



# **The Use of Weld Overlays to Extend the Useful Life of Seam Welded High Energy Piping in Fossil Power Plants**

**1001270**

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# **The Use of Weld Overlays to Extend the Useful Life of Seam Welded High Energy Piping in Fossil Power Plants**

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February, 2001

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This document describes research sponsored by EPRI.

The publication is a corporate document that should be cited in the literature in the following manner:

*The Use of Weld Overlays to Extend the Useful Life of Seam Welded High Energy Piping in Fossil Power Plants*, EPRI, Charlotte, NC: 2001. 1001270.



## ABSTRACT

Replacement of longitudinally welded reheat and main steam lines is very expensive and can result in extended outages. Inspection and re-inspection of such systems every few years is also expensive and time consuming. An alternative to continued inspection or system replacement is weld overlay. This report provides the basis for weld overlay of one component, clam shell elbows. Weld overlay of other piping system components will build upon the technology developed in this program.

### Background

A number of failures in longitudinally welded reheat and main steam lines during the mid-to-late 1980s resulted in a focused utility effort to improve both inspection and assessment programs for continued operation. EPRI developed a set of guidelines in 1987 to address this issue and later updated the guidelines in 1995. Periodic inspections of long seam welds has been embraced by the industry and is now very common. Based on these inspections and damage found, many utilities have made the decision to replace entire piping systems. The present effort is aimed at providing an alternative to entire piping system replacement if creep damage is located.

### Objectives

- Develop an alternative to reducing temperature (and load) if creep damage is located in a main steam or hot reheat line.
- Evaluate and demonstrate the use of weld overlays to extend the life of a long seam welded, high energy component.

### Approach

For weld overlay of long seamed piping components to be economically advantageous, the overlay must be applied in a non-postweld heat-treated condition with reasonably high deposition rates. In Phase 1 of this program, the EPRI Fossil Repair Applications Center set out to establish a temperbead welding approach to deposit the weld overlay using the flux-cored arc welding (FCAW) process. In parallel, finite element analyses was performed to establish the stress levels generated via weld overlay buildup on a double-vee clamshell elbow weldment. A weld overlay design was established with the FEA which was used with the temperbead welding parameters to develop a full scale, clam shell elbow weld mockup. Upon completion, blindhole residual stress measurements were completed to determine the stresses imposed by the weld overlay. Phase 2 (completed in 2000) included metallurgical and crack growth analysis as well as the development of a position paper to support the use of the weld overlay technology by utilities.

## Results

A FCAW temperbead welding approach has been developed which will allow for rapid deposition of the weld overlay and provide excellent heat affected zone and weld properties. The welding approach has been applied to a full scale 38-inch diameter, 2-1/4Cr-1Mo clam shell elbow weld mockup following FEA design of the weld overlay. Residual stresses for the weld overlay have been modeled using FEA and subsequently measured using blindhole residual stress measurement techniques. Residual stresses measured for the weld overlay appear in line with what would be expected for a weld overlay and correlate well with the FEA. Maximum residual stresses along the hoop direction were below 15.0 ksi at room temperature and 2.0 ksi at operating temperature. Creep relaxation calculations suggested that such stresses would relax at 1000F within as few as 400 hours. This project demonstrates an alternative (the use of weld overlays) to lowering the operating temperature (and load) of a piping system.

## EPRI Perspective

During the 1980s, the nuclear industry developed a weld overlay approach for austenitic piping girth welds which is now recognized by the US Nuclear Regulatory Commission as a “permanent” long term repair. The repair technology has literally saved the nuclear industry millions of dollars. A similar repair approach for weld overlay of long seam welds in main steam and hot reheat piping is being developed under this two phase effort sponsored by member utilities of the FRAC. The weld overlay technology will provide utilities with a methodology to address specific plant conditions including:

1. After an inspection is conducted and “no recordable defects” are found, the seam weld overlay could be used to extend the re-inspection interval by a factor of 10X-20X.
2. If “minor” damage is located in a seam weld, the weld overlay could be used to extend the re-inspection interval.
3. If “major” damage is found, the weld overlay could be used to justify continued operation until replacement piping could be procured and installed.

## EXECUTIVE SUMMARY

This report documents the results of the first two phases of a program aimed at development of a weld overlay repair technology to address creep damage in long seam piping weldments. Under Phase 1 (completed in 1999), subscribers requested that the FRAC: 1) develop a temperbead welding repair approach by which a weld overlay could be applied without postweld heat treatment, 2) design a weld overlay and perform finite element analyses to ascertain the level of stresses generated during welding, 3) develop a clam shell elbow weld overlay mockup, and 4) measure the residual stresses generated from welding via the blindhole drilling method. In 2000, Phase 2 of the effort concentrated on evaluation of mechanical and metallurgical properties and the development of a position paper to support the use of weld overlay technology in fossil power plants for long seam applications.

The report begins with a background discussion of the industry experience as it relates to long seam welding failures. An overview of the inspection and life assessment technologies employed to address long seam weld creep damage is provided. The concept of the development of weld overlay technology to address long seam damage is also presented. The excellent 10-plus years experience of weld overlays as utilized by the nuclear power industry is provided, and considerations surrounding its use in the fossil power arena are discussed.

Specifically, the use of weld overlay technology should provide a cost-effective approach to management of high energy piping system damage. Weld overlay should be less expensive than other options such as full piping system replacement or an ongoing program of periodic or 100 percent inspection. The goals of the weld overlay repair effort were to provide a methodology to address each of the following three circumstances:

1. After an inspection is conducted and “no recordable defects” are found, the seam weld overlay could be used to extend the re-inspection interval by a factor of 10X-20X.
2. If “minor” damage is located in a seam weld, the weld overlay could be used to extend the re-inspection interval.
3. If “major” damage is found, the weld overlay could be used to justify continued operation until replacement piping could be procured and installed.

Next, a scope of work is provided in Section 3 to highlight the various tasks associated with the program. Section 4 of the document provides a description of the temperbead welding development. Two different flux-cored arc welding temperbead approaches were considered including a stringer-type weld buildup and a “limited” weave type approach. Two 3-layer weld overlays were applied to 180 degree sections of a service-removed 2-1/4Cr-1/2Mo pipe. Mechanical testing and metallurgical analyses were performed. The “limited” weave approach was determined to provide the best overall weld and heat affected zone properties.

Section 5 provides a detailed discussion of the weld overlay mockup demonstration. The mockup demonstration made use of the developed temperbead welding method and a weld overlay design that was established via finite element analyses. The demonstration was performed

on a 38-inch diameter, 2-1/8-inch thick, service-removed, 2-1/4Cr-1Mo, clam shell welded elbow which had experience over 150,000 hours of service. The mockup consisted of placing the elbow in the correct orientation and securing it on both ends using I-beams. A welding track was attached along the length of the elbow and a 3-layer, 5-3/8-inch wide, 0.550-inch thick weld overlay was applied using. Approximately 33 lbs. of 81T1-B2 FCAW wire was employed (which incidentally would not require recalculation of pipe hanger stresses.)

Section 6 overviews the finite element analyses used to design the weld overlay for the clam shell elbow. Additionally, it projects the residual stresses which will be generated by the weld overlay at both 100F and at operating temperature. The “hoop” residual stresses at the inside diameter surface were projected at 14.0 ksi (tensile) at 100F and relax to 2.0 ksi (tensile) at operating temperature. Hoop stresses are considered of greater importance since stresses along this direction would act perpendicular to the long seam. FEA also predicted that the maximum axial stresses would be compressive along the length of the elbow section.

The results of the blindhole residual stress measurement are provided in Section 7. Hoop residual stresses were measured at 14.0 ksi at room temperature, whereas axial stresses were shown to be tensile at 16.8ksi along the inside surface. The tensile stresses were considered to be the result of the mockup fixturing and constraint.

Section 8 of the report discusses the implications of the weld overlay on the creep performance of the component. Consideration of stress relaxation was taken into account using data provided by ASME Section III, Subsection NH and D. Woodford. The data indicated that an initial residual stress of 15 ksi would relax out in approximately 400 hours, a relatively small time in the life of a component. It is important to point out that residual stresses are associated with all welds or weld repairs and that subsequent postweld heat treatment is commonly used to relax out stresses. The case of a weld overlay is slightly different in that it relies on operating temperature to relax out the residual stresses as opposed to an elevated PWHT temperature.

A discussion of the stress measurement results is provided in Section 9. In this section it is shown that the FEA predicted hoop stresses and the residual stresses measured via the blindhole drilling technique correlate quite well at 100F. Maximum hoop stresses (both predicted and FEA) at the inside diameter surface were shown to be within 4.0 ksi of one another at this temperature. Since blindhole measurement could not be performed at operating temperature, the predicted FEA values were used. At this temperature, the maximum hoop residual stresses were shown to be only 2.0 ksi.

Section 10 discusses other weld geometries that were applied to try and influence the residual stresses on the inside surface of the pipe.

Mechanical testing of the weld overlay is explained in Section 11. The testing included: bends, tensiles, hardness, Charpy impact, and metallographic analyses.

Investigation of the potential service life increase via the weld overlay is explored in Section 12 through the use of crack growth analysis. Two calculation methods were employed;  $C^*$  and  $C(t)$ . Good life extension was noted with either calculation method.

At this point in the program, FRAC staff and subscribers to the FRAC target are very encouraged by the results. A FCAW temperbead welding approach has been developed which will allow for rapid deposition of the weld overlay. A weld overlay mockup has been fabricated and modeled using FEA. Additionally, residual stresses measured for the weld overlay appear in line with what would be expected for an overlay and correlate well with the FEA. The results of metallurgical testing verify that the FCAW temperbead welding technique is suitable to this type of repair and offers an alternative to lowering the operating temperature or pressure for continued service.



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# 1

## BACKGROUND

Failures of longitudinally welded reheater steam lines at Southern California Edison in 1985 and Detroit Edison in 1986 persuaded the industry to pursue a program of inspection and assessment for continued operation. EPRI developed a set of guidelines for inspection and condition assessment of seam-welded piping in 1987 (1) and a revised set of guidelines in 1995 (2). The guidelines included: 1) methods for evaluating the material properties of the welds via sampling and 2) examination of the piping for internal and external flaws by magnetic particle testing (MT), fluorescent particle testing (PT), radiographic testing (RT) and ultrasonic testing (UT).

Most utilities began a program of periodic inspection of the welds, but initially a few utilities looked at the expense of scaffolding, insulation removal, testing and repair and elected to replace longitudinally seam welded piping with seamless piping, justifying the large initial expense by future savings from not having to perform periodic re-inspections. Those utilities that did inspect their lines found problems in longitudinal seam welds, clamshell elbows, girth welds, RT plugs, attachments and other locations. The programs of replacement or inspection in all likelihood prevented many leaks and failures that would have occurred.

Despite all of the efforts, leaks continued to be a problem for the industry. Several leaks occurred during the early 1990s, but were not as well publicized as the mid-1980s problems. These leaks prompted another industry group, the Metal Properties Council to form a High Energy Piping (HEP) Group, to investigate additional technologies for inspection and disposition of welded piping. Information from this program is shared only by participants, but some of the general results and recommendations are well known throughout the industry:

1. More recently developed ultrasonic techniques, specifically Time-of-Flight Diffraction (TOFD) for finding flaws and Focused Array Transducer Systems (FATS) for sizing flaws are now used in conjunction with EPRI developed UT techniques for inspection.
2. A large set of piping samples removed from service have been very useful in characterizing the material condition of various welds made in the 1950 - 1980 time frame. As many longitudinal seam welds have little documentation as to original manufacturing variables, this data set has proven to be useful in characterizing weld properties.
3. A computer code has been developed to assist in determining which welds are most susceptible to cracking and leaking, but does not specifically address the problem of how long it will take a given size flaw in a certain type of weld to grow through wall and cause a leak.
4. The use of acoustic emission techniques for locating growing flaws was investigated, but the certainty of detecting and sizing a flaw growing (during operation) by a combination of creep and fatigue has not been established.

When a longitudinally seam welded main steam line experienced a major leak in the summer of 1996, it focused industry attention once again on the adequacy of available technologies for evaluating the condition and suitability of welded high energy piping for continued operation. Though no formal documentation of this leak has yet been made, presentations to various industry groups have highlighted some of the uncertainties that still exist in welded piping condition assessment. The steamline in question was originally reported to have been inspected approximately one year before the incident occurred and the portion of the steamline that eventually leaked was found acceptable. New information indicated that this steam line had never been inspected.

This incident forced many utilities to re-think inspection strategies. Even the most sophisticated UT techniques cannot detect (due to the physics of ultrasound beams and the material characteristics of the piping welds, or operator misinterpretation of UT signals) every flaw. While some types of cracking in seam welds can grow at very high rates, the scenario that microscopic creep cavities, not detectable by UT, can link up and propagate to failure in one year is not consistent with the overall high reliability of welded high-energy piping.

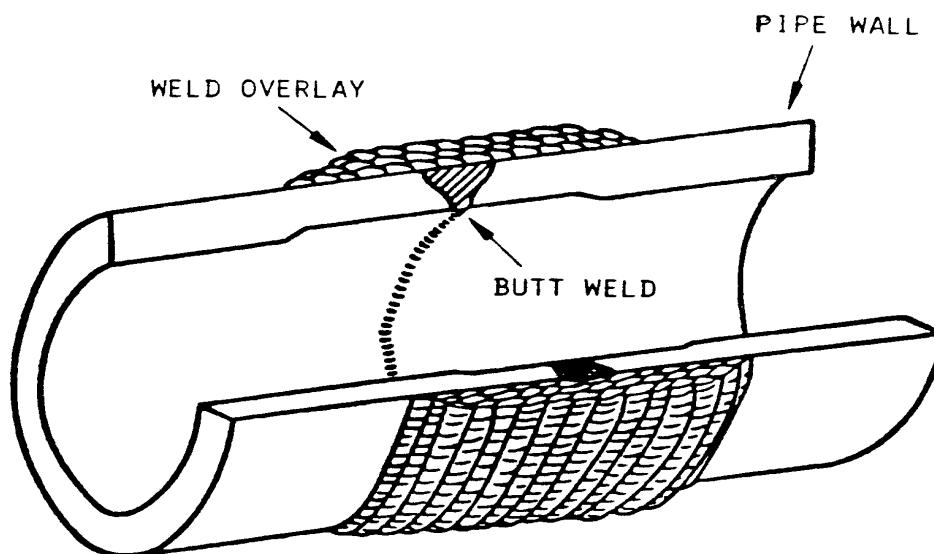
If the industry accepts that small flaws can grow to through-wall in a year of operation, this means that relying on periodic inspection of welds becomes a very expensive life management technique and piping replacement can be justified by economic evaluation.

