energy effect on residual stresses. Trials were also performed with Inconel 625 alloy for a baseline. Bead sequencing was analyzed to determine the effects on residual stresses.

A utility was selected for a field trial of the Type 312 SS filler metal in a utility sized boiler. An area of approximately 1000 square feet was overlayed. Sample panels were removed after 5 months of service and analyzed for durability. Investigation of embrittlement issues were performed and some repair methods were developed.

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Individuals who contributed immensely to this project and report include:

- T. Cullen (consultant) who prepared and conducted the survey discussed in Section 2 and provided consultation and expertise throughout the project.
- T. Andress (American Electric Power Co.) who served as the utility coordinator and advisor for this project. He helped to steer this project to ensure that the materials selected would be of good value to the utility industry.

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1 INTRODUCTION

The rate of wall thickness losses (wastage) from corrosion in fireside waterwall tubing in fossil-fired utility boilers is on the rise. This is the result of burner design improvements to remove nitrous oxide (NOx) emissions, including the installation of low NOx burners and over-fire air systems, to comply with the Clean Air Act. In some cases, wastage rates of 120 mils (3 mm) a year have been measured (see Section 2). Low NOx combustion systems delay the mixing of air and fuel, which produces a high-temperature, fuel-rich reducing gas environment around the burner, thus reducing the formation of NOx. While environmentally beneficial, this condition has accelerated the wastage of water wall boiler tubes made of carbon and low alloy steel.

In 1996, EPRI was asked by several utilities to investigate the problem of accelerated wastage and to make recommendations for limiting or eliminating the problem. In one such project, Sherlock and Wells investigated the various solutions and strategies to overcome the problem through the use of new materials, coatings, and weld overlays (*State of Knowledge Assessment for Waterwall Wastage with Low NOx Burners,* TR-107775). The study looked at corrosion rates, the cost and effectiveness of current repair practices, and strategies for combating the problem and concluded that promising short and long term solutions are available. However, further developments are needed. Several conclusions were drawn from this study and are summarized below:

- Thousands of square feet (meters) of waterwall are affected by accelerated corrosion, resulting in multimillion dollar maintenance costs to correct.
- High alloy materials containing chromium in excess of 20% are needed to protect the tube material from corrosive gases.
- *In situ* weld overlay methods appear to provide the most economical long-term solution, but questions remain as to high residual stresses, which can lead to deformation, cracking, and fatigue.
- Different thermal expansion properties between overlay filler metals and base metals can cause high operating stresses.
- *In situ* thermal spray methods are comparatively inexpensive but have a life expectancy of only one to three years due to cracking and spalling.
- Weld overlaid and chromized replacement panels have a long life expectancy but also have a high up-front cost. Fatigue and corrosion performance at butt welds have also been a problem.
- Alloy 625 has performed well as an overlay material, but it is expensive when compared to Type 309 stainless steel. A less costly overlay material that provides a close coefficient of thermal expansion match with the substrate is desirable.

The conclusions and recommendations provided by the Waterwall Investigation Group (WWIG) to EPRI support further investigation of methods and materials to improve the *in situ* weld overlay method for waterwall wastage mitigation. Areas addressed include: (1) the evaluation of reduced cost corrosion resistant filler materials with improved thermal coefficient compatibility and (2) the development and demonstration of welding techniques that result in lower residual stresses and distortion.

The purpose of this project was to improve the implementation and reliability of the weld overlay process for waterwall wastage of carbon steel and low alloy steel boiler tubes. The objective of the project was to limit welding residual stresses and obtain heat-affected zone (HAZ) properties of *in situ* weld overlays without post-weld heat treatment (PWHT), comparable to overlays performed in the shop with PWHT. The welding development effort also attempted to reduce the base metal thickness of tubes that can be overlaid through welding practices that minimize first layer dilution. Finally, the program evaluated alternative filler materials to Inconel (In) 625 (ER NiCrMo-3) in an effort to find a less costly alloy.

Task 1: Residual Stress Evaluation of Alternative Filler Materials

Welding application trials were performed utilizing commercially available filler metals. The FRAC was able to obtain three solid gas metal arc welding (GMAW) filler wires, two flux-cored arc welding (FCAW) filler wires, and one metal core experimental filler wire. Deposited chemistry (chromium content), weldability, delta ferrite content, and thermal expansion properties were used to select one GMAW wire and the metal core filler wire for continued testing to measure weld residual stress of the deposits.

Task 2: Evaluation of GMAW and FCAW Processes to Optimize Welding Parameters Resulting in Minimal Residual Stress and Improved HAZ Properties

The objective of this task was to evaluate GMAW and FCAW weld overlay application parameters in an effort to minimize shrinkage and residual stresses in single- and multi-bead deposits. Variables such as amperage, voltage, wire feed speed, travel speed, torch angle, oscillation, and interpass temperature were investigated. New advanced GMAW welding systems were evaluated. Weld test coupons were evaluated metallographically to determine weld quality, microhardness in the HAZ, and dilution. The aim of this project was to reduce the residual stresses in the waterwall panels to a level comparable with those that are stress relieved in a shop.

Task 3: Field Demonstration and Analysis

Information developed in task 2 above was utilized to overlay approximately 1000 square feet of overlay in a utility boiler. Samples were removed after five months of service and analyzed metallurgically. Delta ferrite measurements were taken and one small area of cracking was investigated. The primary cause of the cracking was underbead deposits but low delta ferrite also contributed.

Task 4: Investigation of Embrittlement

At elevated temperatures, around 885 ^{o}F, Type 312 SS has a tendency to embrittle. Investigation was performed to determine the effects of this embrittlement with respect to serviceability of the overlay. The primary condition that was found of concern was when the tubing was cool while the boiler was out of service. When the boiler is operating, the material is above the Fracture Appearance Transition Temperature and the Type 312 SS behaves ductily. At the room temperature, the material can fail by brittle fracture. Tubing removed from the field demonstration were pressurized to over five times the operating pressure and no failures could be detected.

Task 5: Investigation of Repair Procedures

One concern with waterwall overlays is how do you repair waterwalls that have been overlayed. Several preliminary welding procedures were tested. Additional testing will continue in 2001.

The weld input variables found to minimize welding residual stresses were used to overlay 3 x 4 ft (0.9 x 1.2 m) T-22 waterwall sections using typical sequencing practices. Residual stresses, distortion, HAZ hardness, and deposited chemistry were measured and documented for comparative results with existing practices.

2 SURVEY

To determine the current state of the art in waterwall overlay welding, T. Cullen was contracted to perform a survey of member utilities with boilers that had been overlaid for prevention of wastage. Results were received from five FRAC sponsors. A copy of the survey and the responses is provided in Appendix A. The following is a summary of the results:

- Wastage is a severe problem, which was made worse by the installation of low NOx burner systems.
- Most of the overlay alloys used by participating utilities have withstood the furnace wastage very well. These alloys contained high chromium content (>20%), which is necessary to provide resistance to sulfur attack.
- The Inconel alloys, In 622 and 625, performed very well in service and provided the standard of comparison for judging other alloys. One participating utility exclusively uses replacement panels laser clad with In 622. These alloys, however, are expensive relative to the other candidates.
- Fully austenitic Type 309 stainless steel withstood sulfur attack in service, but it was subject to dissimilar metal cracking when used over ferritic base metals.
- A ferritic stainless, Type 446, performed well as long as chromium dilution was held in check, but it was difficult to weld.
- A duplex stainless steel, Type 312, performed well in service and offers the promise of being both weldable and relatively inexpensive. A question remained as to the nature of the relationship between ferrite level and the thermal expansion coefficient.

3 ALTERNATIVE FILLER MATERIALS

The standard filler metal for weld overlaying waterwall panels in electric utility boilers is Inconel (In) 625. This filler has good corrosion resistance, thermal expansion properties that closely match base metal expansion properties, and good weldability. Unfortunately, the relative high nickel content of In 625 makes this filler metal more costly than other fillers, namely the 300 and 400 series stainless steels (SS).

Type 309 SS has been used in several repair applications on waterwall tubes. This filler material is less expensive than In 625, but it has other properties that make it less desirable. The coefficient of thermal expansion of Type 309 is quite large compared to carbon and low alloy steel base materials. This causes high residual and operating stresses. Samples removed from service after short service durations have shown dissimilar metal weld damage in the heat-affected zone of the overlay (see Section 2). Large distortions of the waterwalls have also been measured. The primary area of concern is in the transition area between tubing that has been overlayed and bare tubing that has not had an overlay applied. DMW type damage has been found in this area.

Stainless steels in the 400 series have better thermal expansion properties that more closely match the base material but generally have low chromium content in the range of 12%. As-deposited chromium content is even lower than the filler metal content due to dilution. The survey in Section 2 and previous EPRI work (TR-107775) suggested a lower bound on chromium content of 20%.

The objective of this project was to select a low cost filler metal that has:

- Thermal expansion properties that closely match carbon steel and low alloy steel base metal
- High chromium content to resist corrosion
- Low installed costs
- Good weldability

3.1 Thermal Expansion Considerations

One of the first objectives of this project was to evaluate potential alternative filler materials that could be used in lieu of the more expensive (and currently used) In 625 filler. FRAC staff believed it was necessary to consider materials that exhibited similar thermal expansion characteristics to the waterwall tubing first and then look at other characteristics such as chromium content for corrosion performance, cost, weldability, etc. Thermal expansion was considered over a range of temperatures from 100°F up to 800°F (38–427°C) (which represents the upper range of thermal expansion properties provided by ASME Section II, Part D) which is about the current service temperature for supercritical boiler waterwalls.

Thermal expansion is a very important characteristic that should be considered when joining or weld overlaying any alloy. Similar expansion characteristics minimize distortion problems that can occur based simply on the heating or cooling of an alloy. Similar expansion characteristics for weld overlays minimize distortion and tend to reduce residual stresses attendant to welding.

Various families (ferritic, austenitic, and duplex stainless steels) of alloys were considered solely from a thermal expansion standpoint. Several austenitic SS materials were plotted against the tubing alloys: T1/T2, T-11, T-22, and carbon steel. Two of the more common austenitic SS alloys, Types 304 and 309, are shown in Figure 3-1. As can be seen, the pure austenitic SS alloys do not match the tubing alloys very well in terms of thermal expansion characteristics. As mentioned above, it is important to note that Type 309 has seen some use as an overlay material.

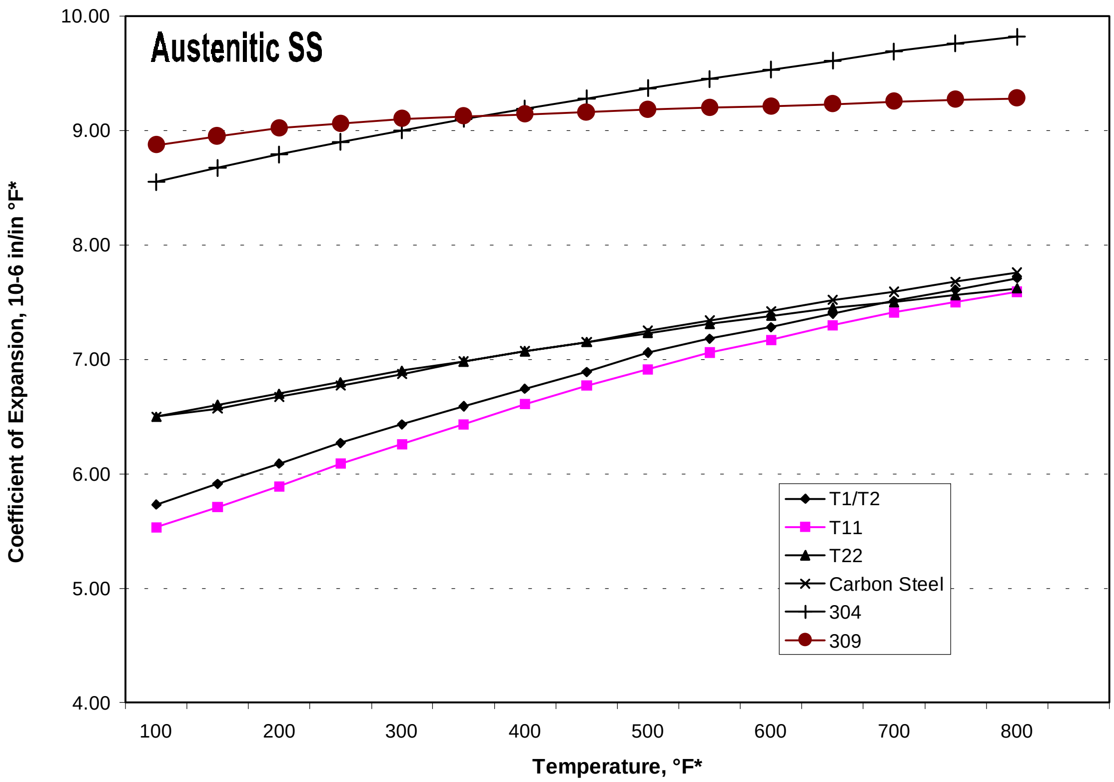

Figure 3-1
Thermal Expansion of Base Metals and 300 Series Austenitic SS from ASME Section II, Part D
** Conversion Factors — To convert inches to centimeters, multiply by 2.54. To convert Fahrenheit temperature to Celsius, subtract 32 and divide by 1.8.*

Next, several ferritic SS alloys were plotted against the currently used tubing alloys. Two representative ferritic alloys are provided in Figure 3-2 for comparison. Again, as with the austenitic SS (though to a lesser degree), one can easily see that the ferritic SS alloys do not match the tubing alloys in terms of thermal expansion characteristics. Particularly at high temperatures, the ferritics tend to deviate from the tubing alloys by a rather wide margin.

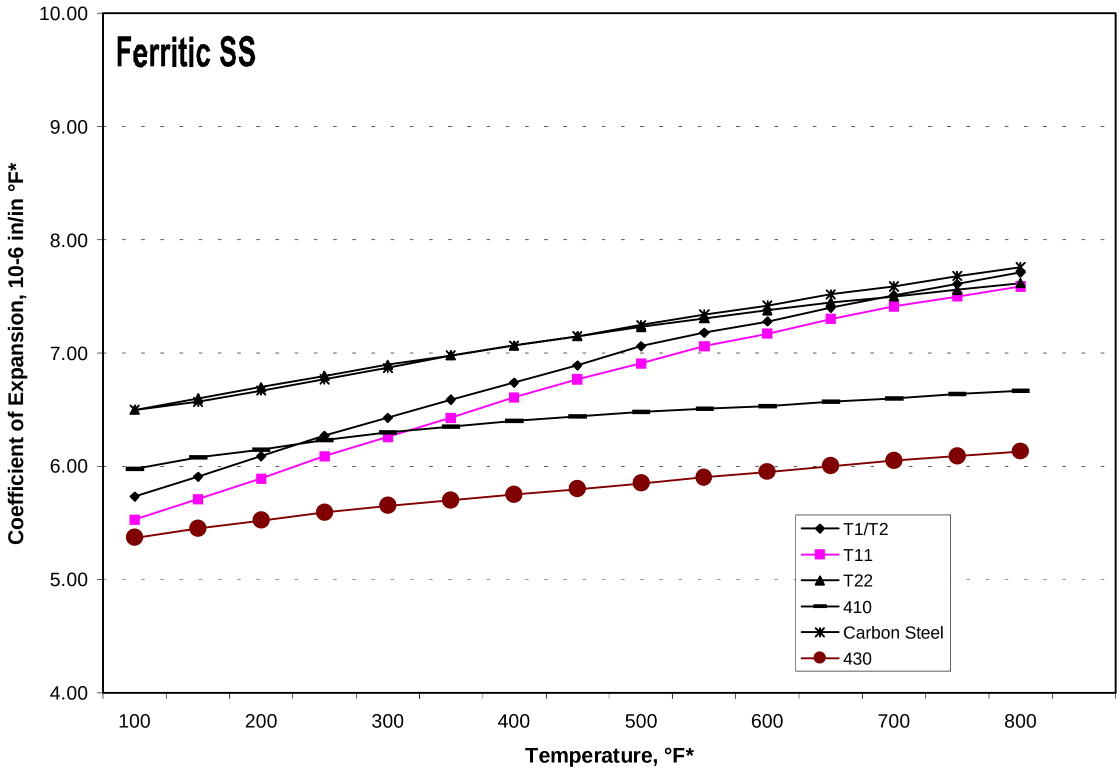

Figure 3-2
Thermal Expansion of Base Metals and 400 Series SS from ASME Section II, Part D

** Conversion Factors — To convert inches to centimeters, multiply by 2.54. To convert Fahrenheit temperature to Celsius, subtract 32 and divide by 1.8.*

The FRAC Steering Committee suggested that duplex alloys be evaluated as an alternative filler metal because their thermal expansion characteristics were believed to be close to those of the tubing alloys and could possibly be altered by varying ferrite content. A few duplex alloys (alloys containing both ferrite and austenite in the microstructure) were considered. Thermal expansion data for duplex alloys were not readily available from the ASME code but typical properties were provided by a filler-metal vendor.

One of the duplex alloys that provided reasonably good thermal expansion characteristics was Type 312 SS. Only two data points for Type 312 SS were available from the filler-metal vendor. A straight-line curve was extrapolated from these two points. The alloy was then plotted versus the tubing alloys and is shown in Figure 3-3. At lower temperatures, the alloy matches the expansion characteristics of the T-11 and T-22 materials fairly well; however, it deviates from the T1/T2 and carbon steel by a sizable margin. Above 500°F (260°C) and up to 800°F (426.7°C), which is incidentally the operating temperature for waterwall panels, Type 312 SS corresponds quite well with all of the tubing materials currently used in boilers. As a result, further attention and investigation, which included actual thermal expansion testing to better define these curves, were targeted toward the Type 312 SS alloy. Discussion of the investigation is provided in the following subsections.

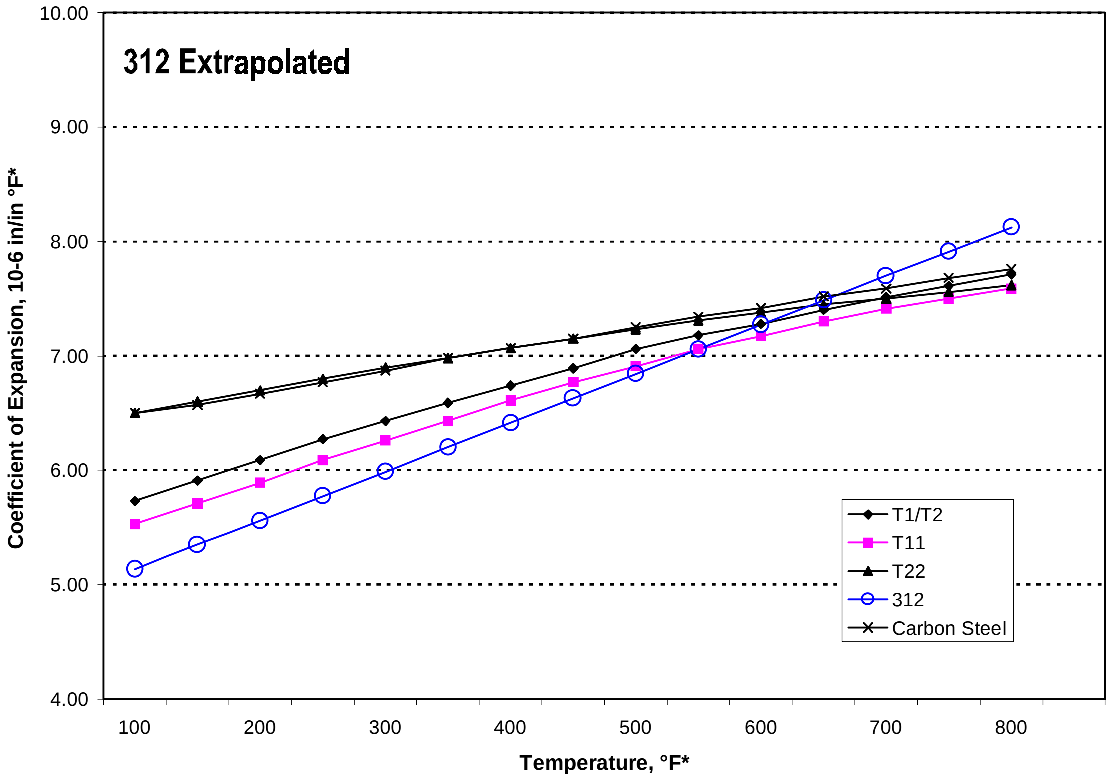

Figure 3-3
Thermal Expansion of Base Metals from ASME Section II, Part D and Type 312 SS
(Type 312 SS properties were provided by Euroweld)
** Conversion Factors — To convert inches to centimeters, multiply by 2.54. To convert Fahrenheit temperature to Celsius, subtract 32 and divide by 1.8.*

One final plot (Figure 3-4) is provided here solely for informational purposes. The plot compares the currently used In 625 alloy with the tubing alloy materials. As shown, In 625 meets the expansion characteristics well over the entire range of temperatures from 100–800°F (38–427°C).

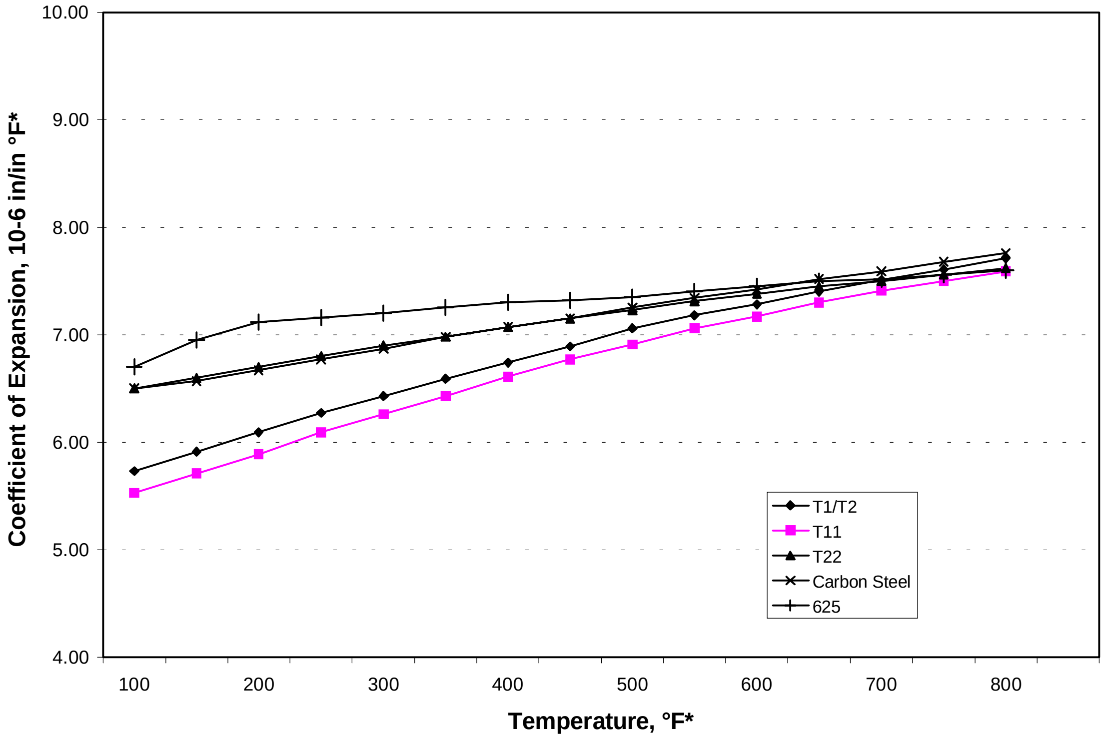

Figure 3-4
Thermal Expansion of Base Metals and In 625 from ASME Section II, Part D
** Conversion Factors — To convert inches to centimeters, multiply by 2.54. To convert Fahrenheit temperature to Celsius, subtract 32 and divide by 1.8.*

3.2 Chromium Content

A preliminary screening of alternative filler metals for waterwall overlays was performed on the alloys above that exhibited thermal expansion properties close to the base metals. The survey discussed in Section 2 indicated that chromium content above 20% was required to resist corrosion in a low NOx environment in the boiler firebox. The 400 series stainless steels do not meet this criterion having chromium levels from 12% to 17%, which is not sufficient to resist oxidation. The 400 series stainless steels were considered not to be a good alternative filler metal for waterwall overlay applications for this reason and were removed from further consideration.

Type 312 SS, having already been shown to have desirable thermal expansion properties, was evaluated on a chromium content basis. Available literature (ASME) indicated that 312 base material contains about 25% chromium. Welding fillers conforming to ER-312 contain about 30% chromium. This is substantially over the 20% minimum chromium content selected as a lower bound cut-off point for alternative filler materials. Type 321 SS was recommended for further testing under this program.

3.3 Costs and Availability

In 625 is an excellent filler metal for waterwall overlay; its main drawback is cost (instances of circumferential cracking have also been reported).REF When purchasing large quantities, a utility can obtain In 625 for about $13.00 per lb ($5.90 per kg). Type 312 SS costs roughly one-half that amount or about $6.50/lb ($2.95/kg). In 2000, the cost of In 625 rose to about three times that of Type 312 SS due to the increase in nickel costs. Installed costs have to take into consideration obtainable application speeds, shielding gas cost differences, and filler metal costs. Estimates suggest that an overlay job of 5000 sq. ft. (464.5 sq. m) using Type 312 SS instead of In 625 could save a utility about $250,000.