Even total replacement of high-energy piping does not resolve the problem entirely. Piping systems must have girth welds, RT plug and attachment welds, as some field erection is required. Even though these welds would be made to the highest quality levels possible, there is still a small, discrete, probability of crack growth and leaking as the weld accumulates service hours and stress cycles. Thus, replacement does not negate a periodic inspection program, and these costs must be figured in a long-term economic evaluation of options.

One method for dealing with a somewhat similar problem in the nuclear industry deserves investigation for application to this problem for the fossil industry. Through the use of weld overlays, the nuclear industry has been able to deal with the problem of intergranular stress corrosion cracking (IGSCC) in boiling water reactor (BWR) piping systems. This problem has some limited physical and metallurgical similarities to the creep/fatigue crack growth problem in fossil piping. The economic similarities are much more evident, in that repair, replacement or continued periodic inspection are the choices presented plant management for evaluation and decision making.

## **Weld Overlays for IGSCC Mitigation in Nuclear Power Plants**

Weld overlays were first applied to stainless steel piping in boiling water reactors (BWRs) in 1982 as an interim repair for intergranular stress corrosion cracking (IGSCC). The weld metal provided structural reinforcement of the pressure boundary which had been damaged by the IGSCC and were only considered an interim measure to permit the piping to operate until the next refueling cycle. This gave utilities time to develop a strategy and adequately plan for replacement. Figure 1 shows a typical weld overlay repair for an IGSCC crack in a circumferential weld.



**Figure 1-1. Typical Weld Overlay Repair (1).**

Since the application of the first weld overlays, a vast quantity of field experience, analytical and experimental evidence has been assembled which indicates that weld overlays can be used in many cases as long term repairs. The basis for long-term acceptance is due to the fact that the weld overlay material is resistant to IGSCC, and that the residual stress patterns produced by the weld overlays inhibit or prevent further flaw growth.

The design basis and experience with weld overlay repairs was first summarized in 1984 (3) and more recently in 1991(4). Because of the enormous cost savings accrued with weld overlay repair, research programs were sponsored by the utility industry, EPRI, the BWR Owners Group and the Nuclear Regulatory Commission (NRC) to quantify and justify the use of weld overlays as long term repairs. Some of the research programs included analytical studies of the weld overlay process, experimental testing programs on laboratory and field specimens, development of various welding schemes and development of non-destructive testing (NDE) techniques for use in inspecting weld overlays. The result of all of these efforts has been positive, and some weld overlays are in their fifth or sixth cycle of operation, with an expectation that they will continue in service indefinitely.

### **Weld Overlay Technology**

A weld overlay on IGSCC damaged piping accomplishes several things:

1. Provides structural reinforcement of the pipe to restore Code margins,
2. Provides an IGSCC-resistant barrier to limit further crack growth,
3. Imposes a favorable residual stress distribution in the original flawed component to inhibit further flaw initiation and growth.

Because weld overlays have historically been applied to satisfy a variety of design bases, a broad spectrum of terms have come into use to describe particular overlays. Such terms as full structural overlays, mini-overlays, engineered overlays (Types I, II, III, etc.) are in common use, but sometimes used inconsistently. Reference (4) designates standard overlays as those used for an assumed 360° circumferential flaw, with the existing piping credited for carrying no axial stress, so the pipe is reinforced with a thick, full circumferential weld. Designed overlays are based on the assumption that some credit is taken for the strength of the remaining uncracked portion of piping and therefore a full circumferential weld is not required. Limited service overlays are designed to be only suitable for a single cycle of service, but may be upgraded later to one of the above categories. Standard and designed overlays include provisions for future testing, whereas limited service overlays may not.

### **Weld Overlay Design Methodology**

The basis for weld overlay design is a fracture mechanics evaluation which has been developed and verified to permit continued operation of structural components containing defects. This methodology has been incorporated into Section XI of the ASME Boiler and Pressure Vessel Code (5). The Code defines the allowable end-of-evaluation period flaw depth in austenitic stainless steel piping as a function of applied stress, flaw length and component wall thickness. If a flaw exceeds the acceptable flaw depth, or is predicted to do so during the evaluation period, then weld overlay serves the simple purpose of providing additional wall thickness so that the flaw depth to thickness ratio is acceptable. The favorable residual stress pattern produced by weld overlays (induction heating is also acceptable for producing similar residual stress patterns) is then used in calculating flaw growth rates (hopefully reducing them to zero), which is the basis for extending the number of fuel cycles for continued operation.

Finally, a program of periodic inspection with ultrasonic testing (UT) techniques is established for the particular weld configuration, which includes overlay surface improvement to provide a more accurate UT inspection. The actual approach is more complicated than this simplified description and the interested reader is referred to (4) for more detail. However, the basic concepts of providing structural reinforcement, favorable residual stresses and an established inspection criteria are considered. These are the same steps which will form the basis of a fossil piping weld overlay program.

### **Fossil Plant High Energy Piping Weld Overlay Justification**

The damage to high energy piping in fossil plants is by a creep-fatigue mechanism as opposed to the IGSCC problem in nuclear plants. Other than the cause of damage, the situations in fossil and nuclear plants are very similar. Both are caused by a time-dependent mechanism, which can be aggravated by the initial condition of the piping due to the welding process used for fabrication, either in the shop or the field. When damage is found, it can cause a major outage extension to correct the problem, even if a local repair is made or if replacement sections of piping can be quickly obtained. A conservative analytical treatment of the potential for flaw growth is dictated, either by Code or potential consequences of a leak or failure. Periodic inspection costs are very high, especially when insulation removal, gaining access to the piping, preparation and potential outage extensions are considered along with the overall cost. From an economic basis, the

situations are very similar in that considerable resources may be required to prevent a problem that has a low probability of occurrence.

Weld overlays in fossil piping can accomplish the same benefits as in nuclear piping:

1. Provide structural reinforcement of the pipe to lower stresses and the potential for flaw growth.
2. Provide a barrier resistant to creep/fatigue, if weld alloys with greater resistance to these high temperature damage mechanisms are used (high temperatures for low alloy steel piping, typically 1000 -1050F, are considered low for stainless or nickel based alloys).
3. Imposing a favorable residual stress pattern at operating conditions to inhibit further flaw initiation and growth.

The one major difference between weld overlays for fossil plants versus nuclear is the stress relaxation that occurs in the low alloy steel piping at 1000 - 1050F. This fact will make the design of weld overlays from a residual stress standpoint much more complex than for nuclear piping, where lower operating temperatures prevent stress relaxation.

### **Considerations Surrounding Use of Weld Overlays in Fossil Plants**

The first consideration for the use of weld overlays in fossil plants is the general acceptance of welding over defects. Few Codes govern these situations, and very often, typical practice is to remove the defect, repair weld the affected area and stress relieve the weld(s). For weld overlays to become viable, they must present a better economic alternative to current practices, and one potential source of savings is in the avoidance of stress relief, which would result in considerable savings from the perspective of outage extensions, supporting the remainder of the piping system, etc. This program for developing fossil plant weld overlays will seek to *avoid of weld stress relief*. The weld overlay techniques developed should have a favorable residual stress pattern that will ensure reliable continued operation.

Another consideration is that weld overlays should provide a *cost effective approach* to the management of high energy piping systems. Thus the total cost of a weld overlay should be less than other options, including replacement of the entire piping system or damaged sections, local repair of damaged sections or an ongoing program of 100% inspection. Thus, economics should be a consideration which will influence the technical aspects of the proposed R&D program. It should be emphasized that local repair of defects by conventional techniques may be an indication that the original weld process may be suspect, and that additional defective areas have a high probability of occurrence and a repair technique that treats the entire weld may be preferable from a time-based cost effectiveness standpoint.

Finally, the developed techniques should rely heavily on *already accepted technologies* used in the nuclear industry. The more closely the fossil weld overlay technology follows that previously developed, the easier the first three barriers will be overcome. The fact that Code cases have been accepted in Section XI of the ASME Code will have a positive effect on acceptance of the Code cases submitted as part of this program.

In summary, for the barriers to acceptance of weld overlay technology for fossil plants to be overcome, the technology should include:

1. Welds that do not require thermal stress relief treatment.
2. Cost effective when compared to replacement, repair and continued 100% inspection.
3. Based on successful existing technologies.

### Current Trends in Fossil Plant Welding

As discussed above, one of the top priorities of this proposed program is to develop a welded overlay approach which can be applied *without stress relief* (high temperature post weld heat treatment (PWHT)). The use of a high temperature stress relief may require the need for elaborate temporary piping supports and the use of outside contractors, with the consequent increase in costs and outage time. The combination could alter the economics of the weld overlay technique.

Between 1993 and 1996, EPRI, under the sponsorship of 20 utility members, has spearheaded a research effort (RP3484-01) to compare temperbead and postweld heat treated repair weldments for various fossil components including: main steam and hot reheat piping, headers and turbine casings. The program has conclusively demonstrated that temperbead repairs (controlled deposition practices, requiring no PWHT) produce comparable or improved remaining life than welds with PWHT (6-11).

Other organizations, including the Pressure Vessel Research Council, Edison Welding Institute, Ontario Hydro and Pacific Gas & Electric have performed successful qualifications of temperbead welding. Many of these were recently highlighted in Welding Research Council Bulletin 412 (11,12).

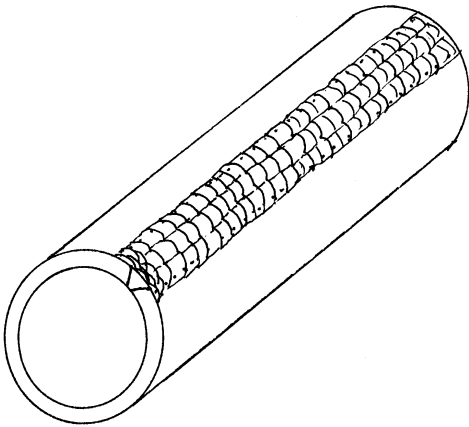
In 1995 the National Board Inspection Code incorporated a change under RD-1040 Welding Method 2 for carbon and low alloy steels when the applicable rules of construction required notch toughness tests. As a result, any low alloy steel component can now be repaired without PWHT when the toughness of the weld metal and HAZ in the as-welded condition is adequate at minimum operating pressure and temperature (13).

This information has been generated over the past five years supporting weld repairs without PWHT for Cr-Mo fossil plant components. This technology will serve as the basis for providing a weld overlay repair method for main steam and hot reheat piping applications. Combining the temperbead approach with an overlay material of sufficient high temperature strength to support operating loads and inhibit crack growth makes the chances of success of this proposed program very likely.

In addition to the subject of weld overlays on seam welded high energy piping (including seam welded elbows), this program forms the basis for exploring the use of weld overlay repairs for a variety of fossil plant components. An example of a seam-welded overlay is provided in Figure 1-2. Components which are often found to contain cracks, and for which no ready replacements are usually available include:

- Valve Bodies

- Headers
- Drums and Mud Drums
- Wyes and Tees
- Steam Chests
- Shells and Casings
- Thinning of Feedwater Piping by Erosion/Corrosion



**Figure 1-2. Schematic of the Full Length Longitudinal Weld Overlay.**

These and other components are often the cause of extended outages and expensive repairs. It has been the experience of the FRAC that a repair technique which would permit continued operation for a few years would be a very desirable tool for utility personnel who discover cracked components during an inspection. The basic technologies developed for welded high-energy piping would be applicable to these and other components and the effort needed to transfer the technologies to these components would be minimal.



# 2

## INTRODUCTION

The cost of piping inspection on an existing steamline is commonly on the order of about \$60/linear foot of piping. This cost does not include costs associated with scaffolding, insulation removal and reinstallation, lost generation, etc. The cost of replacement piping is estimated about \$1000/ft. Either option is quite expensive. A more detailed cost analysis of these two options needs to be performed. Many utilities have subscribed to re-inspections of piping every two or three years. This can be more expensive than replacement on a Net Present Value (NPV) basis, which is a commonly used technique for utilities to make major project decisions.

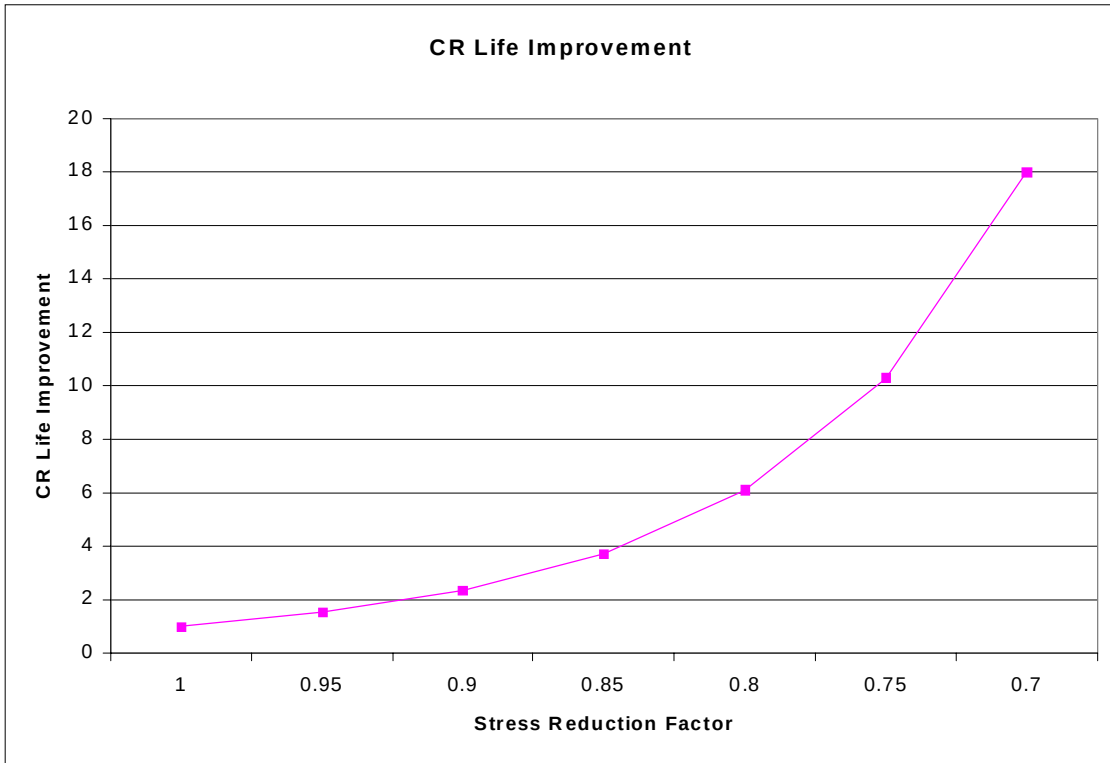
While most degradation phenomena are well known and do not require re-inspection every two years, the phenomenon of creep/fatigue crack growth is less well understood. As seam weld failure represents a potential safety problem, utilities take a very conservative approach to the potential problem and will re-inspect frequently. There are two potential methods to slow down the progression of creep fatigue/crack growth in a component: 1) lower the operating temperature by 50 – 100F (which has been demonstrated for HP/IP turbines and boiler secondary superheater outlet headers) and 2) lower the stress in the component to the point where creep is reduced by a factor of ten or more. The first method has been effectively demonstrated by utilities in the past, but lowers performance and unit output. A method that would allow a plant to continue operating at the same temperature and pressure would be advantageous.