Before the boiler waterwall overlay industry considers an alternative alloy, it must be shown that the alloy is readily available. Large quantities of filler metal are required to overlay a boiler waterwall. Only three vendors were found that currently supply Type 312 SS in a GMAW product form (see Table 3-1). Two other vendors showed interest in producing this material if a market was developed; one of which plans to have a readily available product by early in 2000. Two vendors listed Type 312 SS in their catalogs, but no wire was available.

Table 3-1
Filler Metal Evaluated During This Project

Manufacturer	Product Name	SFA Number	ASME Specification	Product Form
ESAB	Shield Bright 312	5.22-95	E312-T1/T4	FCAW
ESAB	NA*	NA	NA	Metal Core
Midalloy	ER-312	5.9	ER312	GMAW
Kobelco	ER312T0-1	5.22	ER312T0-1	FCAW
Techalloy	Mig 312	5.9	ER312	GMAW
Euroweld	ER312	5.9	ER312	GMAW

* NA = not available.

3.4 Weldability

In-situ welding of boiler waterwalls can be difficult. Filler metals for this application must have good weldability. Welding with a filler that is sluggish and does not “wet out" well leads to porosity and incomplete fusion. Additionally, any area that is not sealed with weld metal is a possible area for localized tube attack.

An attempt was made to evaluate all Type 312 SS filler metals currently commercially available. Solid GMAW wire was acquired from Midalloy and Techalloy. Two FCAW filler metals were obtained, one from Kobelco and one from ESAB. ESAB also supplied a metal core filler wire. A third GMAW filler wire was received from Euroweld late in the program.

Weldability tests were performed on the GMAW and FCAW fillers. The tests were performed on 6” x 1/4” x 12” (15.2 cm x 0.6 cm x 30.5 cm) carbon steel plates in the vertical position. Plates were fastened to a large copper block that was water-cooled. This was performed to simulate water backing in the field. It is believed that water backing must be used in the field to achieve the deposition rates required to make this repair method feasible and to minimize the possibility of weld burn-through.

The GMAW testing used downhill progression, and the FCAW welding was performed uphill. The Midalloy GMAW, Euroweld GMAW, and the ESAB FCAW wires demonstrated the best weldability properties. Three-eighths-inch- (0.95-cm-) thick side bend tests were prepared for each filler and tested according to ASME Section IX. All three of these fillers passed bend tests.

The ESAB metal core wire appeared sluggish when welded. Lack of fusion problems were also encountered at the toe of the weld beads performed with the cored wire. This wire was a special mix that had the chemical composition to give a very high delta ferrite content for other planned testing. The manufacturer indicated that weldability could be easily improved by changing elements in the wire core. Specific welding properties could be developed as required.

Cleanliness of the installed water wall tubing plays a large part in the weldability of the different filler materials. The best surface is a near white blasted surface. There are two schools of thought about who should perform the waterwall preparation for welding. One is to have plant personnel or an outside contractor other than the welding contractor perform the blasting. The other is to have the welding contractor do the blasting. The advantage of the first method is the potential cost savings by using less skilled workers than certified welders to perform the blasting. The disadvantage is that the job might be not be done to the satisfaction of the welding contractor and require extra time to redo areas. This is a balance that must be addressed by the utility on a case-by-case basis.

3.5 Weld Dilution Testing

Dilution samples were prepared by applying single welding passes on a carbon steel test block. The samples were sectioned, mounted, polished, and evaluated metallurgically. Results for the various fillers can be found in Table 3-2. Pictures of the dilution test samples are shown in Figures 3-5 and 3-6. Dilution was measured on a percentage basis using the areas in Figure 3-7 and the formula:

Dilution = Area B/(Area A+Area B).

Weld dilution is important in waterwall applications for two reasons. The first is when thin tubes are being welded, welds with less dilution are less likely to burn through and cause leaks. The second reason to minimize dilution is that changes in dilution cause changes in the chemistry of the deposited weld metal, delta ferrite, and, as will be shown later, thermal expansion.

Table 3-2
Dilution Measurements

Filler Metal	Dilution
ESAB Metal Core	28%
Midalloy	24%
ESAB Flux Core	44%

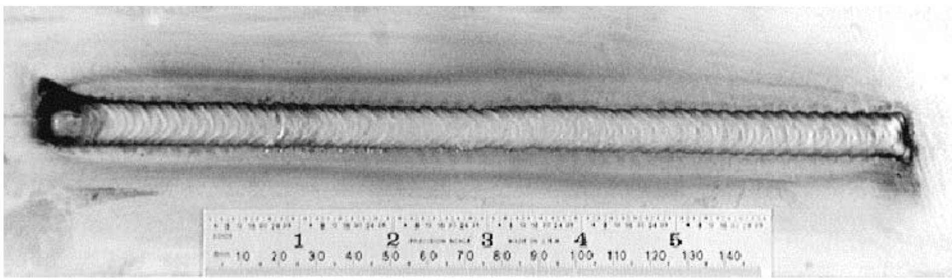

Figure 3-5
Dilution Measurement Coupon After Welding

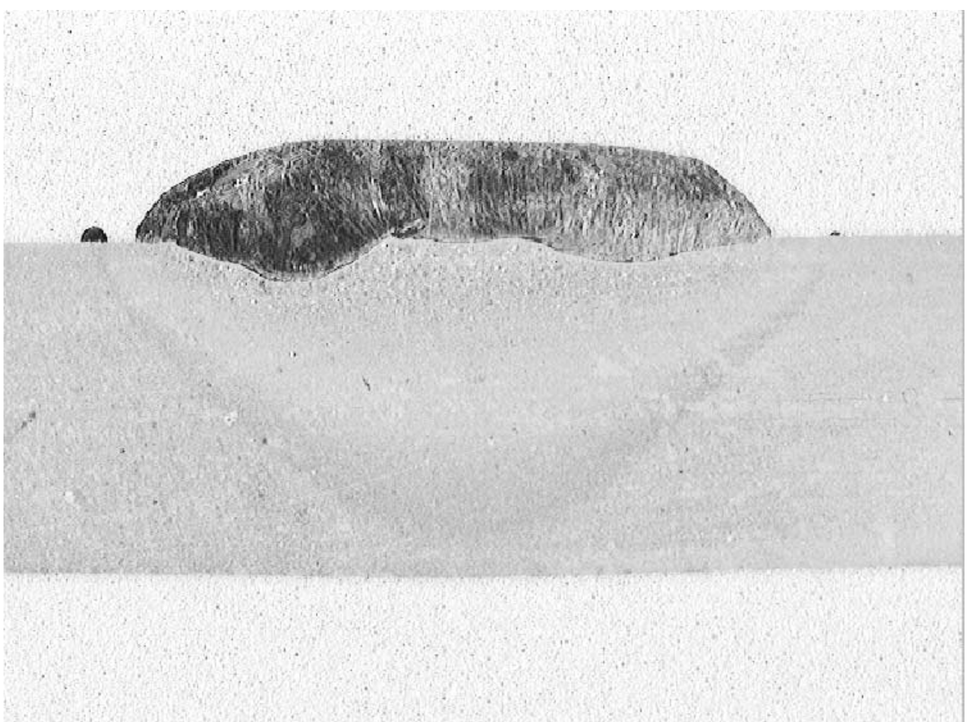

Figure 3-6
Dilution Measurement Coupons After Mounting and Polishing

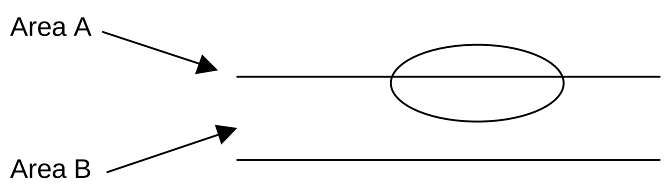

Figure 3-7
Weld Dilution Measurement

3.6 Filler Metal and Deposit Chemistry

Chemical analysis was received from the manufacturer for each alloy tested. The alloys are displayed in Table 3-3.

Table 3-3
Chemical Analysis for Filler Metal – As Received

Chemical Properties – As Received						
Element	**Midalloy**	**ESAB Metal Core**	**Euroweld**	**ESAB Shield Bright**	**Kobelco**	**Techalloy**
Carbon	0.1	0.084	0.1	0.101	0.11	0.11
Manganese	1.83	1.8	1.7	1.29	1.23	1.67
Sulfur	0.001	0.007	0.001	0.004	0.008	0.001
Phosphorus	0.017	0.015	0.009	0.019	0.024	0.02
Silicon	0.48	0.69	0.36	0.76	0.56	0.38
Nickel	9.27	8.7	8.6	9.57	9.95	8.71
Chromium	30.53	31.6	30.83	28.47	28.65	30.74
Molybdenum	0.09	0.05	0.04	0.06	0.02	0.08
Nitrogen	0.072	0.064	0.041	0.066	0.015	
Aluminum	0.003			<.01		
Cobalt	0.1			0.12		
Tin	0.005					
Columbium	0.005	0.01		0.03		
Copper	0.07	0.08	0.04	0.12	0.09	0.04
Iron	Balance	Balance	Balance	Balance		
Measured Fn		79		50.6	56	

Weld coupons were prepared and sent to Metallurgical Technologies, Inc., for chemical analysis in the as-deposited condition to determine what effect dilution would have on chromium content and to provide data for delta ferrite calculations. Testing was performed on the surface of the welds after slight polishing. The weld surface represents the interface of the weld filler metal to the products of combustion. This is where chromium content of the as deposited filler material is important. The results of this testing are shown in Table 3-4.

Table 3-4
Deposited Chemical Analyses

Deposited Chemical Analysis			
Element	**Midalloy**	**ESAB Metal Core**	**ESAB Shield Bright**
Carbon	0.12	0.11	0.11
Manganese	1.69	1.67	1.31
Sulfur	0.002	0.006	0.005
Phosphorus	0.021	0.017	0.021
Silicon	0.39	0.63	0.54
Nickel	7.11	7.49	6.17
Chromium	25.08	26.54	19.34
Molybdenum	0.07	0.05	0.02
Copper	0.07	0.13	0.06
Iron	Balance	Balance	Balance

3.7 Delta Ferrite Measurements

Type 312 SS (SFA 5.9, ER 312) is a duplex stainless steel, which means that the microstructure is comprised of both austenite and delta ferrite. Duplex stainless steels offer several advantages over common austenitic stainless steels. They are highly resistant to chloride stress corrosion cracking and have excellent pitting and crevice corrosion resistance. The austenite in the duplex alloy has a face-centered cubic microstructure, whereas the ferritic phase stainless steel has a body-centered cubic microstructure. Body-centered cubic microstructures have lower coefficients of thermal expansion than face-centered cubic microstructures. This means, in general, the more delta ferrite a stainless steel has, the lower its thermal expansion.

The delta ferrite content in a base metal or weld filler metal is controlled primarily by chemical composition. Increases in chrome, molybdenum, silicon, or columbium increase delta ferrite while increases in nickel, carbon, or manganese lower delta ferrite content. One objective of this project was to determine the delta ferrite level that would provide the best thermal expansion match to the base metal properties.

Delta ferrite in a weld is measured either magnetically or metallurgically. The most accepted pieces of magnetic equipment are the Fischer Feritscope and the Magna Gage. Both methods were utilized by the FRAC to determine the ferrite level on deposited test panels.

Several problems were encountered during testing. The Feritscope owned by the FRAC could read only up to 30% delta ferrite. These are currently under investigation by the FRAC. The Magna Gage is more of a thickness reading instrument that is calibrated to measure delta ferrite. It involves measuring the amount of force required to remove a magnet from the surface of the sample being tested. This instrument requires a large test block prepared in a controlled manner. The 0.070” (1.8 mm) thick overlay on the test panels is not representative of a true reading because of the magnetic steel alloy base metal. Measuring the as-deposited delta ferrite of overlays on comparable base metal thickness to that would be encountered during a repair was desired. This is because the heat sink of a thick substrate would minimize the effect of dilution on a large test block.

Metallurgical counting was performed on several samples. Many different etchants were tested to help bring out the ferrite and allow for automatic counting by a computer. Some of the etchants used include 1.2.3, Vilella’s, Modified Murakami’s, modified Groesbeck’s, and NaOH electrolytic + H_2O. Of the etchants tested, the modified Groesbeck’s was found to provide the largest contrast. Different areas of the same weld showed relatively large differences in ferrite.

Delta ferrite measurements are not very accurate. A Welding Research Council (WRC) Bulletin (Bulletin 132, “The Measurement of Delta Ferrite in Austenitic Stainless Steels”) states that at 10–24% delta ferrite, an error band of ±6% ferrite may exist. This means that for a delta ferrite measurement of 24%, the actual delta ferrite percentage could be from 18–30%. At the high levels of delta ferrite measured during this project, the error could be even worse.