In order to present utilities with both options, a study was begun at the FRAC in 1999 to look at the effects of lowering the stresses in seam welded piping by using the weld overlay technique. This technique has been used very successfully in the nuclear power industry to stop the progress of stress corrosion cracking in circumferential welds. The initial concept of lowering stress via weld overlay started as a “temporary repair” to permit utilities to gain one or two more fueling cycles before replacing the piping. The methodology is now recognized as a “permanent” mitigation technique by the Nuclear Regulatory Commission and has saved the nuclear power industry billions of dollars in replacement power.

For fossil applications, the original thinking was that the seam weld overlay could be considered for one of the following circumstances:

1. After an inspection was conducted and no recordable defects were found, the seam weld overlay could be used to extend the re-inspection interval by a factor of 10X or so.
2. If very minor damage were found, the weld overlay could be used to extend the re-inspection interval.
3. If major damage was found, the weld overlay could be used to justify continued operation until a piping replacement could be planned, resulting in lower costs to the utility.

Preliminary calculations were made to determine the required weld thickness to improve the creep life of the piping with a weld overlay. **Figure 2-1** shows the relative improvement in creep rupture life at 1000F for various stress reductions.



**Figure 2-1. Improvement in Creep Rupture Life at 1000F with Stress Reduction.**

By adding approximately a 25% increase in wall thickness (corresponding to about a 0.75 stress reduction factor), creep rupture life can be increased by greater than a factor of ten. This seemed like a very reasonable amount of material to be added via weld overlay.

A series of calculations were performed for creep crack growth rates and similar results were obtained, although the results were very dependent on how the steamline was cycled (i.e., much greater improvements were obtained with units that cycled less frequently). Creep crack growth improvements also need to be made on a case by case basis, as the initial flaw size will vary.

# 3

## SCOPE OF WORK/TASK DESCRIPTIONS

The primary goal of the program was to develop an alternative to reducing temperature (load) if creep damage is located in a main steam or hot reheat pipeline. To extend the life of a component subject to creep, there are currently two options to a utility: 1) reduce stress/operating pressure and 2) reduce operating temperature. As a rule of thumb, a 50F decrease in temperature results in a 10X improvement in creep performance. The present program considered two avenues for accomplishing continued operation at full operating temperature: 1) increasing thickness of the component or 2) reducing pressure. Reducing pressure is not popular alternative because it has a negative effect on output and heat rate. The route chosen during this project was to increase thickness via weld overlay buildup.

Evaluation of the weld overlay included the following tasks:

- 1.0 Develop temperbead welding technologies for weld overlay of Cr-Mo piping the FCAW process.
- 2.0 Obtain a service-removed clamshell (long seamed) elbow and perform initial finite element (FE) modeling to characterize before and after weld overlay stresses.
- 3.0 Build clamshell elbow mockup and apply weld overlay as designed using FE results.
- 4.0 Measure residual stresses generated using temperbead weld overlay technology.
- 5.0 Perform mechanical and metallurgical testing to verify properties.



# 4

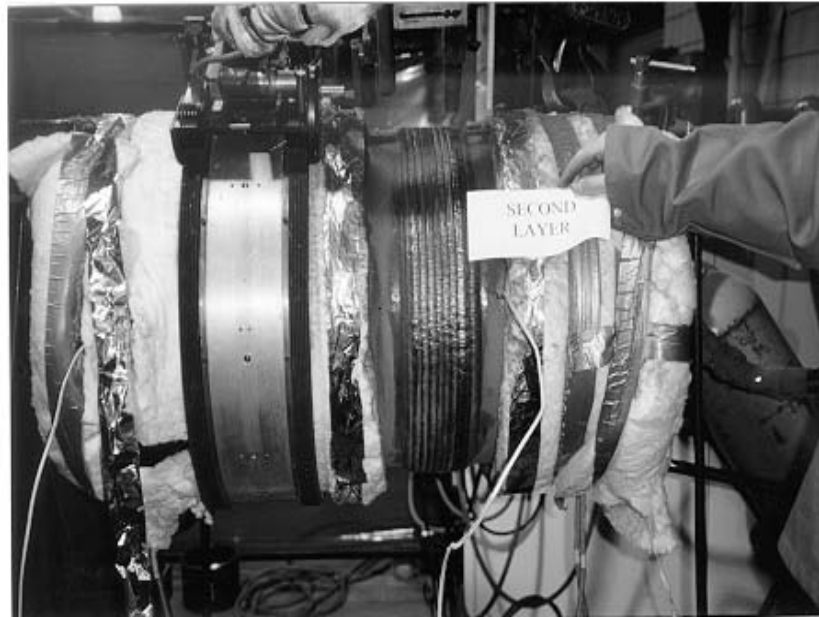
## TEMPERBEAD WELDING DEVELOPMENT

Earlier work sponsored within the FRAC had shown that the FCAW process offered the potential to provide acceptable tempering within the weld heat affected zone and subsequent weld layers when the temperbead welding approach was employed. As a result, FRAC staff set out to develop specific temperbead welding parameters for 2-1/4Cr-1Mo materials with the FCAW process. The development included the use of a 1-1/8-inch thick, 20-inch diameter, pipe section which was positioned in the horizontal 5G welding position.

Two one-half diameter temperbead weld overlays were performed including one using the stringer bead approach and one utilizing a “minimal” weave (<1/8-inch) oscillation approach. Actual welding parameters for the two mockups are provided in **Table 4-1**. Also, a photograph of the weldment is shown in **Figure 4-1**. The welds were performed utilizing the Magnatech Pipeliner II welding system, along with the OTC Diahen Fuzzy Auto EXC 350 power supply. A 450F preheat temperature was employed and no postweld heat treatment was utilized. Approximately 20 weld beads were required for the stringer overlay, while only 11 were required for the weave overlay. Welding progression was in the uphill direction.

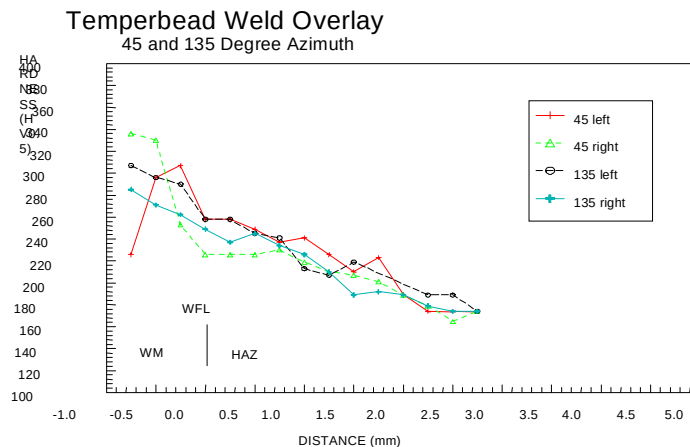
**Table 4-1. Welding parameters employed for two one-half diameter, temperbead weld overlay coupons performed using a stringer and a minimal weave approach.**

|                    | Stringer Overlay | Weave Overlay |
|--------------------|------------------|---------------|
| Amperage           | 160              | 180           |
| Voltage            | 22.8             | 24.3          |
| Wire Feed Speed    | 245              | 290           |
| Travel Speed       | 15.1             | 6             |
| Oscillation        | N/A              | 0.25 max      |
| No. of beads/layer | 20               | 11            |

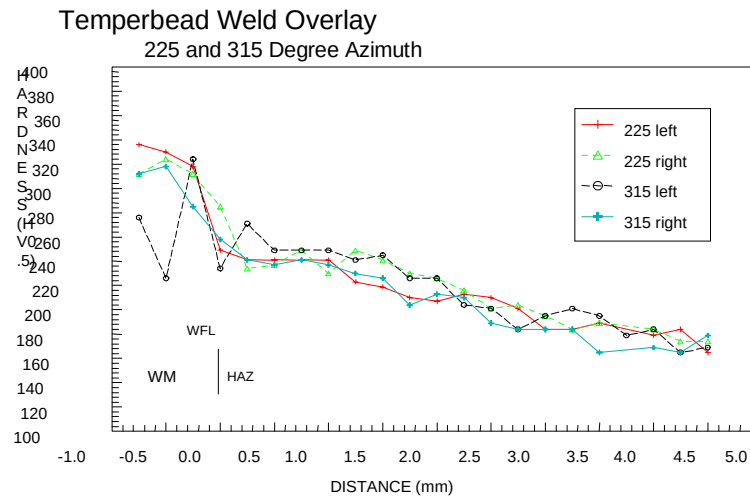


**Figure 4-1. One-half of the temperbead weld development coupon was completed with minimal weave weld layers. Figure shows welding after the second layer.**

Upon completion of the welding, mechanical tests were performed for both the HAZ and base metal of each one-half diameter coupon. The tests included hardness, HAZ Charpy impacts, side bends, and metallographic specimens. Hardness traverses were taken beginning at the edge of the weld metal, continuing throughout the HAZ, and finishing just into the base metal. The Vickers hardness (500g) results for each of the four locations 45, 135, 225, and 315 degrees are shown in **Figures 4-2A to 4-2B**. Maximum recorded values were 258, 258, 241, and 271Hv, respectively. The average base metal hardness was recorded at 174Hv.



**Figure 4-2A. Vickers Microhardness test results for the Stringer temperbead weld overlay.**



**Figure 4-2B. Vickers Microhardness test results for the Limited Weave temperbead weld overlay.**

Side bend tests were also performed for each of the two one-half diameter overlays. Two coupons were removed from the stringer overlay and two from the weave overlay. All four coupons passed 10X examination following bending.

The next series of test performed were Charpy impact tests for the base metal and the HAZ of each coupon. The average base metal impact value for the service-removed, 2-1/4Cr-1Mo steel employed for the weld overlays was 7.5 ft-lbs. Average HAZ impact values were recorded at 17.8 ft-lbs. (stringer overlay) and 32.0 ft-lbs. (limited weave overlay). As can be seen, both easily exceeded the service-removed base metal values; however, FRAC staff believed the values could be improved and an alternative filler metal was considered.

**Table 4-2 Comparison of Charpy Impact Values for a Stringer and “Limited” Weave Temperbead Weld Overlay Application On a 2-1/Cr-1Mo Steel.**

| Sample ID    | Charpy Impact Value @ 72F         | Charpy Impact Average(1) |
|--------------|-----------------------------------|--------------------------|
| Base Metal   | 5.5, 6.0, 10.5,<br>14.0, 3.0, 6.0 | 7.5                      |
| Stringer HAZ | 14.0, 13.5, 26.0                  | 17.8                     |
| Weave HAZ    | 33.5, 38.5, 24.0                  | 32.0                     |

(1) Note: No attempt was made to record lateral expansion or percent shear since the FRAC was only comparing the two temperbead approaches.

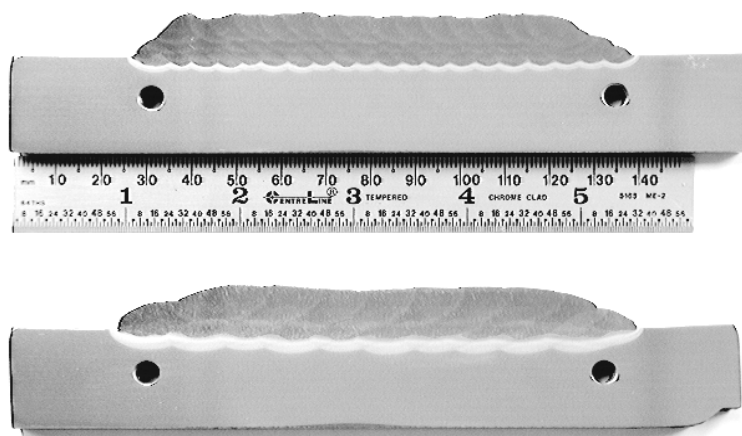
Due to lower than expected “all weld metal” Charpy impact properties, an alternative filler material that would provide values in the 20+ ft-lbs. range was sought. A FCAW wire, Tri-Mark TM811B2, developed for use in both the as-deposited condition and in the PWHT condition was obtained. The wire meets the AWS 5.29 specification. An “all weld metal” pad was fabricated to determine the toughness properties of the weld metal in the as deposited condition. The results of the testing are shown in **Table 4-3**.

**Table 4-3. Charpy test results for an “all weld metal” coupon using a Tri-Mark TM811B2 filler wire.**

| Sample ID | Charpy Impact Value @ 72F | Lateral Expansion (mils) | % Shear |
|-----------|---------------------------|--------------------------|---------|
| A         | 32                        | 16                       | 10      |
| B         | 25                        | 11                       | 0       |
| C         | 25                        | 12                       | 0       |
|           | Ave. 27.3                 |                          |         |

As can be seen from the results, the Charpy impact toughness easily exceeded the 20 ft-lb restriction that was targeted. In fact an average value of 27.3 ft-lb was obtained.

Metallographic analyses of the two cross-sectioned specimens from each weldment was performed to verify that no anomalies were present and that good refinement had resulted. Examples of the stringer and minimal weave cross sections are shown in **Figure 4-2**.