There are also several formulas that can be used to estimate the delta ferrite in either the filler metal or the as-deposited weld metal from chemical analysis. The use of formulas is the method employed during this project because of its the ease of use and because our primary concern was not the delta ferrite percent but the thermal expansion associated with a delta ferrite level,. The methods utilized include a Schaeffler Diagram (Figure 3-8) and an improved chart from ASME Section III, Division 1, Part NB, “weld metal delta ferrite content,” referred to as the improved WRC diagram (Figure 3-9). Estimated delta ferrite level was calculated for the filler wires based on as-received chemical analysis and in the as-welded condition from chemical analysis performed on the welding beads. Both methods above were used, and findings can be seen in Tables 3-5 through 3-7.

A new model of the Feritscope was located that had the ability to read ferrite content up to 100%. This equipment was evaluated for ease of use and repeatability. The FRAC subsequently purchased this Feritscope and utilized this equipment for all ferrite measurements in the shop and in the field.

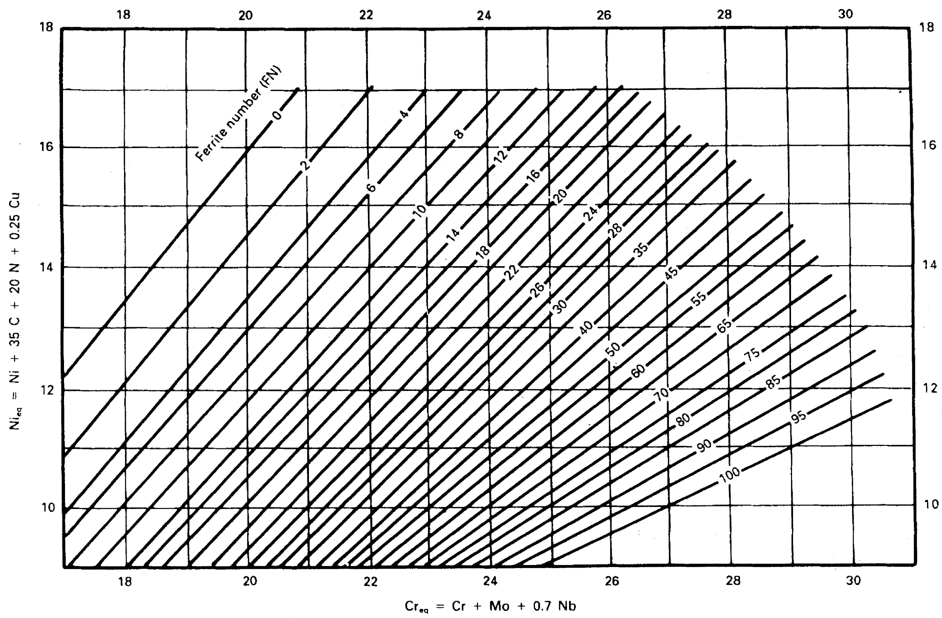

Figure 3-8
WRC Weld Metal Delta Ferrite

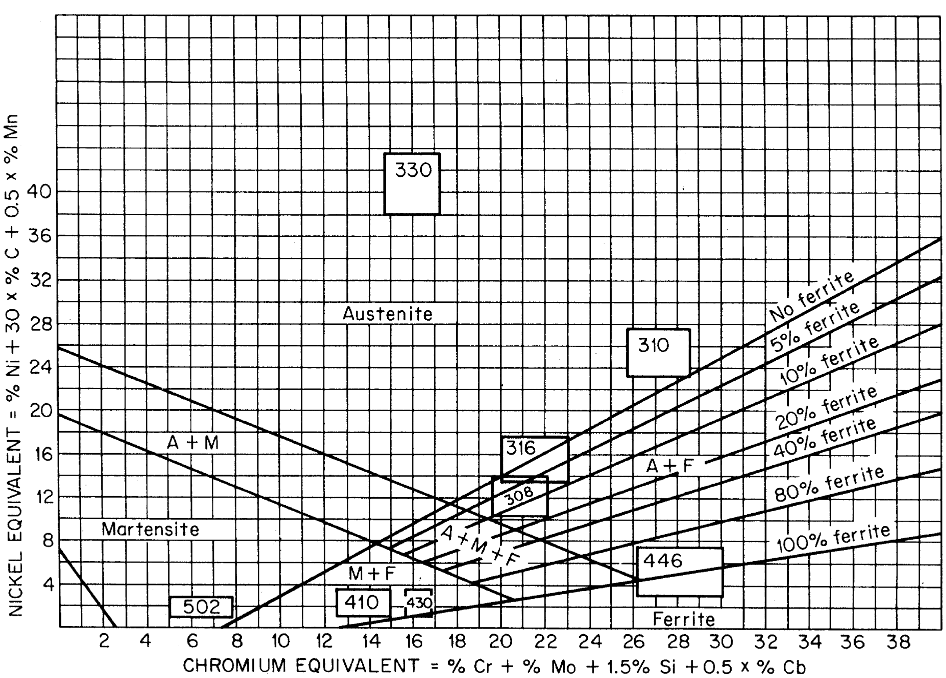

Figure 3-9
Schaeffler Weld Metal Delta Ferrite

Table 3-5
Comparison of Delta Ferrite Calculation Methods – As-Received Filler Metal

Filler Metal	Wire Ferrite Content	
	WRC Method	Schaeffler Diagram
	Fn	% Ferrite
ESAB Flux Core	51	41
Midalloy GMAW	72	50
ESAB Metal Core	79	70

Table 3-6
Comparison of Delta Ferrite Calculation Methods – As-Deposited Metal

Filler Metal	As-Deposited Ferrite Content	
	WRC Method	Schaeffler Diagram
	Fn	% Ferrite
ESAB Flux Core	15	12
Midalloy GMAW	60	38
ESAB Metal Core	75	50

Table 3-7
Comparison of Delta Ferrite Measurement Methods – Metallurgical Counting

Filler Metal	Metallurgical Counting
	As Deposited
	% Ferrite
ESAB Flux Core	NA*
Midalloy GMAW	34
ESAB Metal Core	55

* = Not Available

3.8 Actual Thermal Expansion Testing

Since there was no complete thermal expansion data for Type 312 SS in the ASME Code, samples were prepared for testing. The effect of ferrite on thermal expansion also needed to be investigated. All weld metal samples were prepared using the ESAB flux core, Midalloy, and ESAB metal core filler wires. These fillers were selected because of the different levels of delta ferrite they developed in the as deposited condition. The samples were sent to Materials Innovations, Inc., for testing. The samples were 1" (25.4 mm) long by 3/8" (9.5 mm) diameter. The results of this testing are plotted in Figure 3-10. **As can be seen from this figure, delta ferrite had a large influence on thermal expansion properties.** The Midalloy filler metal was found to have thermal expansion properties that closely match the carbon steel or T-22 base materials and was selected for further testing.

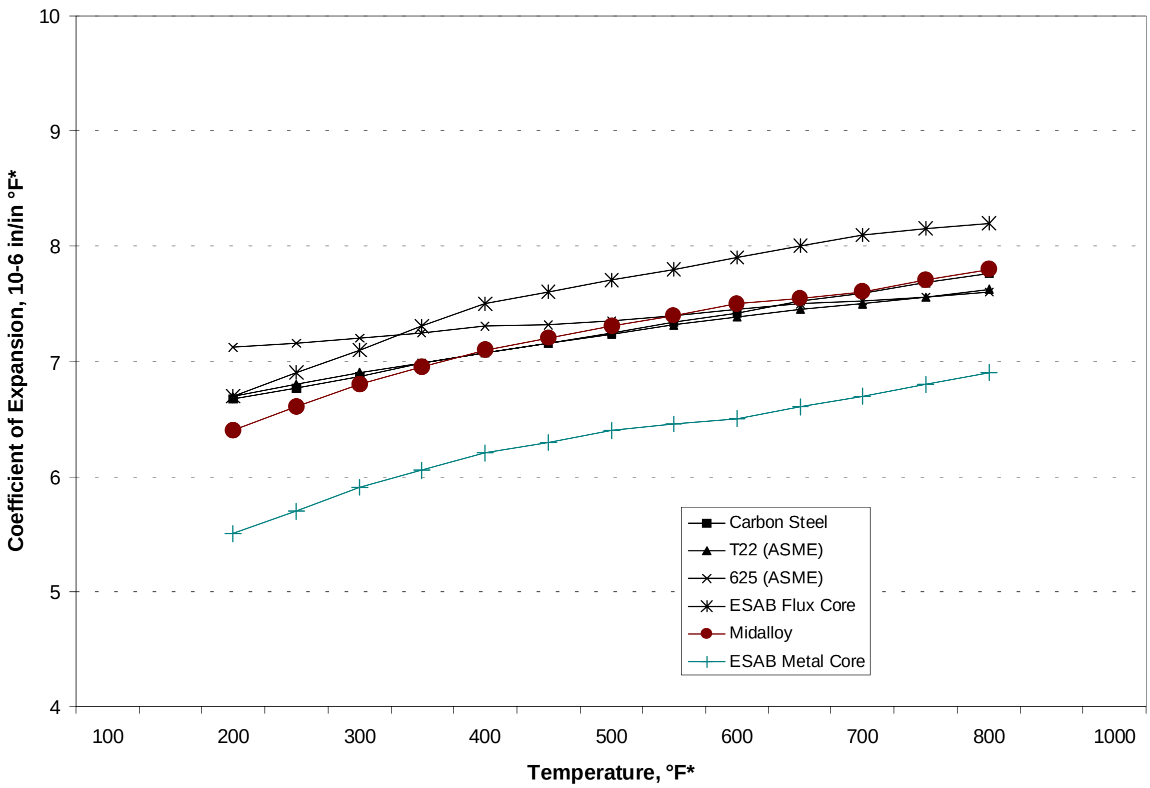

Figure 3-10
Thermal Expansion of Type 312 SS Filler Metals and Base Metals
** Conversion Factors — To convert inches to centimeters, multiply by 2.54. To convert Fahrenheit temperature to Celsius, subtract 32 and divide by 1.8.*

3.9 Effect of Heat Input on Thermal Expansion

The cooling and solidification rate was believed to have an effect on the amount of delta ferrite formed and, therefore, an effect on thermal expansion of the weld metal. Test blocks were prepared for thermal expansion testing using the Midalloy wire. High, medium, and low heat input samples were prepared. All welding was performed in the flat horizontal position because of difficulty making welds in the vertical position at high heat inputs. Water backing was used to simulate cooling rates that would be experienced in the field. Again, samples were machined and sent to Material Innovations, Inc., for testing. An actual sample of T-22 base material was also tested to verify properties on the ASME Section II-D.

The results are shown in Figure 3-11. Very little effect on thermal expansion rate was measured between the three samples. It is believed that the machine settings required to achieve sound welds limit the heat input to a range that has little effect on delta ferrite formation.

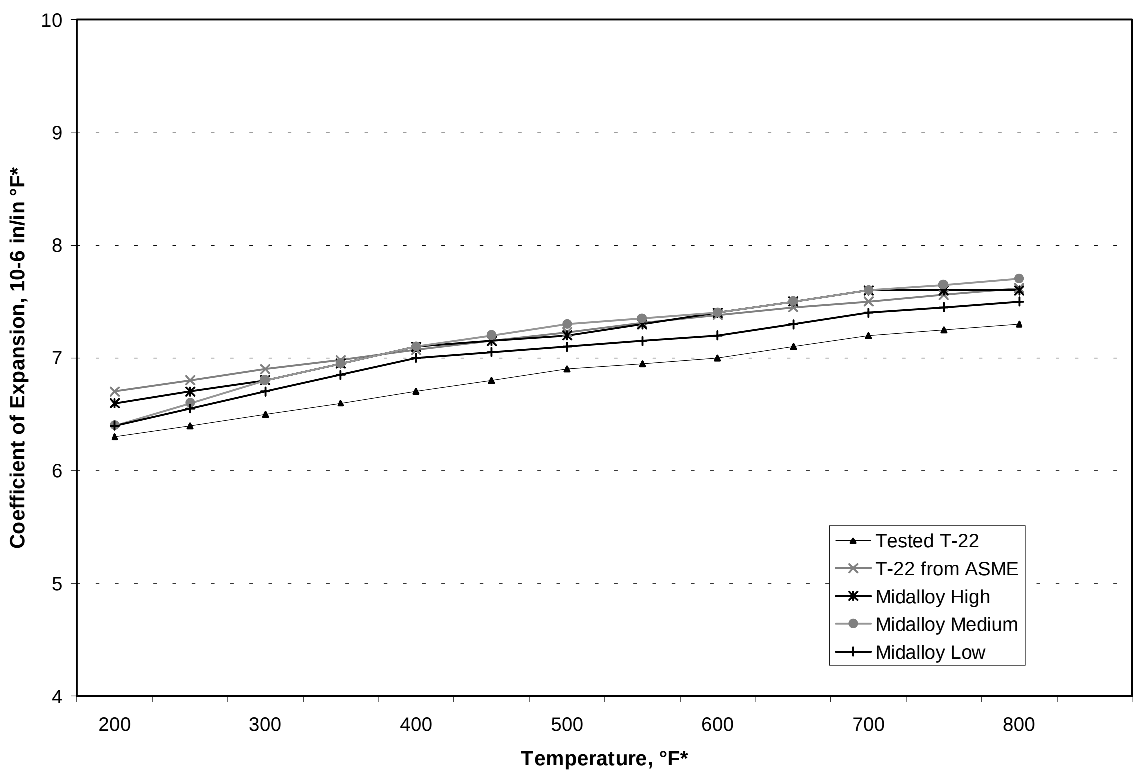

Figure 3-11
Heat Input Effect on Thermal Expansion, Type 312 SS
** Conversion Factors — To convert inches to centimeters, multiply by 2.54. To convert Fahrenheit temperature to Celsius, subtract 32 and divide by 1.8.*

3.10 Shielding Gases

Four commercially available shielding gases were utilized during the welding tests. The gases used were a straight 100% argon, a two-gas mix of argon (75%) and helium (25%), a two-gas mix of argon (99%) and oxygen (01%), and a three-gas mix of argon (66.1%), helium (33%), and carbon dioxide (.9%).