**Figure 4-3. Cross sections representing the stringer and the minimal weave coupons.**

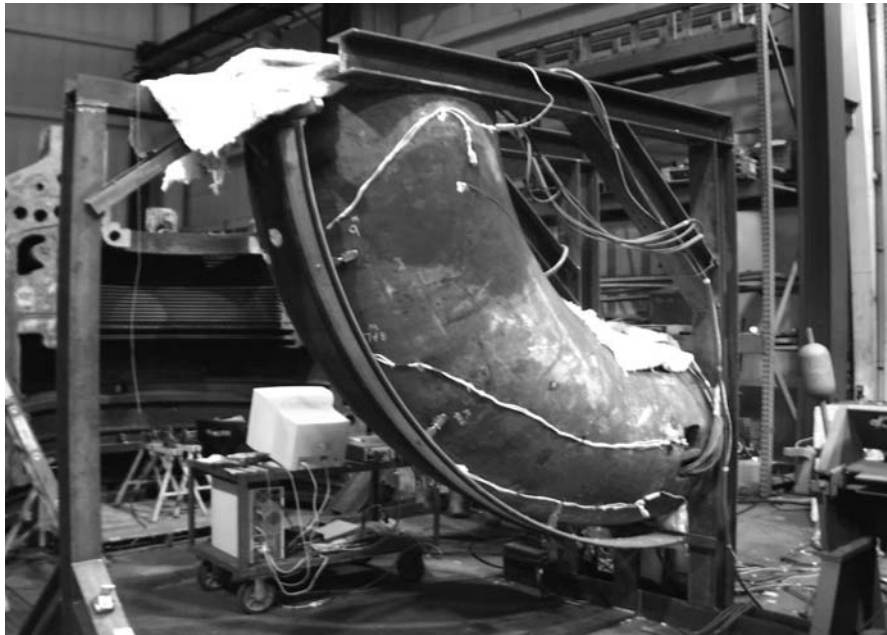
# 5

## WELD OVERLAY MOCKUP DEMONSTRATION

Following the development and demonstration of temperbead welding parameters using the FCAW process, the FRAC initiated work on a full scale, clamshell, elbow mockup. The purpose of the mockup demonstration was to take the knowledge gained during temperbead development (Section 4.0) and the finite element analyses (See Section 6.0), and create a full-scale mockup for residual stress measurement. The demonstration began with the acquisition of a 38-inch diameter, 2-1/8-inch thick, 2-1/4Cr-1Mo, hot reheat clam shell elbow from Western Resources Inc. Jeffery Energy Center. The elbow was recently removed from service after 150,000 hours operation and 150 starts.

Upon receipt of the elbow, it was scanned using ultrasonics to verify if creep damage was indeed associated with the elbow. Both the intrados and extrados of the elbow were scanned and no creep cavitation damage was observed.

The next step of the process was to fabricate a mockup stand to place the elbow at the correct orientation for welding. The stand was fabricated such that the overlay welding could be performed in the overhead-to-vertical welding positions as shown in **Figure 5-1**.



**Figure 5-1. Weld Mockup**

Actual fabrication of the mockup stand was accomplished using 6-inch I-beam materials to restrain the elbow from movement during welding along its axial direction. Considerable discussion regarding the restraint occurred prior to assembly of the mockup. The selection of the

method to restrain the mockup was made following consultation with utility coordinators. The decision was based upon the fact that stresses could be measured following welding in the restrained condition as well as in the unrestrained condition by simply cutting the elbow loose from the I-beams. To date only the stresses (strains) measured prior to welding and after welding in the restrained condition have been obtained. Stresses (strains) after cutting the elbow loose from restraint will be measured at a future date.

Once the mockup assembly was completed, a welding track was acquired from Magnatech and attached to the elbow at various locations along the extrados clamshell weld (See Figure 5-1). Use of the welding track allowed FRAC to utilize the Pipeliner II welding system which was co-developed by EPRI and Magnatech several years earlier. An OTC-Diahen Fuzzy Auto EXC 350 power supply was utilized for to power the Pipeliner system.

A 3-layer weld overlay was applied along the entire length of the seam weld following preheating of the elbow to 450F. The total width of the overlay was 5-3/8 inch, with an average height of 0.550-inch above the surface of the elbow. Approximately 33 lbs. of wire were deposited using a 0.045-inch diameter AWS A5.29, 81T1-B2 FCAW filler wire (Tri-Mark TM-811B2). Actual arc time was measured at 10.2 hours and a total of 39 weld beads were deposited. The welding began by welding overhead and was completed in the vertical position. No postweld heat treatment was employed.

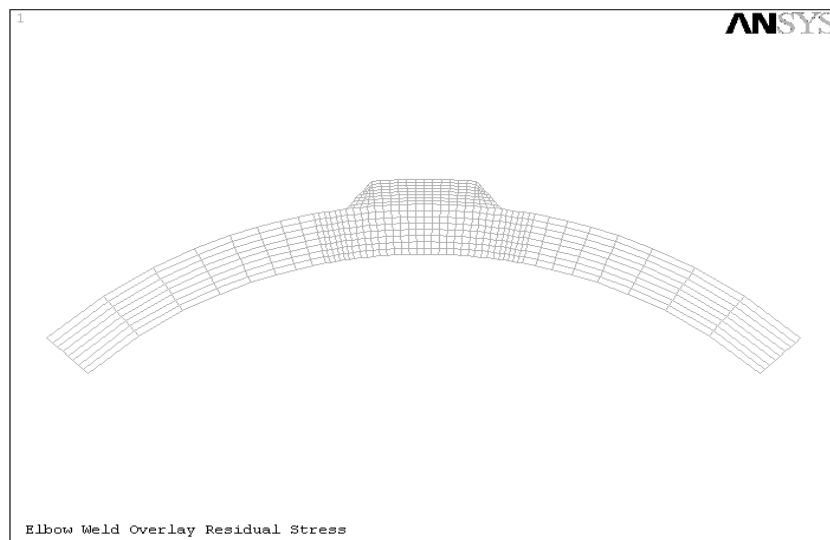
**Table 5-1 FCAW Temperbead Welding Parameters.**

| <b>FCAW Temperbead<br/>Welding Parameters</b> |                        |
|-----------------------------------------------|------------------------|
| Amperage                                      | 180-188 A              |
| <b>Voltage</b>                                | 23.0-23.4 V            |
| Wire Feed Speed (ipm)                         | 285-290                |
| Travel Speed (ipm)                            | 6.0                    |
| Oscillation (inch)                            | 0.250 max              |
| Preheat/Interpass Temp.                       | 450F/550F              |
| Shielding Gas                                 | 75Ar/25CO <sub>2</sub> |
| FCAW Wire Type                                | Tri-Mark TM-811B2      |
| Wire Diameter (inch)                          | 0.045                  |
| Wire Stick-out (inch)                         | 0.75                   |
| Total 3 layer height (inch)                   | 0.550                  |
| No. of Beads/Layer                            | 13                     |
| Total Deposit Weight (lbs.)                   | 33                     |

# 6

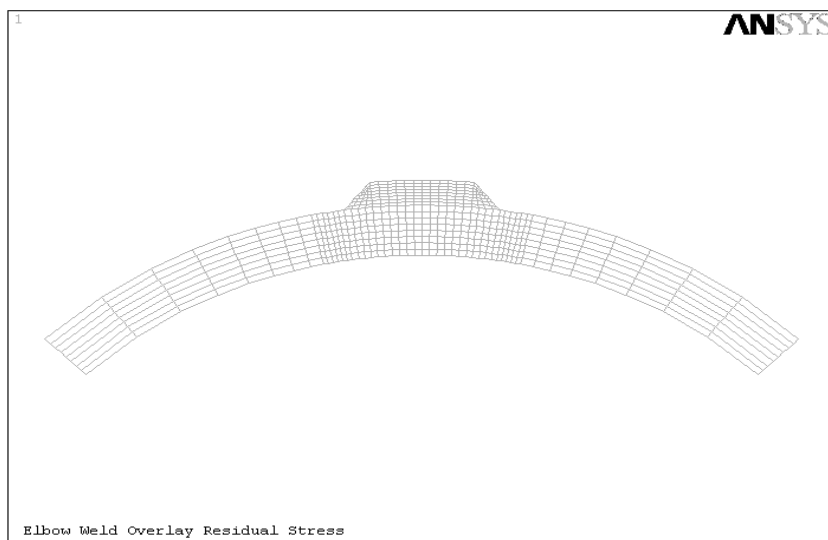
## FINITE ELEMENT ANALYSES

A model of the weld overlay mockup using finite element analysis (FEA) was developed by Structural Integrity Associates to determine the magnitude and state of the residual stresses associated with application of the weld overlay. The model represents a cross section of the elbow with a weld overlay applied directly over the existing double-vee weldment. Cross sections were modeled at 5 locations along the length of the elbow to obtain a good representation of the stresses being imposed on the elbow via weld overlay. **Figure 6-1** provides an example of the ANSYS finite element model and cross-section used in this study.



**Figure 6-1. ANSYS Finite Element Model.**

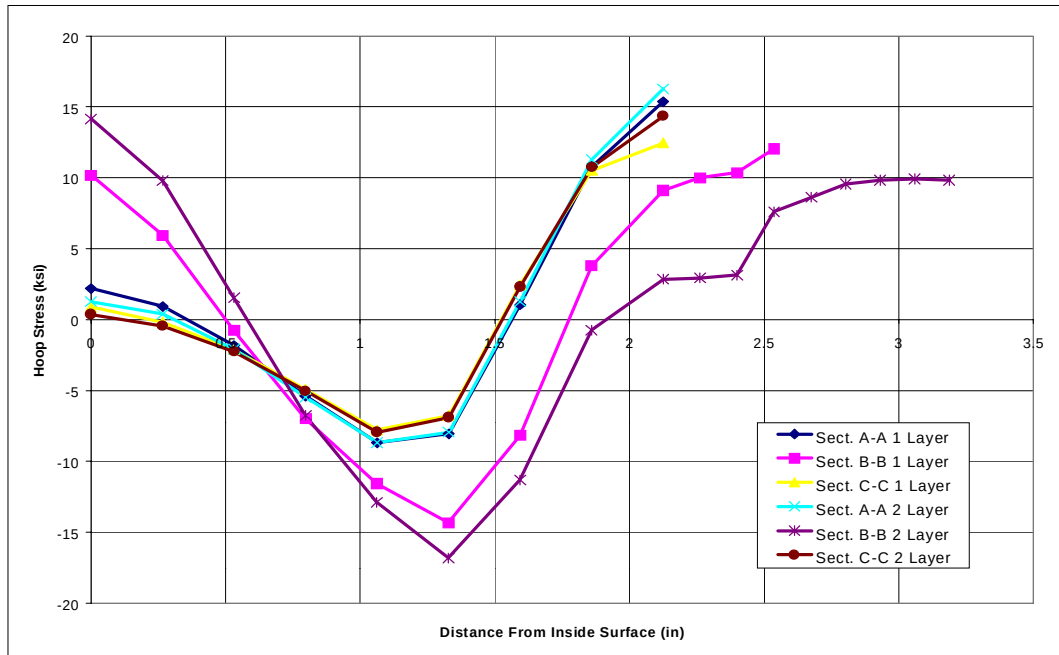
At each cross-section, stresses were calculated for three specific locations: 1) at the weld centerline, 2) at the left most extremity of the overlay and 3) at the right most extremity of the overlay. These locations incidentally correlate with where the highest stresses were anticipated (based on earlier FEA experiences). (See Figure 6-2.)



**Figure 6-2. Planes Through the FEA Model Used to Plot Stresses.**

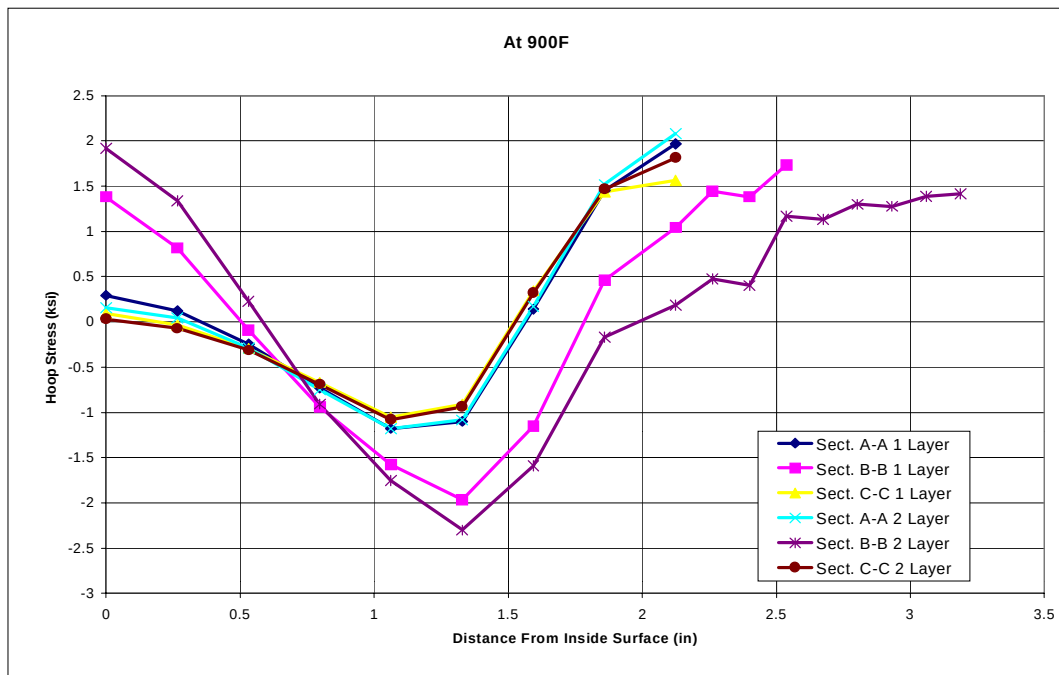
Once the model had been developed, stress plots were developed at specific temperatures to ascertain the level of stress imposed by the weld overlay.

Stress plots at 100F are shown in **Figure 6-3** representing cross sections following application of a single layer and then two layers. Note that the inside and outside surfaces exhibit tensile stresses along the hoop direction, whereas the mid-wall region has high compressive stresses. The tensile stresses encountered at the inside surface were reasonably low for four of the six cross sections modeled; however, two of the cross-sections suggested tensile stresses on the order of approximately 10ksi.