The gas found to be the best suited for the Type 312 was the two-gas mix of argon (99%) and oxygen (01%). The three-gas mix of argon, helium, and carbon dioxide and the 75/25 argon/helium mix welded satisfactorily. The straight argon was the worst.

When welding with Inconel 625, we found that the 75/25 or the 99/01 gas was the best, straight argon was second, and the three-gas mix was the worst.

The three-gas mix was consistently the hottest gas in all trials. When using the 75/25 mix, amperage could be turned up without weld metal being too fluid. Dilution was lower than the three-gas mix and weld beads were consistently wider, allowing higher deposition rates. A two-gas mix of argon (98%) and oxygen (02%) was received just before this report was printed. Initial testing indicated that this may be a better gas than any of the others. Future testing will be performed on this gas.

3.11 Power Supplies

Testing on the flat plates and waterwall panels was initially performed with power supplies that closely matched equipment available in the field. This testing was performed with a Miller Invision 456P DC Inverter Arc Welder operating in pulsed mode. These types of power supplies cannot change voltage to accommodate stick-out changes while welding surfaces with elevation changes. Measured stick-out changes of up to 0.300" (7.6 mm) can occur when welding on the waterwall panels. Past research has shown as much as a 20 amp current change can occur for every 0.100" (2.5 mm) of stick-out change. Voltage is also affected by changes in stick-out with about a 2 volt swing for every 0.100" stick-out change. The voltage and amperage change caused problems when welding on the sides of the tubes including long dwell times to fill at the membrane edge, holes, and very fluid weld metal.

Other power supplies including the Diahen 350 EX Fuzzy Auto, Panasonic Pana Star AE350, and Lincoln 455 STT are also being evaluated.

4
MINIMIZING DISTORTION

Another major task of this project was to investigate methods to minimize distortion during the welding process. Heat input from the welding process and shrinkage of the cooling weld metal on only one side of the boiler tubing, the furnace side, can result in large stresses in the tubing. These stresses are best demonstrated by distortion of the waterwall panels. While distorted panels do not look very good, they appear to have little effect on operation; but the residual stresses that cause the distortion can shorten boiler tubing life, resulting in leaks and forced outages. This section includes overlay demonstrations by welding vendors, bead sequencing, heat input, and filler metal effects.

4.1 Mockup

A mockup of a small waterwall panel was constructed to allow welding trials to be performed in the FRAC facility. Panels were manufactured from SA-213 T-22 tubing that was 1 ¼" OD (31.8 mm) X ¼" wall (6.4 mm). The tubes were on 1 ¾"(44.5 mm) centers with a membrane between. The panels were 20 tubes wide and measured approximately 34" (0.86 m) wide by 65" (1.7 m) tall. A fixture was built to hold the panels in the vertical position, and headers were added to the top and bottom to allow water to be circulated through the panels to simulate water backing. A sample mockup panel can be seen in the fixture in Figures 4-1 and 4-2.

During the welding trials, dynamic distortion measurements were taken using a Measurements Group, Inc., System 5000 stress analysis system coupled to linear variable displacement transducers (LVDT’s).

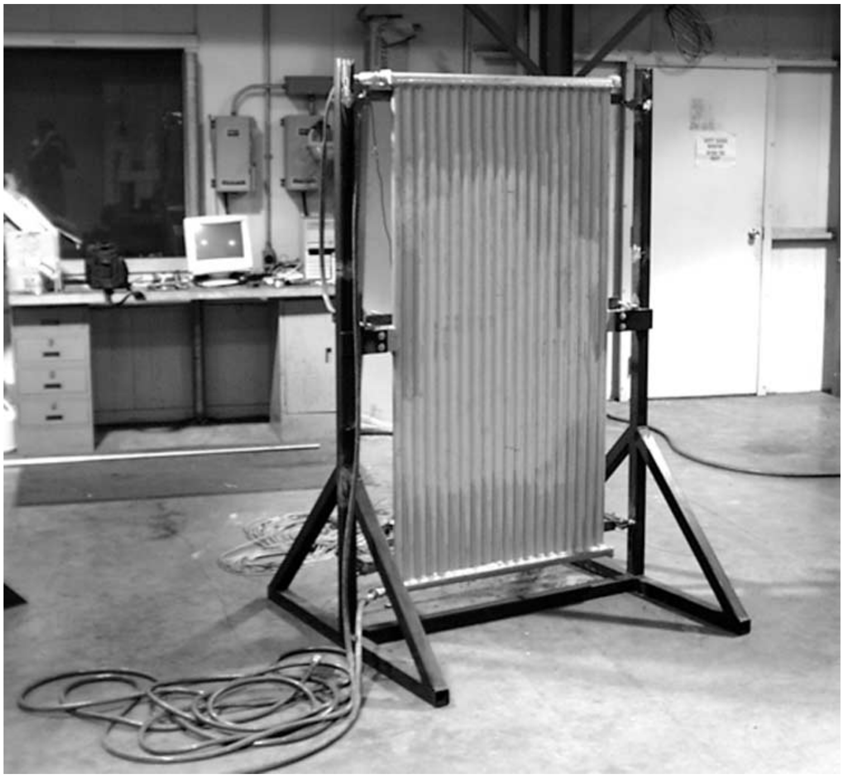

Figure 4-1
Waterwall Panel Mockup – Front View

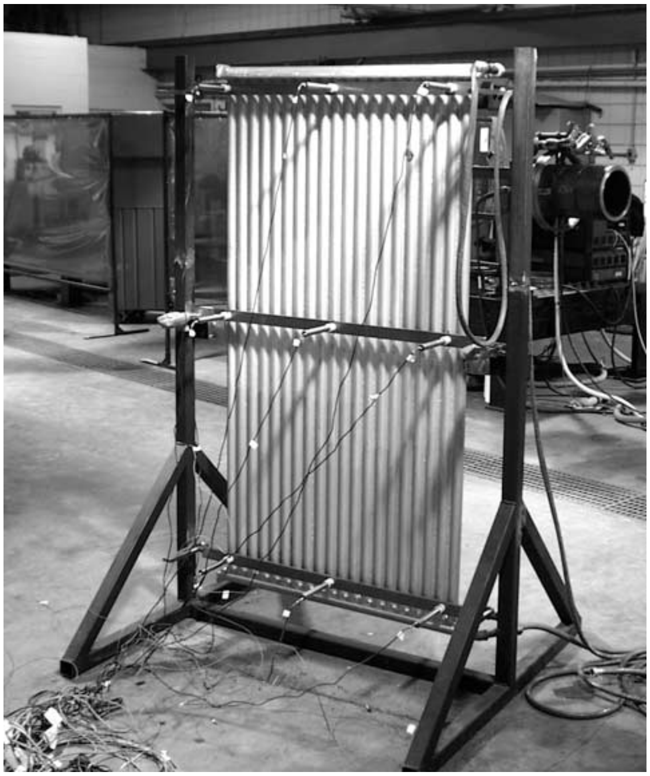

Figure 4-2
Waterwall Panel Mockup - Back View

4.2 Demonstrations by Repair Vendors

Welding demonstrations were performed by PCI Energy, Inc., and GE Welding Services, Inc., to show what types of distortion could be expected while welding on unrestrained waterwall panels. The welding was performed using downhill progression in the vertical position. The filler metal used for both demonstrations was Inconel 625. Both vendors were asked to use welding parameters that would normally be used in the field. Two additional vendors are being considered for the 2000 program.

The original intent of this project was to demonstrate the distortions associated with current application techniques and to attempt to improve them through the use of alternate bead sequencing and heat input. It was quickly learned that very stringent requirements must be placed on the testing to have results that are comparable. Deposit thickness must be measured, and the amount of time needed to deposit a given area of overlay on the waterwall must be specified and monitored closely. This is an area that utilities should watch when quoting overlay work.

There is a tradeoff between welding speed and distortion. A welding contractor can slow down the welding process and decrease the distortion. There should be a balance between production and distortion. One typical distortion achieved by these tests can be seen in Figures 4-3 and 4-4. The jump in the graph in Figure 4-4 at the 160-minute range was caused by running out of travel on the LVDT's, which necessitated repositioning of the instrumentation before additional welding.

All welds were performed with water backing. Welds performed without water backing to investigate the effect of lack of cooling on distortion or production speed are planned later.

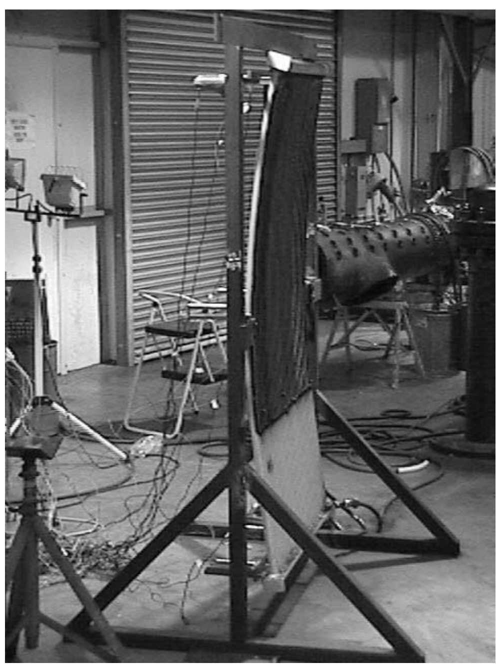

Figure 4-3
View of Panel as Welded

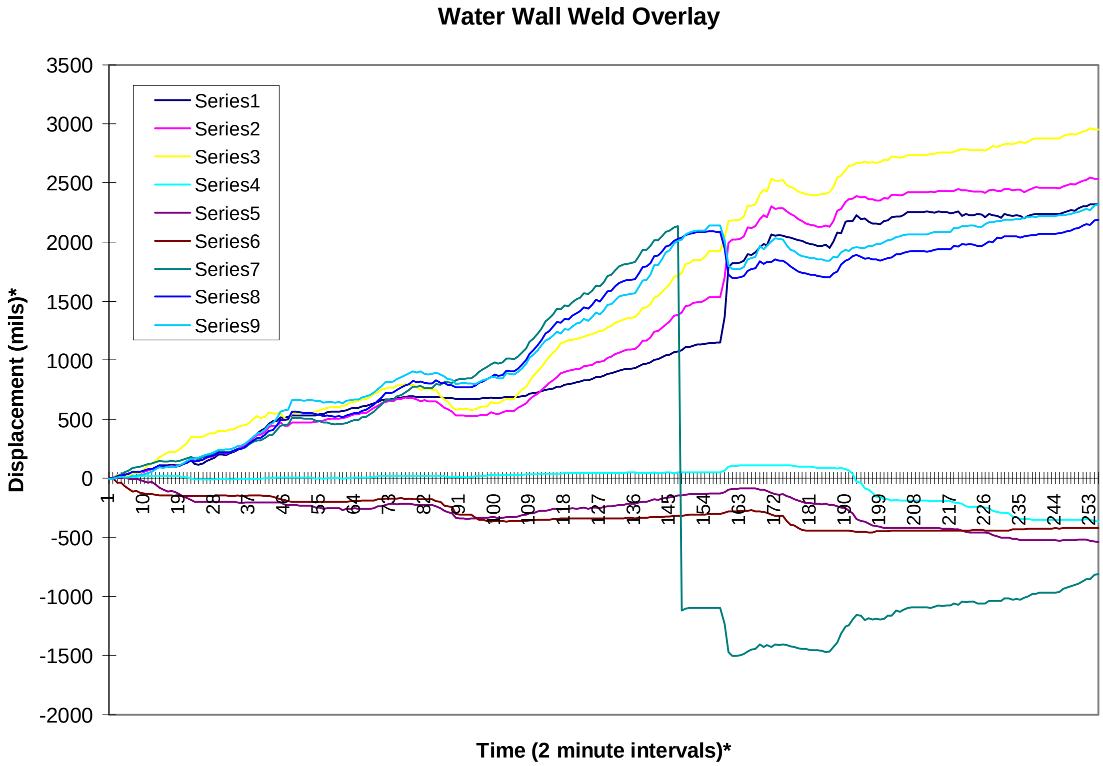

Figure 4-4
Typical Waterwall Distortion
** Conversion Factor — To convert mils to millimeters, multiply by 0.0254.*

4.3 Bead Sequencing

Some of the main objectives when performing weld overlays on waterwall panels are to deposit the weld metal as uniformly as possible and to provide good fusion to the base metal. Experimentation was performed using different bead placement sequences to determine which bead sequence would produce the most uniform weld and fusion characteristics.