**Figure 6-3. Residual Stress Pattern Along the Hoop Direction in the Elbow at 100F.**

Based on these results, FRAC staff requested that additional FEA be performed at the pipe operating temperature. Hoop stresses were calculated at 990F, the approximate operating temperature of the pipe. The results are shown in **Figure 6-4**.



**Figure 6-4. Residual Stress Pattern at 990F.**

At this temperature, the stresses are much lower with maximum hoop stress projected at 2.0ksi. The change in stress going from 100F to 990F is a result of the geometric configuration of the model and its effects on loading/unloading of stresses over this temperature range.

At this point it is important to point out that the stresses imposed by welding are considered secondary stresses, not primary stresses. As a result, such stresses are not normally taken into account during calculation of system stresses and are reported here only to show what level of stresses are generated though application of a weld overlay. The FEA results are quite encouraging and correspond very well with actual measurements performed in the past on weld overlays performed around the diameter of a pipe (as opposed to along the weld seam).

# 7

## BLINDHOLE RESIDUAL STRESS MEASUREMENTS

Following finite element analyses and actual mockup development, residual stresses were measured using the blindhole residual stress method outlined in ASTM 837. Baseline stresses were measured first so that resulting stresses following weld overlay could be compared to a baseline. Maximum inside and outside diameter residual stresses in the as-received condition at the weld centerline (prior to weld overlay) were shown on the order of 7.0-8.0 ksi. Though somewhat high for a component which had seen 150,000 hours service, FRAC staff believed the stresses were accurate. Furthermore, the goal of the residual stress measurements was to confirm the “change” in stresses in the before overlay and after overlay condition.

Following establishment of the baseline stresses, residual stresses were recorded at two locations along the outside diameter (OD) of the elbow and two locations along the inside diameter (ID), each approximately 12 inches from the end of the elbow mockup. The measurements coincided with both the vertical and horizontal sections of the elbow mockup. It is important to point out once again that the mockup was secured at both ends via I-beams to inhibit axial movement.

Specific locations for each measurement included: 1) weld centerline and 2) either side (left and right) of the weld overlay near the outside of the weld overlay. These measurement locations correspond with those modeled during FEA and are recorded in **Table 7-1**.

**Table 7-1. Measured residual stresses resulting from weld overlaying of a clam shell elbow.**

| Elbow Seam Weld Overlay –<br>Residual Stress Measurement Results (ksi) |       |      |        |             |       |      |
|------------------------------------------------------------------------|-------|------|--------|-------------|-------|------|
| Inside Diameter Measurements                                           |       |      |        |             |       |      |
|                                                                        | Left  |      | Center |             | Right |      |
|                                                                        | Axial | Hoop | Axial  | Hoop        | Axial | Hoop |
| Vertical Location                                                      | 16.1  | 10.6 | 13.0   | <b>14.6</b> | 12.5  | 14.1 |
| Horizontal Location                                                    | 17.2  | 9.0  | 20.6   | <b>20.0</b> | 14.5  | 9.2  |
| Outside Diameter Measurements                                          |       |      |        |             |       |      |
|                                                                        | Left  |      | Center |             | Right |      |
|                                                                        | Axial | Hoop | Axial  | Hoop        | Axial | Hoop |
| Vertical Location                                                      | 9.9   | 17.5 | 65.3   | -34.8       | 22.2  | 11.4 |
| Horizontal Location                                                    | 18.8  | 11.6 | 61.5   | -11.3       | 21.5  | 18.8 |

\* Negative numbers indicate compressive stresses, while positive numbers indicate tensile stresses.

Note the maximum measured stresses along the hoop direction have been italicized and bolded for emphasis. Stresses along the axial direction are considered of less importance since the primary driving stresses to unzip a seam weld lie in the hoop direction. The stresses presented in this table are provided only for reference, however. Those of real importance are presented below in **Table 7-2** since they represent the actual change in residual stress from before to after weld overlay.

**Table 7-2. Change in clamshell residual stress values following weld overlay.**

| Change in Residual Stress Values (ksi) |       |      |        |             |       |      |
|----------------------------------------|-------|------|--------|-------------|-------|------|
| Following Weld Overlay                 |       |      |        |             |       |      |
| Inside Diameter Measurements           |       |      |        |             |       |      |
|                                        | Left  |      | Center |             | Right |      |
|                                        | Axial | Hoop | Axial  | Hoop        | Axial | Hoop |
| Vertical Location                      | 6.6   | 3.3  | 3.5    | <b>7.3</b>  | 3.0   | 6.8  |
| Horizontal Location                    | 7.7   | 1.7  | 11.1   | <b>12.7</b> | 5.0   | 1.9  |
| Outside Diameter Measurements          |       |      |        |             |       |      |
|                                        | Left  |      | Center |             | Right |      |
|                                        | Axial | Hoop | Axial  | Hoop        | Axial | Hoop |
| Vertical Location                      | -0.3  | 9.5  | 55.1   | -42.8       | 12.0  | 3.4  |
| Horizontal Location                    | 8.6   | 3.6  | 51.3   | -19.3       | 11.3  | 10.8 |

\* Negative numbers indicate compressive stresses, while positive numbers indicate tensile stresses.

The change in maximum stresses at the ID surface along the hoop direction are again bolded and italicized for emphasis. As shown, the maximum change in inside diameter, hoop residual stress is 7.3ksi and 12.7ksi (both tensile) at the weld centerline for the vertical and horizontal locations respectively. Those at the left and right locations (again corresponding roughly with the outer extremities of the overlay—along the inside surface) were even less. The change in stresses is viewed very positively along the inside diameter surface and is similar to those stresses measured for other weld overlays applied around the full diameter of a pipe.

The change in maximum stresses at the OD surface along the “hoop direction” are shown to be compressive at the weld centerline and somewhat tensile at the left and right locations. Extremely high tensile stresses were measured along the “axial direction” at the weld centerline, while those at the left and right locations ranged from neutral to 12.0ksi. High compressive stresses are to be expected in the hoop direction at the weld centerline due to the bending moment imposed by the applied weld metal. It was however very surprising to see the higher tensile axial stresses at the centerline. The high tensile stresses would suggest that severe constraint was imposed on the elbow overlay not allowing it to move during welding along this axis.

In 2000, the FRAC severed the ends of the mockup, thereby allowing the stresses to redistribute as they would in normal operation. Additional residual stress measurements were performed at that point and no substantial reduction in stresses were measured. If these high restraints were not encountered in actual repairs, this high residual longitudinal stress should be less. A higher preheat might also minimize the effect of the restraint as less temperature differential between the base metal and weldmetal would result in a smaller thermal expansion stress.

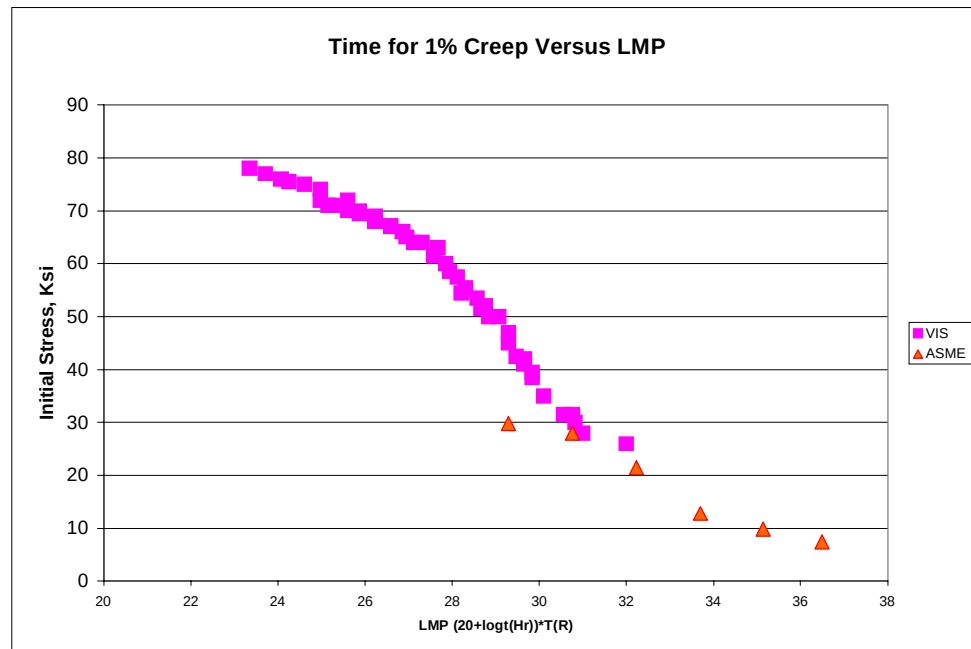


# 8

## IMPLICATIONS ON CREEP PERFORMANCE

### Relaxation of Stresses

While the hoop residual stresses at operating temperature are much smaller, there is still some concern as to how quickly such stresses would relax (the tensile stresses at the ID were of greatest concern). It was anticipated that the stresses would slowly dissipate during operation by the phenomenon of stress relaxation. A study was conducted to determine the rates at which they would relax and two sources of data were found. The first was provided to EPRI by D. Woodford and the second source was the isochronous creep curves from ASME Section III, Subsection NH. The time to reach 1% creep (generally accepted as the point at which all stresses have relaxed to zero) was plotted against the Larson-Miller parameter and the results are shown in **Figure 8-1**.



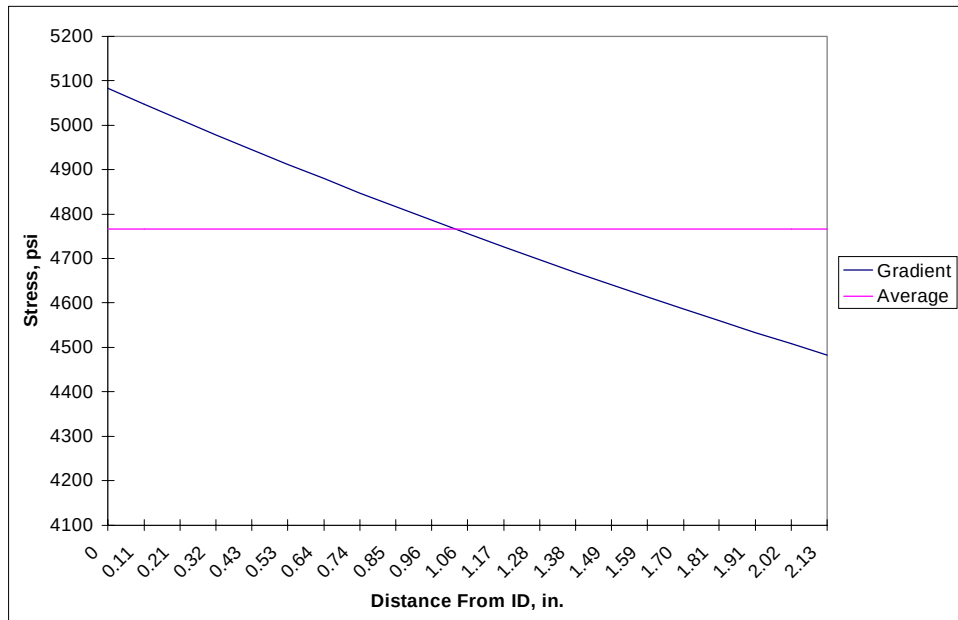
**Figure 8-1 Time for 1% Creep Versus LMP for Cr-Mo Steels.**

An initial residual stress of 15 ksi would experience 1% creep at a parameter of 33, or about 400 hours at 1000F. This information aids in the prediction of operating stresses when the steamline is at full pressure and temperature.

## Pressure Stress Calculations

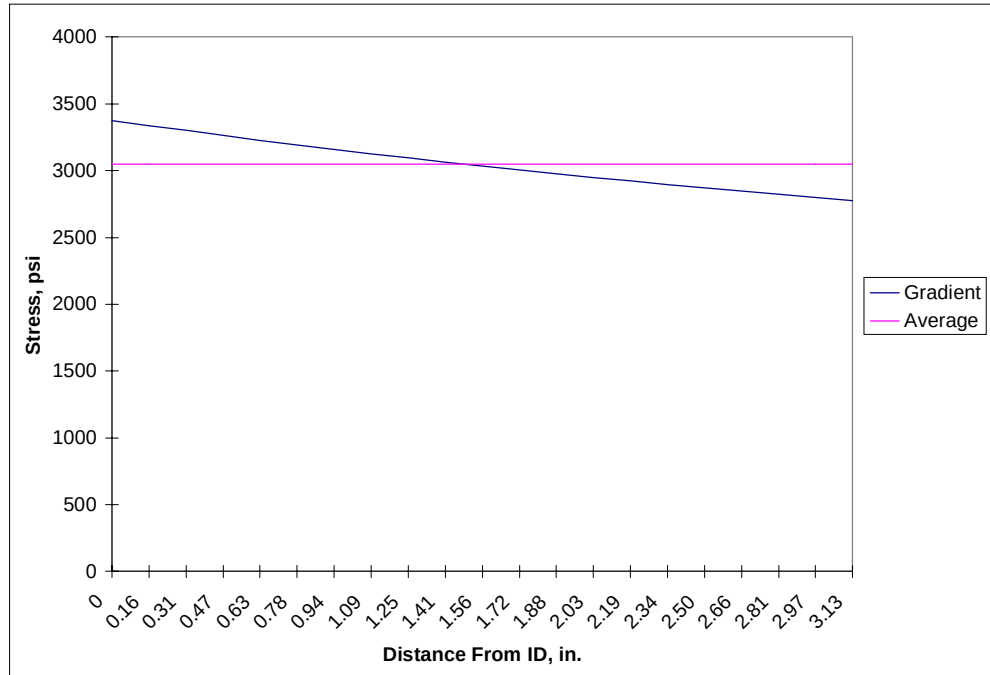
Pressure stresses were calculated using the closed-formed solutions for stresses in a cylinder.

**Figure 8-2** shows the stress versus distance from the ID for the clamshell at its original thickness of 2.125 inches.



**Figure 8-2. Through-Wall Hoop Stress for the Original Configuration.**

Note that the peak stress at the ID is about 5.1 ksi and the average stress is about 4.77 ksi. Stresses were recalculated for the 1" weld overlay and are plotted in **Figure 8-3**.



**Figure 8-3. Through-Wall Hoop Stress for the Weld Overlay.**

Note that the peak stress has been reduced from 5.1 ksi to 3.3 ksi and that the average stress from 4.77 ksi to 3.1 ksi. This amounts to a stress reduction factor of 0.65, which should increase creep by a factor of greater than 20, **Figure 2-1**.

These calculations are very involved. An easier method that can give a utility a quick estimate of the expected increase in life is to use a common calculation for the average stress in a thinwalled

$$\sigma = \frac{pD}{2t}$$

cylinder.

Where:  $\sigma$  = Stress

$p$  = internal pressure

$t$  = thickness of the cylinder

$D$  = internal diameter

Using a pressure of 700 psi. and an inside diameter of 33 3/4", we can calculate the different stress seen by the pipe at the original 2 1/8" thickness and with a 1/2" or 1" overlay added. This results in an original stress of 5.6 ksi. If the thickness is increased to 2 5/8" by addition of a 1/2"

overlay, the resulting stress is 4.5 ksi. This is a reduction in the hoop stress of almost 20 percent and a stress rupture factor of 0.80. The resulting gain in life would be about 6 times (see Figure 2-1). If a one-inch overlay is used, the resulting stress is 3.8 ksi. and a stress rupture factor of .67 which indicates about a 20 times improvement in life. While this method is not as accurate as the closed form solutions method and only supplies average stress, comparable results are achieved.

# 9

## DISCUSSION OF STRESS MEASUREMENT AND FEA RESULTS

There are three types of stresses that are of concern in a piping system: sustained, cyclic, and temporary. Sustained stresses represent those stresses that are considered continuous and include items such as pressure and piping weight. Cyclic stresses are those that arise from thermal expansion or dynamic loading events. Temporary stresses are considered non-continuous and include residual stresses, thermal gradients, etc. Stresses resulting from forming or welding are considered residual or temporary stresses.

ANSI B31.1 does not consider temporary stresses in the calculations for allowable stresses in piping designs. The only stresses considered in piping design are internal pressure stress, external pressure stress, expansion stress, and longitudinal stresses.

How do stresses relate to the yield strength of a material? If sustained stresses are above the yield strength, the material will continue to yield until failure. If cyclic stresses are above yield strength the material will fail by fatigue. If the yield strength of the material is exceeded by a temporary stress, the material will yield until the stresses are relieved; then no further yielding will occur. This is the process that occurs during a normal postweld heat treatment (stress relief) operation. The yield strength of a material decreases with increasing temperature. During the normal stress relief operation, the temperature is raised until the yield strength of the material decreases sufficiently to allow residual stress to decay through yielding.

All piping systems in service are assumed to have met allowable stresses for sustained loads when the system was designed. The addition of a temperbead weld overlay (as described herein) can only reduce these stresses due to the same loads being spread over a larger material cross-sectional area (hence reducing the stress per unit area). Welding can cause only temporary stress. These stresses will only result in strain in the piping system until the stresses are relieved, and then will have no effect on future operation of the piping system. The only time these stresses are of concern is when they are encountered in a material that has a low Fracture Appearance Transition Temperature (FATT). This temperature is the temperature below which fractures occur in a brittle manner. Materials exposed to a high stress below their FATT can have cracks initiated. Materials utilized in high energy piping generally have a low FATT and hence this phenomenon is not a concern. These piping materials will yield plastically until these temporary stresses are below yield. When the piping system is placed in service, the yield strength of the piping material decreases inversely proportionally to the temperature and further stress reduction occurs.

The results of the FEA predicted stresses and those measured using the blindhole drilling technique are described in Sections 6 and 7, respectively. Comparison of the predicted and measured stresses demonstrated good correlation in the “hoop” direction (which is the direction of concern for long seam rupture) near room temperature. Blindhole stress results showed 10ksi (tensile) at room temperature and the FEA projected 14.0ksi tensile stress at 100F. At 990F, only

2.0ksi tensile stresses were projected via FEA since stresses could not be measured using the blindhole technique at this temperature.

**Table 9-1 Comparison of FEA and Blind-hole Stress Results at the Inside Diameter Surface.**

| Comparison of FEA and<br>Blind-hole Residual Stress Results<br>@ ID Surface |                   |            |            |
|-----------------------------------------------------------------------------|-------------------|------------|------------|
|                                                                             | Blind-hole @ 100F | FEA @ 100F | FEA @ 990F |
| Hoop                                                                        | 10.0              | 14.0       | 2.0        |
| Axial                                                                       | 16.8*             | -23.0      | -13.5      |

- Axial value may be result of mockup fixturing &constraint.

As described earlier in this report, residual stresses associated with the weld overlay will be relaxed only through operation. As a result, creep relaxation calculations were considered necessary to determine if the stresses would be relaxed during a reasonable operating period of time. The results proved very encouraging. Even for residual stresses as high as 15 ksi (tensile), it was determined that it would take only a short period, approximately 400 hours (16.7 days) to diminish the stresses to near zero.

The main concern from a design standpoint for seam welds is the “hoop” pressure stresses. From the standpoint of reducing hoop stresses, the weld overlay did achieve its goal of increasing the creep rupture life of the material by a factor greater than 20. Similar increases in life by reductions in crack growth rates are shown in section 12.

# 10

## INVESTIGATION OF OTHER WELD GEOMETRIES

The weld completed in 1999 was 5 3/8" wide with an average height of a little over 1/2". This weld, while providing good life improvement for a damaged seamweld, did not develop compressive hoop stress on the ID of the elbow. The FRAC staff was hoping to develop a more favorable stress field on the ID of the component through the application of the weld overlay even though this benefit would disappear in as little as 400 hours. Full circumferential overlays in stainless piping in the nuclear industry have been shown to produce a compressive stress field on the inside surface of piping. In 2000, an investigation was performed to see if the weld geometry could be altered to change the residual stress field on the inside surface of the pipe. To avoid the cost of a finite element analysis, welding trials and subsequent residual stress measurement were performed on the pipe mockup.

The effect of a wider weld overlay and a thicker weld overlay on ID residual stresses were investigated. The weld previously applied to the elbow was divided into three sections along its 14 foot length. The top 1/3 of the weld had additional weld metal applied to double the width. The resulting weld overlay was about 10 inches wide and a little over 1/2 inch thick. The weld on bottom 1/3 of the pipe retained its width but additional weld metal was deposited to bring the total weld metal thickness to a little over 1".

Blind hole residual stress measurements were then completed to determine the effect of the additional weld metal. Results of this investigation are shown in Figure 10-1. The original data from Section 7 is repeated in this table for clarity. The new information is noted as with additional weld metal. The vertical readings are where the weld was widened and the horizontal location is where the thickness of the overlay was increased

| <b>Elbow Seam Weld Overlay –<br/>Residual Stress Measurement Results (ksi)</b> |       |      |        |       |       |      |
|--------------------------------------------------------------------------------|-------|------|--------|-------|-------|------|
| <i><b>Inside Diameter Measurements</b></i>                                     |       |      |        |       |       |      |
|                                                                                | Left  |      | Center |       | Right |      |
|                                                                                | Axial | Hoop | Axial  | Hoop  | Axial | Hoop |
| Vertical Location                                                              | 16.1  | 10.6 | 13.0   | 14.6  | 12.5  | 14.1 |
| Horizontal Location                                                            | 17.2  | 9.0  | 20.6   | 20.0  | 14.5  | 9.2  |
| Vertical (add. Weld)                                                           | 17.4  | 10.9 | 14.5   | 14.8  | 13.9  | 14.7 |
| Horizontal (add. Weld)                                                         | 18.0  | 11.2 | 19.1   | 17.7  | 15.6  | 12.8 |
| <i><b>Outside Diameter Measurements</b></i>                                    |       |      |        |       |       |      |
|                                                                                | Left  |      | Center |       | Right |      |
|                                                                                | Axial | Hoop | Axial  | Hoop  | Axial | Hoop |
| Vertical Location                                                              | 9.9   | 17.5 | 65.3   | -34.8 | 22.2  | 11.4 |
| Horizontal Location                                                            | 18.8  | 11.6 | 61.5   | -11.3 | 21.5  | 18.8 |
| Vertical (add. Weld)                                                           | 12.3  | 14.5 | 57.2   | -29.0 | 24.1  | 13.6 |
| Horizontal (add. Weld)                                                         | 17.2  | 15.9 | 54.6   | -12.5 | 19.1  | 18.7 |

**Figure 10-1 Residual Stress Measurements following the addition of weld metal to the original mockup**

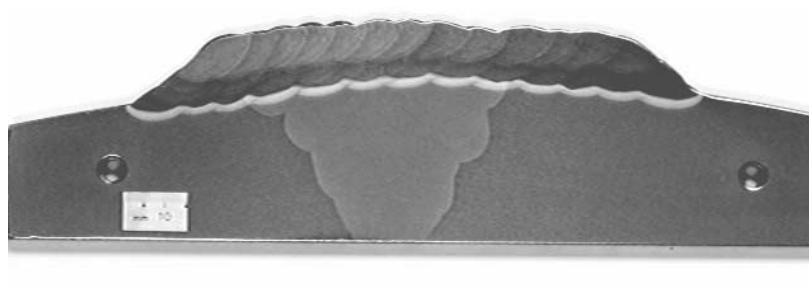
Note: Vertical values indicate weld was widened  
Horizontal values indicate weld was increased in thickness (height)

. No dramatic changes were noted in the stress levels. This was attributed to the relative large thickness of this elbow. Further investigation of residual stresses in more common pipe diameters and thickness is ongoing.

# 11

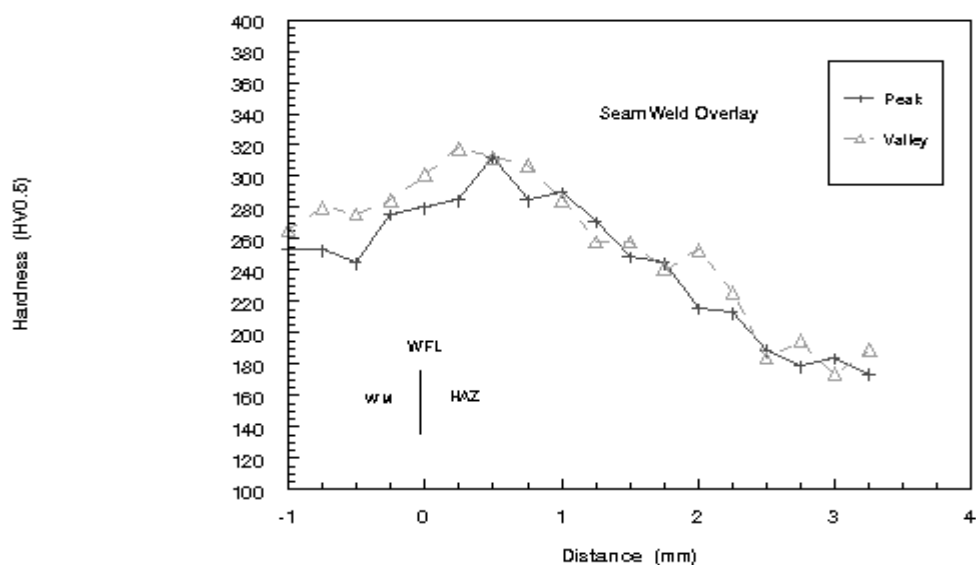
## MECHANICAL TESTING

After welding and residual stress measurements were completed, the elbow was removed from the test stand and sectioned for mechanical testing. Samples were cut and polished for metallurgical evaluation. Figure 11-1 shows a typical cross section of the weld overlay. The original weld can clearly be seen in this figure. No anomalies were seen in the weldmetal or HAZ.



**Figure 11-1 Cross-section of overlay weld showing original longitudinal seam weld.**

Hardness traverses were completed of the weld metal, HAZ and base metal. These results are shown in Figure 11-2. The maximum hardness measured was 318 Hv (32 Rc) in the HAZ. This is typical hardness value for a HAZ resulting from temperbead operations and should provide good service.



**Figure 11-3 Hardness values of overlay**

The weld overlay was to be qualified per ASME guidelines. For this test, four side bend coupons were prepared and bent according to ASME Section IX. All sidebends passed testing. A typical test specimen is shown in Figure 11-4



**Figure 11-4 Typical Side bend**

Coupons were then prepared for tensile and toughness testing. Toughness readings are shown in Table 11-1. The toughness of the weld metal was lower than expected. The previously tested weld metal toughness with this filler indicated toughness readings in the mid twenties (see table 4-3). The weld metal toughness was roughly one half that value. No explanation could be provided for this inconsistency.

Investigation of preheat temperature's effect on weld metal toughness is ongoing. Additional work is also ongoing to find a fillermetal with better toughness in the as welded condition. The HAZ toughness was better than the weld metal or base metal which indicated good tempering and suitability of the welding to temperbead welding procedures

**Table 11-1 Weld Metal, HAZ, and Base Metal Toughness**

| <b>Impact Tests</b> | <b>Average Absorbed Energy (ft-lb)*</b> |
|---------------------|-----------------------------------------|
| All Weld Metal      | 12.3                                    |
| Base Metal          | 13                                      |
| Heat Affected Zone  | 15                                      |

\* Represents average of three tests

The filler metals tested to date were developed to be utilized in conjunction with a PWHT operation. With the increased interest in FCAW temperbead repair operations, Metrode initiated development of a FCAW filler to be used in the as welded condition. Preliminary testing is underway on this new filler metal. Early results on impact strength are shown in Table 11-2

**Table 11-2 Impact strength of new filler metal**

| <b>Impact Tests (ft-lb)</b> | <b>Charpy Impact Value (ft-lb)*</b> | <b>Lateral Expansion (mils)*</b> | <b>% Shear*</b> |
|-----------------------------|-------------------------------------|----------------------------------|-----------------|
| Longitudinal                | 32.5                                | 29.7                             | 30              |
| Transverse                  | 56.2                                | 46.3                             | 48.3            |

\* Represents average of three tests

Further testing is underway to evaluate tensile strength and weldability of this fillermetal. Additionally, the effect of preheat temperature will be evaluated with this fillermetal.



# 12

## CRACK GROWTH CALCULATIONS

For the weld overlay of longitudinal seamed pipe to be a viable repair option that can be utilized when creep damage is found, it must be demonstrated that the repair will hold up in service. The primary question that needs answered is will the reduction of stress via the weld overlay extend the life of the piping system? This is primarily a concern when sub-surface creep damage or flaw indications are detected during inspections. To evaluate the effectiveness of this repair technique, a series of creep crack growth calculations were performed for a wide variety of material properties, flaw sizes, cycling conditions, operating pressure, etc. to determine if a sufficient extension in time to failure could be realized after application of the weld overlay.