It was learned that the best results were achieved when the membrane areas of the panel were covered with weld metal first, as opposed to the tube. Some of the bead placement sequences that were experimented with are shown in Figure 4-5. Of these different scenarios, sequences B and C, which placed the first weld bead in the center of the membrane web, provided the best overall welding characteristics.

If the corners were welded first, as is shown in sequence A, lack of fusion was noted in the corners of the third bead. The stick-out changes of the filler metal during the welding process were also minimized by this bead placement, allowing better voltage and amperage control. It should also be noted that these are weld bead sequences for one pair of tubes. During the actual weld overlay operation, the welding head should be moved around on the waterwall to keep from curving the panels sideways.

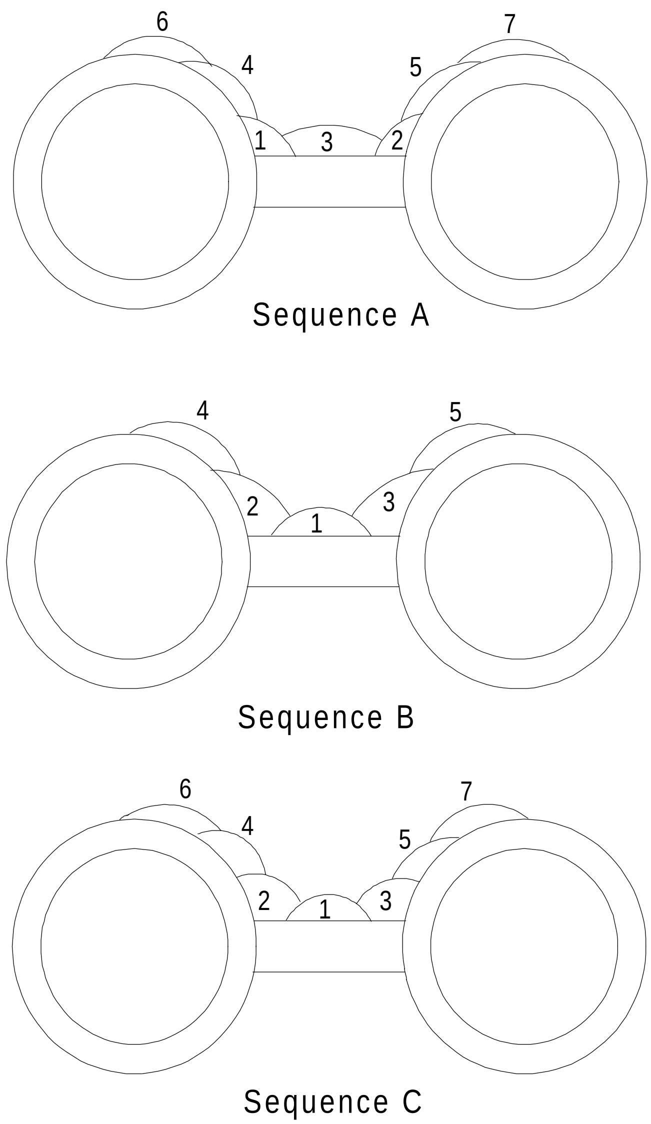

Figure 4-5
Weld Bead Placement Scenarios

4.4 Effects of Welding Heat Input

To evaluate the effects of heat input on distortion, one of the waterwall test panels was split to three tube panels using a plasma cutter. Different groups of three tubes were overlaid with In 625 and the Midalloy Type 312 SS at both high and medium heat input.

The distortion was measured dynamically as above and on the macro level by cutting the panel apart and measuring the remaining distortion of each of the three tube panels. Table 4-1 shows that there was not much difference between the high and low heat input distortion with the Type 312 SS, but both had less distortion than the In 625.

Table 4-1
Distortion Measurements of Wall Panel Tests

	Tube 1	Tube 2	Tube 3
Medium Midalloy	0.6525	0.7125	0.7425
High Midalloy	0.7425	0.755	0.735
In 625	0.905	0.915	0.915

5 FIELD TRIALS

For an overlay to be of great value to utilities, it must demonstrate good service in a utility boiler. To examine if the Type 312 SS would provide good service, a utility was sought to install a trial overlay. American Electric Power Corporation (AEP) volunteered to apply this filler metal in one of their boilers. In the Fall of 1999, approximately 1200 square feet of waterwall was overlayed in AEP Big Sandy Unit Two boiler using Type 312 SS filler.

Big Sandy Unit 2 is a supercritical unit rated at 800,000 KW. It was built in 1969 and operates at a design pressure of 3334 psi. at 1000 °F. The waterwalls operate around 800 °F. This unit had low NOx burners installed in 1994. NDE inspections indicated that waterwall thickness were as low as 0.080”. All of the wastage was assumed to have occurred since the installation of the low NOx burners. The original thickness of the tubing was specified at 0.250.” Nominal wall thickness was 0.270.” This indicates an average wall loss of about 0.040” each year.

The original membrane tube panels were manufactured from SA213-T2 material. AEP had several replacement panels in stock and replaced the worst panels prior to applying the overlay. Additional tubing was built up to minimum wall with ER80S-B2 prior to applying the Type 312 SS overlay. One area where a replacement panel was not available was judged too thin to buildup utilizing weld overlay and was scheduled to be replaced at a later outage.

The unit was returned to service and subsequently removed from service after five months to replace the thin tube panel that was left in service and perform inspection of the overlay. In general the overlay looked very good. Scaffolding was erected in the boiler and one foot bands were blasted at each scaffold elevation to allow for ultrasonic thickness measurements. Virtually no wastage was noted. Visual inspection of the original weld ripples indicated no wall loss. A typical section of the waterwall overlay can be seen in Figure 5-1. The weld ripples can be seen clearly in the blasted areas.

Figure 5-1
View of overlay after 5 months of service

Delta ferrite measurements were performed on the overlayed waterwall panels. Most readings indicated ferrite content in the upper twenty percent range. One area of the overlay contained some crack indications. About four transverse cracks were noted. All of the cracks were contained in a four square foot section adjacent to the thin panel that was scheduled for replaced during this outage. The panel with the crack indications was also replaced with a new panel. This panel was located in the center of the waterwall panel. This is the area where the most severe wastage was measured prior to the original overlay. After installation in the boiler waterwall, the new panels were overlayed with Type 312 SS.

Water backing was utilized during most of the overlay welding. During the time new panels were being installed, some tubing was welded without water in the tubing. While most of the overlay indicated delta ferrite content of about 30 percent, the overlay around the crack indications measured less than three percent. It was unclear from reviewing the records if this area was welded without water backing. The absence of water backing would change the cooling rate of the weld and result in different delta ferrite formation. All of the crack indications were in areas where the waterwalls had been built up with ER80S-B2.

The overlayed panel containing the cracks was shipped to the EPRI Charlotte Facility for metallurgical evaluation. While the depressed delta ferrite content is thought to have been a contributing factor in the cracks, all of the cracks contained underbead deposits. Most were at the start or stop of an ER80S-B2 welding bead. No cleaning was performed between the weld buildup with the ER80S-B2 filler and application of the Type 312 SS filler. The underbead deposit could possibly have been caused from deposits on the tubing that were not originally blasted off before repair welding with ER80S-B2 was performed that floated to the surface of the repair weld. When the Type 312 SS overlay was applied, the deposit acted to cause the cracking. No analysis was performed of the deposit chemistry. A typical crack and underbead deposit can be seen in Figure 5-2.

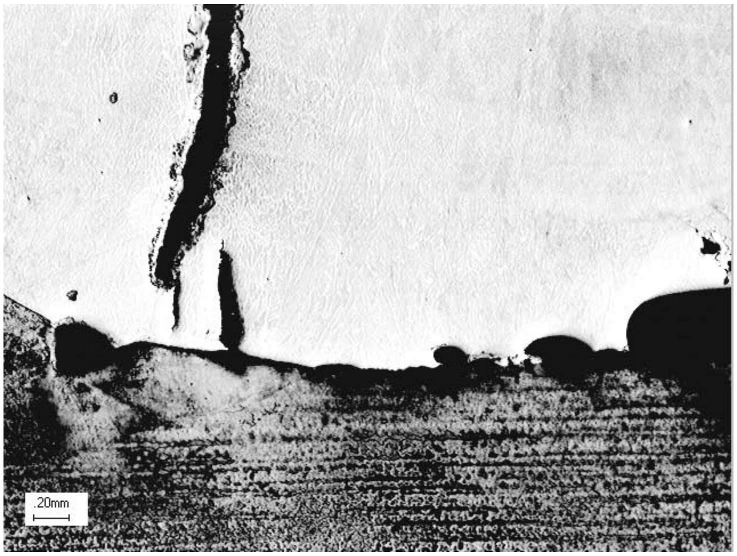

Figure 5-2
Photomicrograph of crack indication showing underbead deposits

Additionally, some areas of tubing were found to have not been completely covered with Type 312 SS weld metal. This can be seen in Figure 5-3. Care must be performed during the welding and inspection stage of waterwall overlays. Any area that is not completely covered will result in a tube failure in a short duration.

Figure 5-3
Cross section of overlayed tubing with incomplete coverage

6
EFFECT OF 885°F (475°C) EMBRITTLEMENT

Stainless steels with chromium (Cr) content over 15% can be subject to a phenomenon called 885°F (475°C) embrittlement. This embrittlement forms most quickly at 885°F, but it can start forming as low as 600°F (316°C). The cause of 885°F embrittlement is the decomposition of the ferrite (α) into chromium-rich body-centered cubic ferrite (α′). These Cr-rich precipitates then begin to segregate at the grain boundaries. The mechanism of 885°F embrittlement varies within a certain temperature range given the chemical composition. This form of embrittlement results in lower tensile strengths, lower ductility, and higher harnesses at room temperature; however, it retains its desirable mechanical properties at operating temperatures (500°F [260°C] and higher). Materials that have experienced 885°F embrittlement can have toughness restored by heating to 1020°F (549°C).

Embrittlement which occurs at higher temperatures (1000–1600°F or 538–871°C) is due to the precipitation of the sigma (σ) phase. The presence of Si and cold working can promote this high temperature embrittlement. This phase is difficult to form when there is less than 20% Cr.

The composition of the duplex stainless steel has an effect on the susceptibility to 885°F embrittlement. Nickel (Ni) can improve low temperature toughness; however, it also accelerates the formation of Cr-rich BCC precipitates (α′) in the ferrite. Many other constituents besides interstitials influence embrittlement at 885°F. Mo, Si, Ti, Nb, Al, and Cu all promote embrittlement as well as slow cooling after annealing and the presence of more than 30% ferrite. The embrittlement can be restricted by the presence of un-embrittled austenite (γ). The tendency to embrittle increases with increasing Cr content (ferrite-forming) and increasing time in the susceptible temperature range. Cr, Mo, Si promote the formation of ferrite; C, Ni, Mn promote the formation of austenite.

The following characteristics are associated with 885°F embrittlement:

- Lowering of impact and bend ductility (at room temperature); decrease in toughness
- Changes in electrical resistivity, specific gravity, and magnetic coercive forces
- Decreased resistance to acid attack
- Increased grain-boundary attack
- Darkening of ferrite
- Increase in fracture appearance transition temperature (FATT)
- Decrease in upper-shelf Charpy energy

To better understand the effect of 885°F embrittlement on Type 312 SS the following questions were proposed:

- How do changes in ferrite effect 885°F embrittlement?
- Do welding procedures have any effect?