Two different methods were utilized to calculate creep crack growth rates. These methods used the  $C(t)$  and  $C^*$  parameters. Discussion of these methods is outside the scope of this project but for more information on these subjects, the reader is directed to Saxena(14), Riedel(15), and Bloom(16).

Calculations were performed for several operating conditions and flaw types. Different cycle times and operating pressures were utilized as well as flaw locations (ID, mid-wall, or OD connected). The results of a sample number of calculations are shown in Table 12-1.

**Table 12-1 Percent Increase in Life versus % Stress Reduction**

| <b>Percent Life Increase Associated with Stress Reduction</b>       |                           |      |      |       |
|---------------------------------------------------------------------|---------------------------|------|------|-------|
| <b>Calculation Conditions</b>                                       | <b>Stress Reduction %</b> |      |      |       |
|                                                                     | 10                        | 20   | 30   | 40    |
| <b>PCPIPE using <math>C(t)</math></b>                               |                           |      |      |       |
| 2 ¼ Cr WM, 1000F, 700psi<br>1000 Hour Cycles, Surface Flaw          | 40%                       | 100% | 190% | 350%  |
| Same except Buried Flaw,                                            | 50%                       | 130% | 260% | 480%  |
| <b>Pc_CRACK using <math>C(t)</math></b>                             |                           |      |      |       |
| 2 ¼ Cr WM, 1000F, 980psi<br>1000 Hour Cycle, Surface Flaw           | 80%                       | 180% | 340% | 580%  |
| Same, but Buried Flaw                                               | 80%                       | 210% | 440% | 800%  |
| <b>Pc_CRACK using <math>C^*</math></b>                              |                           |      |      |       |
| 2 ¼ Cr WM, 1000F, 980psi, 1000 Hour Cycle,<br>Buried Flaw and $C^*$ | 90%                       | 300% | 990% | 2130% |

As discussed earlier in this report, on this application, on a clamshell elbow with an original thickness of 2.125", an overlay of ½" results in a stress reduction of about 20 percent and an overlay of 1" results in a stress reduction of about 35%. The EPRI Boiler Life Evaluation and Simulation System (BLESS) was also utilized to predict life of the repaired elbow. Similar results were found and can be seen in Table 12-2

**Table 12-2. Life Improvement with ½"(24% of wall) Overlay Calculated with BLESS**

| <b>Percent Life Increase Associated with Stress Reduction</b>   |       |
|-----------------------------------------------------------------|-------|
| <b>EPRI BLESS</b>                                               |       |
| 1000F, 700psi, ID connected Flaw, 0.025" deep, 1000 Hour Cycles | >300% |
| 1000F, 700psi, ID connected Flaw, 0.250" deep, 1000 Hour Cycles | 275 % |

Structural Integrity Associates was contracted to perform the crack growth analysis. The information developed by this analysis is presented in more detail in the appendix. Included in this appendix are calculations for different material properties including base material, weld metal, and HAZ evaluated using C(t) and C\* parameters at various applied stresses and flaw locations. Consistently this data indicates substantial life improvement with weld overlay.

While use of C(t) and C\* parameters in Table 12-1 produced different results (as they have since the development of creep crack growth technology), the results show that life increases of several hundred percent or more are possible with the weld overlay technology. This is verified in Table 12-2 with the BLESS software.

Two conclusions can be drawn from the calculations:

- 1.) Independent of the many variables, the percentage increase in life using weld overlays is consistent with the % stress decrease, and
- 2.) Calculations performed using the C(t) creep crack growth parameter (which accounts for first stage creep-stress relaxation) and the C\* creep crack growth parameter (which only includes steady state creep rates) result in favorable values of stress reduction.

In the case of the elbow utilized for the demonstration on the temperbead weld overlay technology, a 25% weld overlay demonstrated a substantial improvement in life. FRAC recommends that crack growth calculations be applied to specific components before this repair technology is utilized to determine if life improvement is sufficient for continued operation. Thus this project has met its goal of providing time for disposition of flawed piping via the temperbead weld overlay technique.

# 13

## CONCLUSIONS

This project successfully demonstrates the ability of weld overlays to extend life of clamshell elbows. Additional analyses of additional filler metals and investigation of results on different pipe geometries is on going. FRAC subscribers requested that we slightly alter the plan for 2000 to develop a “position paper/report” that could be provided to management in the event that creep damage is found. Upon further investigation and in light of the NBIC Rules under RD-1000, subscribers felt that a Code Case was unwarranted. A paper/report was believed to be the more appropriate route at this time. This paper was completed in November of 2000.

To allow weld overlay technology to be utilized immediately in the event that creep damage is found in longitudinal piping, utilities must have procedures qualified. To assist with this and to provide a repair vendor to assist in this type of repair, a common procedure qualification will be performed in conjunction with a welding vendor in 2001. All utilities represented at the demonstration will have a qualified procedure that can be utilized for this type of repair.

The following provides a list of the primary conclusions obtained during this project:

- Maximum measured “hoop” residual stresses (acquired through blindhole drilling technique) correlated quite well with the FEA predictions at 100F. Maximum hoop stresses were measured at 10ksi, while FEA predicted 14.0ksi. At operating temperature (990F), FEA predicted the stresses at 2.0ksi.
- Maximum “axial” stresses predicted by the FEA were highly compressive at 100F (-23.0ksi) and at 990F (-13.5ksi). Blindhole measurements showed the stresses to be tensile at 16.8ksi at 100 °F.
- Temperbead welding parameters were demonstrated using two FCAW techniques including stringer and “limited” weave approaches. The latter technique was employed for the weld overlay mockup performed in this study.
- Acceptable weld metal and heat affected zone properties were achieved using the “limited” weave temperbead technique employed in this study as confirmed by bends, tensiles, Charpy impacts, and metallography.
- The entire weld overlay required only 33 pounds of deposited filler. In a plant application, a weld overlay of this magnitude would not require re-calculation of hanger stress loads.
- Residual stresses caused by the welding appear to be insignificant at operating temperature as

determined by creep relaxation calculations and should relax out over a reasonable short time (<1000 hrs). Primary stresses are addressed by the addition of the weld overlay.

- Creep rupture life of the existing clamshell weld was improved by a factor of greater than 20 by applying the weld overlay.
- FCAW fillers are being developed that exhibit good properties in the non-PWHT as deposited condition. Impact strength in the as welded condition is very good. Other testing of this filler is ongoing.
- Average stress calculations can be performed by a utility to estimate required thickness of weld overlay required for expected service
- A weld overlay equal to as little as 25% of the original elbow thickness would substantially increase the life of the elbow.

# 14

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# APPENDIX

## 1.0 Introduction

As part of the ongoing FRAC Project “The Use of Weld Overlays to Extend the Useful Life of High Energy Piping in Fossil Power Plants”, creep crack growth calculations were performed to estimate the reduction of crack growth resulting from lower stress levels in the seam weld. These calculations were performed for a variety of material properties, flaw sizes and locations and unit cycling parameters. The calculations were performed using two SI programs, PCPIPE and pc-CRACK. PCPIPE was developed by Dr. Ashok Saxena of Georgia Institute of Technology and SI is licensed to sell it to utility engineers. PCPIPE uses the Ct parameter for crack growth, which is the most conservative of the parameters used to estimate crack growth. pc-CRACK also uses the C(t) and C\* parameters, which are not as conservative.

Materials properties used in the analysis are listed in Table 1.

**Table A-1. Materials Properties Used in the Analyses.**

| Material  | YS   | Plasticity Exponent | Creep Exponent | Creep Constant<br>PCPIPE | Creep Constant<br>pc-CRACK | Plasticity Constant<br>PCPIPE | Plasticity Constant<br>pc-Crack | CCG Exponent | CCG Coefficient |
|-----------|------|---------------------|----------------|--------------------------|----------------------------|-------------------------------|---------------------------------|--------------|-----------------|
| 2 1/4 BM  | 22.5 |                     | 7.79           | 3.78E-16                 | 0.13                       | 7.90E-13                      | 1.937                           | 0.805        | 9.40E-02        |
|           |      | 5.4                 |                |                          |                            |                               |                                 |              |                 |
| 1 1/4 BM  | 19   |                     | 10.1           | 4.22E-16                 | 4.296                      | 2.82E-10                      | 0.28                            | 0.805        | 9.40E-02        |
|           |      | 5.4                 |                |                          |                            |                               |                                 |              |                 |
| 2 1/4 WM  | 19.8 |                     | 9.36           | 1.59E-15                 | 2.586                      | 5.25E-11                      | 2.264                           | 0.674        | 0.131           |
|           |      | 5.83                |                |                          |                            |                               |                                 |              |                 |
| 2 1/4 HAZ | 22.5 |                     | 9.9            | 1.39E-16                 | 3.536                      | 7.90E-13                      | 1.937                           | 0.546        | 0.123           |
|           |      | 6.93                |                |                          |                            |                               |                                 |              |                 |
| 1 1/4 WM  | 19   |                     | 8              | 2.20E-13                 | 4.621                      | 2.82E-10                      | 2.804                           | 0.805        | 9.40E-02        |
|           |      | 5.4                 |                |                          |                            |                               |                                 |              |                 |
| deted     | 22.6 |                     | 9.9            | 1.41E-16                 | 3.536                      | 7.90E-13                      | 1.937                           | 0.809        | 0.221           |
|           |      | 6.93                |                |                          |                            |                               |                                 |              |                 |

These are for 2 ¼ Cr – 1 Mo and 1 ¼ Cr – ½ Mo steels for Base Metal (BM), Weld Metal (WM) and Heat Affected Zones (HAZ).

Flaw sizes ranging from 0.025” deep to 0.25” deep in 0.025” increments were used as initial sizes in the pipe and infinitely long axial flaws were used for comparison basis. Both surface flaws and buried flaws were considered.

Unit on/off cycling times of 1000 hours (roughly 8 starts/year) were use for the base calculations. Comparisons were made with 2000 hours (base load), 500 hours and 100 hours (up and down more than once per week).

## 2.0 Calculations

The first set of calculations performed was for a 38" diameter, 2.125" thick pipe which is identical to the one used in the weld overlay trials. PCPIPE was used for calculating creep crack growth. An operating temperature of 1000F and a pressure of 700psi were used for operating conditions. The flaw was a surface flaw and the material properties were for 2 ¼ Cr – 1 Mo weld metal. The calculation results are shown in Table 2. Lowering operating pressure reduced stresses by 10% increments.

**Table A-2. Remaining Lives as a Function of Flaw size and Pressure (Stress).**

| Flaw<br>Depth |        |        |          |         |         |
|---------------|--------|--------|----------|---------|---------|
|               |        |        | Pressure |         |         |
| 0             | 700    | 630    | 560      | 490     | 420     |
| 0.025         | 37,000 | 53,000 | 75,000   | 110,000 | 168,000 |
| 0.05          | 31,000 | 44,000 | 62,000   | 91,000  | 140,000 |
| 0.075         | 26,000 | 37,000 | 54,000   | 79,000  | 120,000 |
| 0.1           | 23,000 | 33,000 | 46,000   | 68,000  | 105,000 |
| 0.125         | 21,000 | 29,000 | 41,000   | 61,000  | 93,000  |
| 0.15          | 18,000 | 26,000 | 36,000   | 53,000  | 82,000  |
| 0.175         | 16,000 | 23,000 | 32,000   | 48,000  | 74,000  |
| 0.2           | 15,000 | 21,000 | 29,000   | 43,000  | 66,000  |
| 0.225         | 13,000 | 18,000 | 26,000   | 38,000  | 59,000  |
| 0.25          | 12,000 | 16,000 | 24,000   | 33,000  | 53,000  |

These data show that considerable increase in remaining lives of cracked steamlines can be achieved by overlay welding. Next, the ratio of remaining lives were calculated for the data (life at reduced pressure (stress)/life at normal pressure). This approach was used to simplify the stress reduction/life improvement algorithms. There is so much variation in the life of a defect in a weld (material properties, flaw size, surface/buried, etc., that it is not the actual remaining life of the component that is important (to this project), but how the use of weld overlays improves that life. The data are presented in Table 3.

**Table A-3. Life Ratios (Reduced Stress/Normal Stress) from Table 2.**

| Flaw<br>Depth | Stress Reduction, % |     |     |     |
|---------------|---------------------|-----|-----|-----|
|               |                     |     |     |     |
| 0             | 10                  | 20  | 30  | 40  |
| 0.025         | 1.4                 | 2.0 | 3.0 | 4.5 |
| 0.05          | 1.4                 | 2.0 | 2.9 | 4.5 |
| 0.075         | 1.4                 | 2.1 | 2.7 | 4.6 |
| 0.1           | 1.4                 | 2.0 | 3.0 | 4.6 |
| 0.125         | 1.4                 | 2.0 | 2.9 | 4.4 |
| 0.15          | 1.4                 | 2.0 | 3.0 | 4.6 |
| 0.175         | 1.4                 | 2.0 | 3.0 | 4.6 |
| 0.2           | 1.4                 | 1.9 | 2.9 | 4.4 |
| 0.225         | 1.4                 | 2.0 | 2.9 | 4.5 |
| 0.25          | 1.3                 | 2.0 | 2.8 | 4.4 |
|               |                     |     |     |     |
|               | 1.4                 | 2.0 | 2.9 | 4.5 |

The data shows remarkable consistency. Independent of flaw size, a 10, 20 30, or 40% stress reduction produces 40, 100, 200 or 350% increase in life. Even though site specific calculations will probably be required when electing to use a weld overlay (the EPRI BLESS Code would be available to EPRI members for that task), one can easily state their desired life improvement and closely calculate the amount of weld metal required to accomplish that goal. The reason for the remarkable consistency is that the only two variables are stress and flaw size for estimating the potential improvement in life using weld overlays.

The pressure of 700 psi did not stress the pipe near the allowable stress of 7.8 ksi for P22 material at 1000F. Another series of calculations was run at an initial pressure of 980 psi, reduced in 10% increments with all other variables remaining the same. Results are show in Table 4.

**Table A-4. Life Ratios for an Increased Original Stress (7.8ksi)**

| Flaw  |                     |     |     |      |
|-------|---------------------|-----|-----|------|
| Depth | Stress Reduction, % |     |     |      |
|       |                     |     |     |      |
| 0     | 10                  | 20  | 30  | 40   |
| 0.025 | 1.6                 | 2.6 | 4.1 | 6.8  |
| 0.05  | 1.6                 | 2.6 | 4.4 | 7.1  |
| 0.075 | 1.6                 | 2.6 | 4.1 | 7.0  |
| 0.1   | 1.7                 | 2.7 | 4.3 | 7.2  |
| 0.125 | 1.6                 | 2.8 | 4.6 | 7.4  |
| 0.15  | 1.8                 | 3.0 | 5.0 | 8.3  |
| 0.175 | 1.5                 | 2.8 | 4.5 | 7.3  |
| 0.2   | 2.0                 | 3.3 | 5.3 | 9.0  |
| 0.225 | 1.7                 | 3.0 | 4.7 | 8.0  |
| 0.25  | 2.0                 | 4.0 | 6.5 | 10.5 |
|       |                     |     |     |      |
|       | 1.7                 | 2.9 | 4.8 | 7.8  |

Next, a buried flaw was considered. The operating pressure was returned to 700 psi. Every thing else was as the original runs. While the actual remaining lives were much longer, the ratios remained nearly the same, as shown in Table 5.

**Table A-5. Life Ratios for Buried Flaws, 700 psi.**

| Flaw  |                     |     |     |     |
|-------|---------------------|-----|-----|-----|
| Depth | Stress Reduction, % |     |     |     |
|       |                     |     |     |     |
| 0     | 10                  | 20  | 30  | 40  |
| 0.025 | 1.5                 | 2.2 | 3.4 | 5.4 |
| 0.05  | 1.5                 | 2.2 | 3.4 | 5.4 |
| 0.075 | 1.5                 | 2.3 | 3.5 | 5.6 |
| 0.1   | 1.5                 | 2.3 | 3.6 | 5.7 |
| 0.125 | 1.6                 | 2.3 | 3.6 | 5.8 |
| 0.15  | 1.6                 | 2.4 | 3.7 | 5.9 |
| 0.175 | 1.5                 | 2.2 | 3.6 | 5.8 |
| 0.2   | 1.5                 | 2.4 | 3.8 | 6.1 |
| 0.225 | 1.5                 | 2.3 | 3.7 | 6.0 |
| 0.25  | 1.5                 | 2.4 | 3.8 | 6.2 |
|       |                     |     |     |     |
|       | 1.5                 | 2.3 | 3.6 | 5.8 |

Next, the same calculations were made for 2 ¼ Cr – 1 Mo HAZ material properties. The results are shown in Table 6.

**Table A-6. Life Ratios for HAZ Properties, 700 psi.**

|       |     |                    |     |     |
|-------|-----|--------------------|-----|-----|
| Flaw  |     |                    |     |     |
| Depth |     | Stress Reduction % |     |     |
|       |     |                    |     |     |
| 0     | 10  | 20                 | 30  | 40  |
| 0.025 | 1.3 | 1.8                | 2.4 | 3.4 |
| 0.05  | 1.4 | 1.8                | 2.4 | 3.4 |
| 0.075 | 1.3 | 1.7                | 2.4 | 3.4 |
| 0.1   | 1.3 | 1.8                | 2.5 | 3.7 |
| 0.125 | 1.4 | 2.0                | 2.8 | 4.0 |
|       |     |                    |     |     |
|       | 1.3 | 1.8                | 2.5 | 3.6 |
|       |     |                    |     |     |
|       |     |                    |     |     |
| Flaw  |     |                    |     |     |
| Depth |     | Stress Reduction % |     |     |
|       |     |                    |     |     |
| 0     | 10  | 20                 | 30  | 40  |
| 0.025 | 1.3 | 1.8                | 2.5 | 3.5 |
| 0.05  | 1.3 | 1.7                | 2.6 | 3.5 |
| 0.075 | 1.3 | 1.8                | 2.5 | 3.5 |
| 0.1   | 1.3 | 1.8                | 2.5 | 3.6 |
| 0.125 | 1.4 | 1.8                | 2.5 | 3.6 |
|       |     |                    |     |     |
|       | 1.3 | 1.8                | 2.5 | 3.5 |

The upper group of numbers is for a surface flaw and the lower group is for buried flaws. Note that the average life ratios are again fairly consistent. Since PCPIPE only measures life in 1000 hour increments when that is entered as the cycling time and since we are dealing with very short lives for HAZ properties, more scatter would be expected in the data. The short lives are the reason for only looking at flaws 0.125" deep and less, as larger flaws have lives less than 5000 hours.

Finally, for PCPIPE calculations, the effects of cycling times were investigated. Using the Ct parameter, the most damage is accumulated with short cycle times. Weld metal properties and 100 hour cycling times were combined with 700 psi and 1000F operation to generate the data presented in Table 7.

**Table A-7. Life Ratios for 100 Hour Cycles, 700 psi.**

| Flaw  |     |     |                  |     |
|-------|-----|-----|------------------|-----|
| Depth |     |     | Stress Reduction |     |
|       |     |     |                  |     |
| 0     | 10  | 20  | 30               | 40  |
| 0.025 | 1.4 | 2.0 | 3.0              | 4.7 |
| 0.050 | 1.4 | 2.1 | 3.0              | 4.8 |
| 0.075 | 1.4 | 2.1 | 3.2              | 5.0 |
| 0.100 | 1.4 | 2.1 | 3.2              | 5.0 |
| 0.125 | 1.5 | 2.2 | 3.3              | 5.3 |
| 0.150 | 1.5 | 2.3 | 3.4              | 5.5 |
| 0.175 | 1.5 | 2.3 | 3.6              | 5.7 |
| 0.200 | 1.5 | 2.4 | 3.7              | 5.9 |
| 0.225 | 1.6 | 2.5 | 4.0              | 6.4 |
| 0.250 | 1.6 | 2.6 | 4.4              | 6.7 |
|       |     |     |                  |     |
|       | 1.5 | 2.3 | 3.5              | 5.5 |

The next set of calculations was made using pc-CRACK. The first calculations were for a surface flaw at 7.8 ksi stress, weld metal data and 1000 hour cycles. Table 8 shows the results of these calculations.

**Table A-8. Life Ratios for pc-CRACK Calculations as Noted Above.**

| Flaw  |     |                     |     |     |
|-------|-----|---------------------|-----|-----|
| Depth |     | Stress Reduction, % |     |     |
|       |     |                     |     |     |
| 0     | 10  | 20                  | 30  | 40  |
| 0.025 | 1.6 | 2.7                 | 4.6 | 8.6 |
| 0.05  | 1.4 | 2.4                 | 3.4 | 5.2 |
| 0.075 | 2.0 | 3.0                 | 4.5 | 6.5 |
| 0.1   | 1.5 | 2.5                 | 4.0 | 6.0 |
| 0.125 | 1.6 | 2.5                 | 3.7 | 5.0 |
| 0.15  | 2.7 | 4.0                 | 6.0 | 9.0 |
| 0.175 | 2.0 | 3.6                 | 5.0 | 8.0 |
| 0.2   | 2.0 | 3.0                 | 5.0 | 7.0 |
| 0.225 | 1.8 | 2.7                 | 4.0 | 6.7 |
| 0.25  | 1.0 | 2.0                 | 3.9 | 6.0 |
|       |     |                     |     |     |
|       | 1.8 | 2.8                 | 4.4 | 6.8 |

The next set of results were repeated using the same conditions, but for a buried flaw. The data is presented in Table 9.

**Table A-9. pc-CRACK Results for Buried Flaw.**

| Flaw<br>Depth | Stress Reduction, % |     |     |      |
|---------------|---------------------|-----|-----|------|
|               |                     |     |     |      |
| 0             | 10                  | 20  | 30  | 40   |
| 0.025         | 1.8                 | 3.2 | 5.5 | 10.0 |
| 0.05          | 2.0                 | 3.1 | 5.3 | 8.1  |
| 0.075         | 1.8                 | 2.8 | 4.6 | 7.5  |
| 0.1           | 1.7                 | 2.9 | 5.0 | 7.9  |
| 0.125         | 1.6                 | 3.2 | 5.3 | 8.7  |
| 0.15          | 1.7                 | 3.0 | 5.0 | 8.2  |
| 0.175         | 1.8                 | 3.0 | 5.2 | 8.7  |
| 0.2           | 2.0                 | 3.8 | 6.5 | 11.3 |
| 0.225         | 2.0                 | 3.5 | 6.0 | 10.3 |
| 0.25          | 1.9                 | 3.0 | 5.5 | 9.0  |
|               |                     |     |     |      |
|               | 1.8                 | 3.1 | 5.4 | 9.0  |

These results follow the same pattern as the others. Next, calculations for a buried flaw were performed using the C\* parameter for buried flaws. Since C\* only uses the steady state portion of the creep curve, cycling time is not a factor. The results of C\* calculations are shown in Table 10.

**Table A-10. C\* Results for Buried Flaw.**

| Flaw<br>Depth | Stress Reduction % |     |     |      |
|---------------|--------------------|-----|-----|------|
|               |                    |     |     |      |
| 0             | 10                 | 20  | 30  | 40   |
| 0.025         | 1.9                | 3.9 | 8.9 | 22.1 |
| 0.05          | 1.9                | 3.9 | 8.8 | 22.0 |
| 0.075         | 1.9                | 4.0 | 8.8 | 22.2 |
| 0.1           | 1.9                | 3.9 | 8.8 | 21.6 |
| 0.125         | 1.9                | 3.9 | 8.8 | 21.9 |
| 0.15          | 1.9                | 4.0 | 8.9 | 22.1 |
| 0.175         | 2.0                | 4.1 | 8.9 | 22.5 |
| 0.2           | 2.0                | 4.0 | 9.1 | 22.7 |
| 0.225         | 2.0                | 4.1 | 9.1 | 22.9 |
| 0.25          | 2.0                | 4.0 | 9.2 | 23.3 |
|               |                    |     |     |      |
|               | 1.9                | 4.0 | 8.9 | 22.3 |

While the results are very consistent, the life ratio increase is much higher than for using Ct. Next, C(t) calculations were run for the same conditions and the results are shown in Table 11.

**Table A-11. C(t) Calculation Results for a Buried Flaw, 100 Hour Cycles.**

| Flaw  |     |                    |     |     |
|-------|-----|--------------------|-----|-----|
| Depth |     | Stress Reduction % |     |     |
|       |     |                    |     |     |
| 0     | 10  | 20                 | 30  | 40  |
| 0.025 | 1.7 | 2.4                | 3.3 | 4.4 |
| 0.05  | 1.7 | 2.3                | 3.3 | 4.4 |
| 0.075 | 1.7 | 2.5                | 3.6 | 4.8 |
| 0.1   | 1.8 | 2.7                | 3.8 | 5.2 |
| 0.125 | 1.9 | 3.0                | 4.3 | 5.8 |
|       |     |                    |     |     |
|       | 1.7 | 2.6                | 3.7 | 4.9 |

The C(t) calculation results are much the same as the Ct results, i.e., showing the same relative life increases.

Finally, C\* calculations were run for an axial surface flaw, weld metal properties and high stresses. The results are shown in Table 12.

**Table A-12. C\* Results for Axial Surface Flaw.**

| Flaw  |     |                    |     |      |
|-------|-----|--------------------|-----|------|
| Depth |     | Stress Reduction % |     |      |
|       |     |                    |     |      |
| 0     | 10  | 20                 | 30  | 40   |
| 0.1   | 1.9 | 3.9                | 8.3 | 20.8 |
| 0.125 | 1.9 | 3.7                | 8.3 | 20.9 |
| 0.15  | 1.9 | 3.8                | 8.4 | 21.0 |
| 0.175 | 1.9 | 3.8                | 8.5 | 21.1 |
| 0.2   | 1.9 | 3.8                | 8.4 | 21.1 |
| 0.225 | 1.9 | 3.9                | 8.4 | 20.9 |
| 0.25  | 1.9 | 3.8                | 8.4 | 21.0 |
|       |     |                    |     |      |
|       | 1.9 | 3.8                | 8.4 | 21.0 |

As can be seen these are very similar to the C\* calculations shown in Table 10, with much higher life ratios than the Ct or C(t) parameters.

### 3.0 Summary of Results

The Life Ratios for all of the various sets of calculations are summarized in Table 13.

**Table A-13. Percent Increase in Life Versus Stress Reduction Data for All Calculations.**

| Calculation Conditions                                             | Stress Reduction % |      |      |       |
|--------------------------------------------------------------------|--------------------|------|------|-------|
|                                                                    | 10                 | 20   | 30   | 40    |
| PCPIPE, 2 ¼ Cr WM, 1000F, 700psi<br>1000 Hour Cycles, Surface Flaw | 40%                | 100% | 190% | 350%  |
| Same, but Pressure = 980psi                                        | 70%                | 190% | 380% | 680%  |
| Buried Flaw, 700psi                                                | 50%                | 130% | 260% | 480%  |
| Same, but 2 ¼ Cr HAZ                                               | 30%                | 80%  | 150% | 250%  |
| PCPIPE, 2 ¼ Cr WM, 100 Hour Cycles                                 | 50%                | 130% | 250% | 450%  |
| Pc_CRACK, Ct, 980psi, 2 ¼ Cr WM, 1000<br>Hour Cycle, Surface Flaw  | 80%                | 180% | 340% | 580%  |
| Same, but Buried Flaw                                              | 80%                | 210% | 440% | 800%  |
| Same, but Buried Flaw and C*                                       | 90%                | 300% | 990% | 2130% |
| Buried Flaw, C(t)                                                  | 70%                | 160% | 270% | 390%  |
| C*, Axial Surface Flaw, 980psi, HAZ<br>Properties                  | 90%                | 280% | 740% | 2000% |

## 4.0 Discussion

The most influencing parameter regarding the increase in life versus overlay weld stress reduction is whether C\* (the steady state creep parameter) or Ct/C(t) (creep parameters which consider first stage creep) are used for the calculations. If the user selects C(t) or C\* (available in SI programs) a 50 – 60% increase in life can be gained with a 10% stress reduction, 100 – 200% increase with a 20% stress reduction ,etc.

Should the user select the EPRI BLESS Code , which contains the C\* parameter, larger gains will be realized





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