- Do any of the above characteristics result in operational problems for waterwall applications?
- How much do impact and hardness values change after time at temperature?
- Will thermal cycling of overlayed panels cause cracking?
- Will hydro testing of the boiler cause failure of the overlay?

Effect of embrittlement

Several tests were performed to investigate the effect of the embrittlement. The first was a thermal aging test to evaluate if the Type 312 SS filler metal was susceptible to embrittlement. Several coupons were prepared for this testing utilizing filler metals from different manufacturers and a variety of welding heat inputs. A total of three different filler metals were used of which one filler metal was welded with two different travel speeds (heat input). The coupons were sectioned in to ½” X 6” strips prior to aging to allow for side bend testing for evaluation of the degree of embrittlement. Coupons from each of the manufacturers and heat inputs were then aged at 885 °F for different times. A different coupon was used for each time at temperature. The times utilized were 25, 100, 250, and 1000 hours. The samples were prepared by heating an oven to 885 °F all of the samples were placed into the oven at the same time. When the specific time had occurred, one set of samples was removed. To evaluate the effect of the time at temperature, measurements were made of delta ferrite content and hardness then the samples were machined to 3/8” wide and subjected to an ASME side bend test.

All of the Type 312 SS fillers were effected by at 885 °F embrittlement. Noticeable hardness increases could be measured after as little as 25 hours at temperature. Maximum hardness was obtained in about 100 hours. This can be seen graphically in Table 6-1.

Table 6-1
Hardness and Delta Ferrite of aged samples

	0 hrs.	25 hrs.	100 hrs.	250 hrs.	1000 hrs.
312 SS Hardness	272	322	335	320	345
312 SS Delta Ferrite	47	38	37	34	32

The embrittlement is a direct result of carbide formation wherein the chromium and carbon combine to form chrome-carbides. This same amount of decrease was found regardless of the starting delta ferrite content. As can be seen by Table 6-2, the different starting levels of delta ferrite caused by different heat inputs and cooling rates each reduced by 14 percent after 1000 hours at 885 ^{o}F.

Table 6-2
Heat input effect on Delta ferrite and embrittlement

Heat Input	High	Low
Travel Speed	18 in/min	21 in/min
As Welded	47	43
25 hrs	38	36
100 hrs	38	35
250 hrs	34	32
1000 hrs	33	29

Although the data did not correlate quite as well the same general trend can be seen in Table 6-3 of the effect of the embrittlement on hardness starting from different delta ferrite content.

Table 6-3
Heat input effect on Hardness after thermal aging

Heat Input	High	Low
Travel Speed	18 in/min	21 in/min
As Welded	261 Hv	274 Hv
25 hrs	327 Hv	302 Hv
100 hrs	367 Hv	349 Hv
250 hrs	367 Hv	355 Hv
1000 hrs	369 Hv	322 Hv

The thermal aging had an effect on the delta ferrite level, hardness, and ductility. ASME side bend tests were performed on all of the test coupons above. All of the samples passed bend tests in the as welded condition and after 25 and 100 hours at 885 ^{o}F. Only the high heat input failed after 250 hours. All of the other coupons aged for 250 hours passed. All of the coupons failed after 1000 hours at 885 ^{o}F.

Thermal Cycling Testing

To determine if thermal cycles encountered when boilers are taken off line would be detrimental to the weld overlay, coupons were prepared and cycled between room temperature and 885 ^{o}F. The same coupon conditions as above were utilized for this test with three different filler metals and two different heat inputs. Additionally a sample was prepared using In 625 filler metal for the overlay. The coupons were approximately four inches square. After welding, the surface of the coupons was machined smooth to allow for easier detection of any damage with dye penetrant testing. All samples were checked for cracks prior to any heat aging. The samples were then aged at 885 ^{o}F for 1000 hours and then dye checked for cracks. After verification that none of the samples had any indications, the samples were cycled between room temperature and 885 ^{o}F. To make this test as severe as possible, the samples were placed in a preheat oven for one hour then removed and placed in front of a fan and rapidly cooled to room temperature. The samples were then placed in the oven again.

After every 25 cycles, the coupons were again dye penetrant tested to look for crack indications. The coupons were subjected to a total of 125 temperature cycles. No crack indications could be detected in any of the coupons. A few of the coupons did indicate minor warpage transverse to the direction of welding. No warpage was detected longitudinal to the welding direction. The coupon that exhibiting the most deflection was the coupon welded with In 625. The deflection is more than likely the result of the greater difference in thermal expansion between the In 625 and the base material than the Type 312 SS and the base metal.

Pressure tests

Fracture Appearance Transition Temperature (FATT) is defined as the temperature at which a material exhibits 50% brittle- 50% ductile failure characteristics. Above the FATT, all materials perform in a predominantly ductile manner- even materials which are considered embrittled. For this reason the concern about effect of the embrittlement during service is less than while the unit is off line and cool. The highest concern about the embrittlement issue would occur when the boiler is off line and hydrostatic testing is being performed to check for leaks.

To investigate this concern, tube samples were taken from the waterwall panel that was removed from the demonstration at Big Sandy Unit 2. Plugs were inserted and welded into the ends of the tubing, one of which was threaded for a pressure connection. The design operating pressure of this boiler is 3334 psi. The tube samples were pressurized to this pressure using room temperature water. Dye penetrant testing was then performed to determine if any crack indications were developed. Several tests were performed at about 1000 psi steps. The final test was performed at 20,000 psi. This pressure represents the maximum pressure that could be developed with the test equipment available. Even after testing at this pressure, no crack indications were found. This testing indicates that the embrittlement issue is not a concern for the serviceability of this overlay material.

7
REPAIR OF OVERLAYED PANELS

One area expressed by the FRAC membership as a concern was how to perform repairs to panels once they have a corrosion resistant overlay applied. During welding, mixing of the overlay material into the welding joint could develop properties in the weld metal that are undesirable. To evaluate this, several welding procedures were proposed. Analysis of these welding procedures was completed using ASME Section IX bend tests. Tube samples were removed from the waterwall panel from Big Sandy Unit 2 for use in the welding procedure qualification. This tubing had seen about five months of service and was assumed to be in an embrittled state. Verification of the state of embrittlement was performed by testing bend coupons removed from the tubing. All of the side bend specimens in the service removed condition failed bend testing.

Literature indicated that the effects of the embrittlement could be reversed by heating the embrittled weld metal to 1020^{o}F (549°C). Investigation of this ability to reverse the embrittlement was performed on 3/8" side bend coupons from the tubing. Coupons were heated to 1100 ^{o}F and 1200 ^{o}F for one hour. These coupons were then subjected to side bend testing. The coupons subjected to 1100 ^{o}F demonstrated improved ductility over the serviced aged samples but still failed. The 1200 ^{o}F samples passed bend tests. Sample bend test coupons can be seen in Figure 7-1. The top coupon was tempered at 1100 ^{o}F , the middle coupon was as removed from the boiler, and the bottom coupon was tempered at 1200 ^{o}F.

Figure 7-1
Weld overlay tests after tempering and bending

Weld Tests

Evaluation of preliminary repair welding procedures was completed on weld coupons prepared from the Big Sandy Unit 2 waterwall panel. These tubes were machined to a standard 37 1/2^{o} welding bevel. Coupons were also machined as above only the overlay was machined back approximately 3/8". This was performed to demonstrate a standard tube replacement then addition of a localized corrosion resistant overlay over the repair weld. Inco A, Inco 82, ER 80-S2, E8018-B2, and ER312 fillers were utilized. Figure 7-2 shows the joint geometries and fillers that might typically be utilized in the replacement of a damage tube section. The first weld joint in Figure 7-2 utilized a GTAW root with Inco 82 filler followed by an Inco A fill using the SMAW process. Side bends of this procedure failed in the root pass. Next a procedure was tried using the bottom weld joint in Figure 7-2. The weld joint passed bend tests in the weld region but failed about 3/16" out into the Type 312 SS overlay. As indicated earlier, some softening of the embrittlement was accomplished in the HAZ. This is indicated because the overlay did not crack adjacent to the replacement weld.

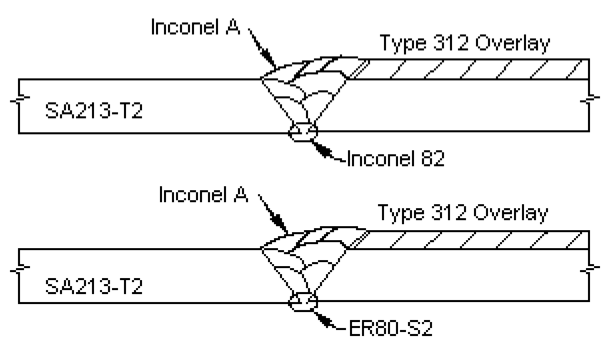

Figure 7-2
Typical joint geometries for tubing replacement

Figure 7-3 shows a typical overlay technique that could be applied to a field weld to protect the pressure retaining joint weld metal. In this demonstration, the damaged tube was replaced with a piece of tubing that had previously been overlayed with Type 312 SS to about ½" of the pressure retaining weld joint. The circumferential pressure retaining weld joint would be completed using typical welding procedures that require a GTAW root pass followed with SMAW fill passes utilizing filler metals that match the base metal chemistry. A Type 312 SS overlay would then be applied to protect the low alloy steel tubing and weld from the products of combustion.

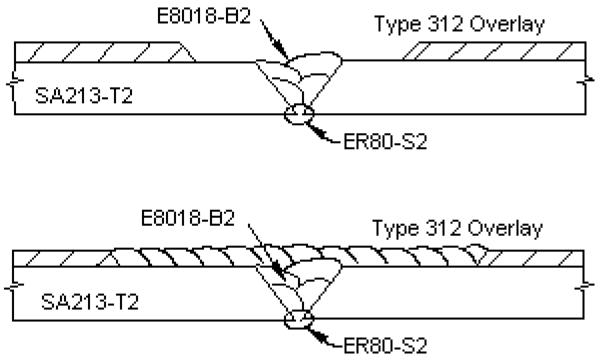

Figure 7-3
Possible procedure for repair welds using matching filler metal followed by corrosion resistant overlay

Additional testing of repair procedures will be performed under the 2001 scope of this program.

8 CONCLUSIONS

The following conclusions are based on the testing performed using Type 312 SS fillers for weld overlays on waterwall panels to date. Additional testing is planned during 2001.

1. *Weldability.* Of the five alloys evaluated in this program, the Midalloy GMAW and the ESAB FCAW wires provided the best overall weldability. Two additional Type 312 SS wires are currently being evaluated at the time of preparation of this report
2. *Thermal expansion*. One filler metal, Midalloy, was found to offer expansion characteristics that paralleled the base material over the entire 100–800°F (38–427°C) temperature range. A flux-cored alloy and a metal-cored alloy were found to deviate from the T-22 considerably.
3. *Heat input.* Heat input was found to have little effect on the thermal expansion characteristics when welding the Midalloy Type 312 SS on T-22 base metal. It is believed that the welding power supply settings, which are required to achieve sound welds, limit the actual heat input range over which one can work.
4. *Delta ferrite.* Heat input appears to have little effect on the delta ferrite formation in the Midalloy Type 312 SS alloy. Again, this may be tied to the welding power supply and the ability to achieve sound welds over a fairly small range of settings. The Midalloy filler wire produced delta ferrite contents in the 30–60% range. Cooling rate did have an effect on the delta ferrite percentage formed.
5. *Chromium content.* The chromium content of Type 312 SS filler metals exceeds 30% for most alloys in both the as-received and as-deposited condition. This should be sufficient to provide good corrosion resistance in waterwall applications.
6. *Costs and availability*. Type 312 SS filler material cost was roughly one-half that of In 625 in 1999. This difference grew to the Type 312 SS costing only one third as much as the In 625 in 2000 due to the increase in the price of nickel. For large waterwall applications, the cost of the filler material alone can be much of the cost of the job. One estimate, based on a 5000 sq. ft (464.5 sq. m) job, is that a $250,000 savings could be realized using Type 312 SS instead of In 625.
7. *Shielding gases.* Of the shielding gases evaluated for welding Type 312SS, the 99% argon, 1% oxygen appeared to perform best when welding with solid wires. A 75% argon, 25% helium mixture also performed well. Some initial testing has been performed with a 98% argon, 2% oxygen gas mixture. This gas appears to be better than the 99/01 gas and will be tested more in the future. Some small addition of nitrogen, although not having a large effect on delta ferrite formation, has been shown to minimize hot cracking of the Type 312 SS.

8. *Weld dilution* – As would be expected, the solid GMAW and metal-cored wires provided less overall weld dilution than the flux-cored wires. The GMAW and metal-cored wires provided dilution values ranging from 24–28%, with the flux-cored wires approached 50%.
9. *885°F (475°C) embrittlement* – The issue of embrittlement which occurs in certain stainless steels between 600–885°F (315–474°C) is currently was investigated for the Type 312 SS alloy. The Type 312 SS developed significant embrittlement in as little as 100 hours of exposure at 885°F. The embrittlement is only a concern when the boiler is off line. Hydrostatic testing was shown to not develop stresses in the tubing sufficient to damage the overlay at room temperature.
10. *Welding filler metal.* Of the six alloys tested to date (which included two flux-core alloys, ESAB Shield Bright and Kobelco; a metal-core alloy, ESAB; three solid wires, Midalloy, Euroweld, and Techalloy), the Midalloy and Euroweld appear to be the best alloys for waterwall applications. It is important to note that EPRI neither endorses nor promotes specific products; we only present the results of testing. The testing performed in this program suggests that the Midalloy and Euroweld solid wire Type 312 SS provide excellent weldability, low dilution, greater than 25% chromium (as deposited), and good thermal expansion characteristics.
11. *Distortion control.* The as-deposited distortion caused by residual welding stresses appears to be less with the Type 312 SS than with the current industry standard In 625. Heat input does not have a great effect on distortion when varying the heat input within the constraints of producing sound welds.
12. *Serviceability.* One of the first applications of Type 312 SS was performed at American Electric Power's Big Sandy plant in October of 1999. The boiler was removed from service for a maintenance outage in the Spring of 2001. Inspections indicated that in general the overlay provided good protection for the boiler tubing. One small area contained limited cracking. This cracking was caused underbead deposits caused by poor welding. This area of damage was located where the worst wastage of the original tubing had occurred.

The technology developed in this research project provides utilities with another option to manage their boiler waterwall assets. This program strives to develop a complete waterwall management program that involves material selection, application, and repair procedures for overlays.

9
FUTURE RESEARCH

This project is currently funded for further research under EPRI FRAC during the year 2001. Some of the planned activities include:

- Performing additional metallurgical testing on samples removed from American Electric Power's Big Sandy Plant (this is contingent on the unit outage schedule)
- Investigation of repair methods and procedures for previously overlaid panels.

APPENDIX

Waterwall Survey Questions

1. Utility
2. Utility Representative
3. Date
4. Location
5. In the past, has this utility had a serious problem with waterwall deterioration?
6. If yes, what form(s) has the deterioration taken?
   Wastage
   Circumferential Cracking
   Membrane Cracking
   Other
7. If other, please describe
8. If you have experienced circumferential cracking, have you had a metallurgical analysis performed on specimens removed from the furnace?
9. If yes, what were the results?
10. Has the problem gotten worse since the installation of Low NOx Burners?
11. Have you mapped any of your units to establish a wastage rate?
12. If yes, what rates were measured and how did these compare to pre-modification wastage rates?
13. If yes, did the rates vary with furnace location?
14. If yes, where have the highest rates been observed?
15. What company supplied the Low NOx Burner system(s)?
16. Did the supplier meet the performance guarantees?
17. What is the sulfur content of your coal?

18. Has the sulfur content of your coal changed in recent years?

19. If yes, what was the former sulfur content?

20. If so, have you noted a change in the extent or severity of the waterwall deterioration?

21. Have you attempted to use weld overlays to extend waterwall life?

22. If yes, were these applied over existing panels in the furnace or on new panels or both?

23. If applied to existing panels, which vendor performed the overlay? Which welding method was used?

24. If applied to new panels, which vendor performed the overlay? Was the overlay applied in the unit or at the vendor's facility?

25. In either case, were the panels preheated prior to the operation?

26. Were the panels stress relieved after overlay application?

27. What filler materials have you used?

28. What has been your experience with each?

29. Have you measured the deterioration or wastage rate of each overlay alloy?

30. If you have compared the performance of several alloys, were the exposure conditions similar?

31. Can you summarize the design specs for each furnace? Supercritical or subcritical? S content of the coal? OEM? MW rating?

32. Which factors do you consider in the selection of candidate overlay alloys? i.e., cost, weldability, chromium content, structure, thermal expansion, etc.?

33. Can you list the top three factors in order of importance? Do you verify the accuracy of the supplied information? For example, do you check the Cr level of each lot of wire if Cr content is rated as important?

34. Have you used inconel filler metals? If so, which alloy? Which unit? What has been the service performance of the overlay?

35. Have you used austenitic filler metals as overlay alloys? If so, which? If so, have you observed dissimilar metal cracking at the interface between the austenitic and ferritic components? What unit or units were involved? Was the service performance of the overlay satisfactory?

36. Have you used a duplex stainless as an overlay filler metal? If so, which alloy? What unit? Has the service performance of the overlay been satisfactory?

37. Have you used ferritic filler metals as overlay alloys? If so, which alloy(s)? Which unit(s)? What has been the service performance of the overlay?

38. Have you used any of the ferritic stainless steels in overlay applications? If so, which alloy or alloys? Which Unit? What has been the performance of the overlay in service?

39. Would you consider using laser clad panels as replacements for existing panels when they have reached the end of useful service?

40. If you were to purchase replacement panels for a unit exhibiting aggressive deterioration, what type of protective coating would you specify, if any?

41. Have you used any of the new stabilized Cr-Mo steels in your fossil units? If yes, what were the alloys? What was the application? What has been their performance? Do you believe such alloys offer promise for waterwall applications?

Waterwall Overlay Questionnaire

Q1	Utility	BGE	GPU	Allegheny Power	Pepco	TVA	Comment
Q2	Representatives	DonWright	Frank Madden K. Rumbaugh	Tim Banfield Bill Linhart	Neal Titer Alex Bonnington	Steve Merry Willie Mills	
Q3	Date	3/8/99	3/2/99	2/2/99	2/19/1999	3/18/99	
Q4	Location	Ft Smallwood	Conemaugh	Phone Conference	PSC	Colbert Unit 5 Tuscumbia, AL	
Q5	Serious WW Deterioration	No	yes	post LNB	yes	Yes	A common problem especially with CE supercritical units
Q6	Form	NA					
	Wastage			X 10 mils/yr Hatfield	X		
	Circ Cracking				x		
	Membrane Cracking				x		
	Other		x		x		
Q7	If other	NA	Corrosion 100 mils/yr		sootblower erosion burner nest erosion	Fireside Corrosion Sulfur oxidation/corrosion	
Q8	If circ crack, met exam performed	Yes	Yes		yes	NA	
Q9	If yes, results?	Alligator Hiding slow rate	fatigue		wedge cracks with S spines some rippled magnetite	Sulfidation high temperature oxidation slight speroidization, no creep damage	
Q10	Worse since LNB?	too early to tell	yes	yes at Hatfield & Pleasants	possibly	yes	
Q11	Mapped?	Baseline only	yes	yes at Hatfield after LNB	yes	yes	
Q12	Wastage Rates?	NA	100 vs 30 mils/yr pre LNB	62 vs 15 mils/ yr	50 vs 15 mils/yr	pre 1 to 16 post 4 to 40 mils/yr	50 to 100 mils/yr After LNB installed
Q13	Vary with Location?	NA	yes	yes	high wastage areas moving up in furnaces	yes	
Q14	Where Highest?	NA	Between Burners & Over fire air	Top of Burners	At top of Burners	around 2nd & 3rd burners from top	Consistently worst at top of burners.
Q15	LNB Supplier	B&W	ABB	B&W Hatfield FW Pleasants	ABB Morgantown Riley Chalk Point	B&W	

Q16	Performance Guarantees Met?	Yes Brandon Shores 1 & 2 No Wagner 2	yes	not yet but close	ABB yes Riley no	No	
Q17	S Content?	Brandon Shores 7% Wagner 1%	1.6 to 2.2%	Hatfield 2.2% Harrison 3.3 to 3.5+% Pleasants 4.1%	1.40%	1.7 to 2.2%	Wastage requires sulfur but not much
Q18	S Changed over time?	No	yes	yes	No	No	
Q19	If yes, former level?	NA	under 2%	Harrison 3.0% Pleasants 3.5%	NA	NA	
Q20	Noted change in WW deterioration?	NA	not now clad	difficult to tell	NA	NA	
Q21	Used WW weld overlays?	NA	yes	only test panels	yes	yes	Commonly used
Q22	If yes, where?	NA	to existing panels & new panels	test panels new at Hatfield existing panels at Pleasants	existing panels except one shop welded test panel	existing panels	
Q23	If to existing Panels, Vendor? Method?	NA	WSI GMAWautomatic	WSI	WSI Rentjes Pepco Semi-auto or fully auto MIG	Unifuse - mechanized pulsed spray GMAW process	WSI seems to be an aggressive marker
Q24	If to new panels - vendor? in field or at vendor shop?	NA	WSI WSI Shop	WSI WSI Shop	Stardyne (now Praxair) Stardyne Shop	NA	Many new panels are laser welded
Q25	Were these panels preheated prior to overlaying?	NA	yes	?	no	no	
Q26	Were these panels stress relieved after overlaying?	NA	yes	?	yes	no	
Q27	What filler metals were used?	NA	625 (ERNiCrMo-3)	test areas of 309, 312, 622, 625 & 410	309, 312, 446	625	
Q28	What has been your experience with each?	NA	NA	No samples have been evaluated, but appearance is good	309- no deterioration in 7 yrs of sucritical service at Dickerson. Good corrosion experience in supercritical service at Morgantown but subject to DMW cracking 312-Good corrosion resistance but subject to initial application problems at Chalk Point. 446- Good behavior when proper chromium content is maintained. Better performer than 309 at Morgantown.	no failures in 3 yrs of service	Need Chromium (20%?) for effective protection Inconels behave well in service. 309 subject to dissimilar metal weld cracking 312 avoids DMW cracking via duplex structure. 446 protective but difficult to weld
Q29	Has deterioration rate been measured?	NA	yes	no	No corrosion damage in any of the stainless steels. Cracking is the main cause for concern.	no	

Q30	Similar exposure conditions for different alloys?	NA			no	yes			yes			NA	
Q31	Design Specs	Wagner 2	Wagner 3	BrdShr 1&2	Conemaugh 1&2	Hatfield	Harrison	Pleasants	Chalk Point	Morgantown	Dickerson	Colbert 5	
	MW	100	300	650	900	555	640	623	355	585	185	900	
	Supercritical		x		x	x	x	x	x	x			
	Subcritical	x		x							x	X	
	S content	1%	1%	0.70%	1.6 to 2.2%	2.2%	3.3-3.5%	4.10%	1.4%	1.4%	1.4%	1.7 -2.2%	
	OEM	B&W	B&W	B&W	ABB-CE	B&W	F-W	F-W	B&W	ABB-CE	ABB-CE	B&W UP	
Q32	Overlay factors considered?	NA				NA							
	cost				x				x				
	weldability				x				x				
	chromium content				x				x				
	structure								x				
	expansion coefficient				x				x				
Q33	Top 3 Factors? Field Verification?	NA			Cr, Exp, Weldability Certs & alloy anolys	Expansion Coeff			Weldability, Exp Coeff, Cr content alloy analysis on production mock-ups				Keys - >20% Cr, weldability and expansion coeffocient close to waterwall tubing
Q34	Inconel Used	NA			625, both units acceptable thus far	622 & 625 at Pleasants & at Hatfield			Only test girth weld caps of Inco A at Morgantown; This alloy has too little Cr to be corrosion resistant			625	Inconel 622 & 625 are effective but expensive
Q35	Has DMW cracking been observed?	NA			No observed DMW cracking	Not in the 309 & 312 test panels			No 309 deterioration in 7 yrs at Dickerson Significant DMW cracking at Morgantown & Chalk Point			no	309 effective but subject to DMW cracking
Q36	Used a duplex stainless?	NA			No	Test panel containing 312 area installed at Hatfield in 1997			312 used at Morgantown and Chalk Point with good success.			no	312 effective and does not appear to be subject to DMW cracking
Q37	Used a ferritic overlay?	NA			No	No			9018 B-3 on T11 caused reheat cracking			no	
Q38	Used a ferritic stainless?	NA			No	No			446 as a laser clad overlay at Morgantown with satisfactory results with proper Cr content present in the overlay			no	
Q39	Would you consider using Laser clad panels in your units?	No			yes	Yes - now the standard corporate approach for replacement panels			Yes - One panel installed and four more on order for Morgantown			yes	Laser cladding with inconel is a viable choice for troublefree new panels
Q40	Present preferred coating?	inconel overlay or chromized panels			inconel overlay ERNiCrMo-3	laser clad inconel 622 panels			Depending on the particular situation, Pepco would use chromized panels, field overlays, laser cladding or even bare panels			laser clad	
Q41	Used a stabilized Cr-Mo steel?	NA			No	Grade 91 used in header and superheater replacements - WW applications could cause welding problems			No			no	

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EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

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EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com