Materials Reliability Program: Evaluation of the Capabilities and Limitations of Existing Technologies for Mitigation of PWSCC (MRP-122)

Technical Report

Materials Reliability Program: Evaluation of the Capabilities and Limitations of Existing Technologies for Mitigation of PWSCC (MRP-122)

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PRODUCT DESCRIPTION

The EPRI Pressurized Water Reactor (PWR) Materials Reliability Program (MRP), specifically the Mitigation Working Group of the Alloy 600 Issue Task Group (ITG), has initiated an effort to evaluate the potential of emerging and available mitigation techniques as remedial measures to primary water stress corrosion cracking (PWSCC). The measures to be identified include the mechanical, non-environmental methods that have been previously developed as mitigation measures for intergranular stress corrosion cracking (IGSCC) in boiling water reactors (BWRs). This effort is focused on the stress remedies (such as heat-sink welding or mechanical stress-improvement process (MSIP), corrosion-resistant cladding, weld overlay, and induction heating stress improvement), as well as potential emerging technologies that can be applied to existing installed components.

This task evaluated the capabilities and limitations of existing remedial "mechanical" technologies that address PWSCC of nickel-based alloys and will document findings in a stand-alone report. The following two technologies were evaluated: induction heating stress improvement (IHSI) and weld overlay repair technology (weld overlay stress improvement is considered a subset of weld overlay technology).

Results and Findings

The report reviewed and documented the technical basis, process information, qualifications and inspection experience, and requirements for IHSI in BWR applications and produced the following results:

- IHSI is a viable process for mitigating unfavorable residual stresses in PWR piping components. The process requires specific qualification for the piping sizes and thicknesses attendant to PWR applications.
- The report reviewed and documented the technical basis, process information, qualifications and inspection experience, and requirements for weld overlay in BWR applications, resulting in the following conclusion:
    - Weld overlay is a viable process for mitigating unfavorable residual stresses in PWR. Overlays that are applied for mitigation or to prevent any potential leakage from axial defects would be thin, requiring only two or three layers. Given the nature of the weld application process, the overlay and weldment should be capable of being inspected by ultrasonic testing (UT) with minimal surface preparation, if any. Weld overlay not only improves the residual stress distribution but also provides a corrosion barrier of material selected to be resistant to PWSCC. The process would require qualification

for PWR applications and approval from the Nuclear Regulatory Commission (NRC) until the code cases, currently being pursued, are issued and approved.

– Weld overlay for stress improvement is a viable process for mitigating unfavorable residual stresses in PWR piping components. The weld overlay would be designed and located to minimize interference with UT of the weldment. Inspection of the overlay should be minimal because the overlay is non-structural. Future in-service inspection credit for the stress-improvement overlay would have to be established with the American Society of Mechanical Engineers (ASME) Code and subsequently endorsed by the NRC.

Challenges and Objectives

This report is of value to technical and management personnel tasked with finding solutions and evaluating costs for mitigating components susceptible to PWSCC. There are no apparent challenges to the application of these processes.

Applications, Values, and Use

The report provides information to aid an owner in evaluating mitigation in lieu of costly repair and replacements of components subject to PWSCC.

EPRI Perspective

The report contains technical information for EPRI members that would not be available to the general public given its proprietary nature from an economic perspective.

Approach

The goals of the report were to review existing technologies and determine if they were viable for PWR applications for mitigating PWSCC. Those goals were met by the results and information included in the report.

Keywords

Induction heating stress improvement
IHSI
Weld overlay
Mitigation
PWSCC
Primary water stress corrosion cracking

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1 INTRODUCTION

An issue has developed in the pressurized water reactor (PWR) industry involving primary water stress corrosion cracking (PWSCC) of Alloy 600 and its weld metals. This issue has manifest itself in PWSCC of upper and lower reactor pressure vessel head penetrations, large-diameter reactor coolant system piping, some lower head pressurizer penetrations, and in other components. The current measures initiated to address these issues have generally involved the repair of the components. There is an increasing need, however, to complement this repair technology. Implementation of remedial measures are needed for non-defective (as well as potentially defective) components to improve their resistance to PWSCC, thereby extending the reliable, useful life of the components.

To this end, within the EPRI PWR Materials Reliability Program (MRP), the Mitigation Working Group of the Alloy 600 Issue Task Group (ITG) has initiated an effort to evaluate the potential of emerging and available mitigation techniques as remedial measures to PWSCC. The measures to be identified include the mechanical, non-environmental methods that have been previously developed as mitigation measures for intergranular stress corrosion cracking (IGSCC) in boiling water reactors (BWRs). This effort is focused on the stress remedies (such as heat-sink welding or mechanical stress improvement process [MSIP[1]], corrosion-resistant cladding weld overlay, and induction heating stress improvement), as well as potential emerging technologies that can be applied to existing installed components.

This task will evaluate the capabilities and limitations of existing remedial "mechanical" technologies that address PWSCC of nickel-based alloys and will document findings in a stand-alone report. The following technologies will be evaluated:

- Induction heating stress improvement
- Weld overlay repair technology

Weld stress improvement is considered a subset of weld overlay technology.

[1] MSIP is a trademark of AEA Technology Engineering Services, Inc.

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BACKGROUND

2.1 Induction Heating Stress Improvement

Induction heating stress improvement (IHSI) is perhaps the most widely applied stress remedy in BWR piping applications. IHSI was first studied as a residual stress mitigation technique for Type 304 stainless steel piping intergranular stress corrosion cracking (IGSCC) in Japan in the mid-1970s and was applied to plants in that country in the late 1970s. The process is shown schematically in Figure 2-1, taken from a paper called “An Update on IHSI” [1]. The technology was carefully examined by EPRI in 1978 prior to use in the United States. Since completion of the initial EPRI program, the practical application of IHSI to new weldment configurations, new materials, and different cooling water flow conditions was studied by Ishikawajima-Harima Heavy Industries Company (IHI), NUTECH, GE, Hitachi, and others. Subsequent studies by EPRI and Japan examined weldments of different sizes, geometric complexity, and material types. These studies utilized different residual stress measurement techniques, addressed the sensitivity of residual stress results to varying process control parameters, and investigated the effects of operating temperatures and cyclically applied stresses on long-term effectiveness of the process. Figure 2-2 shows the process-control parameters for implementing IHSI.

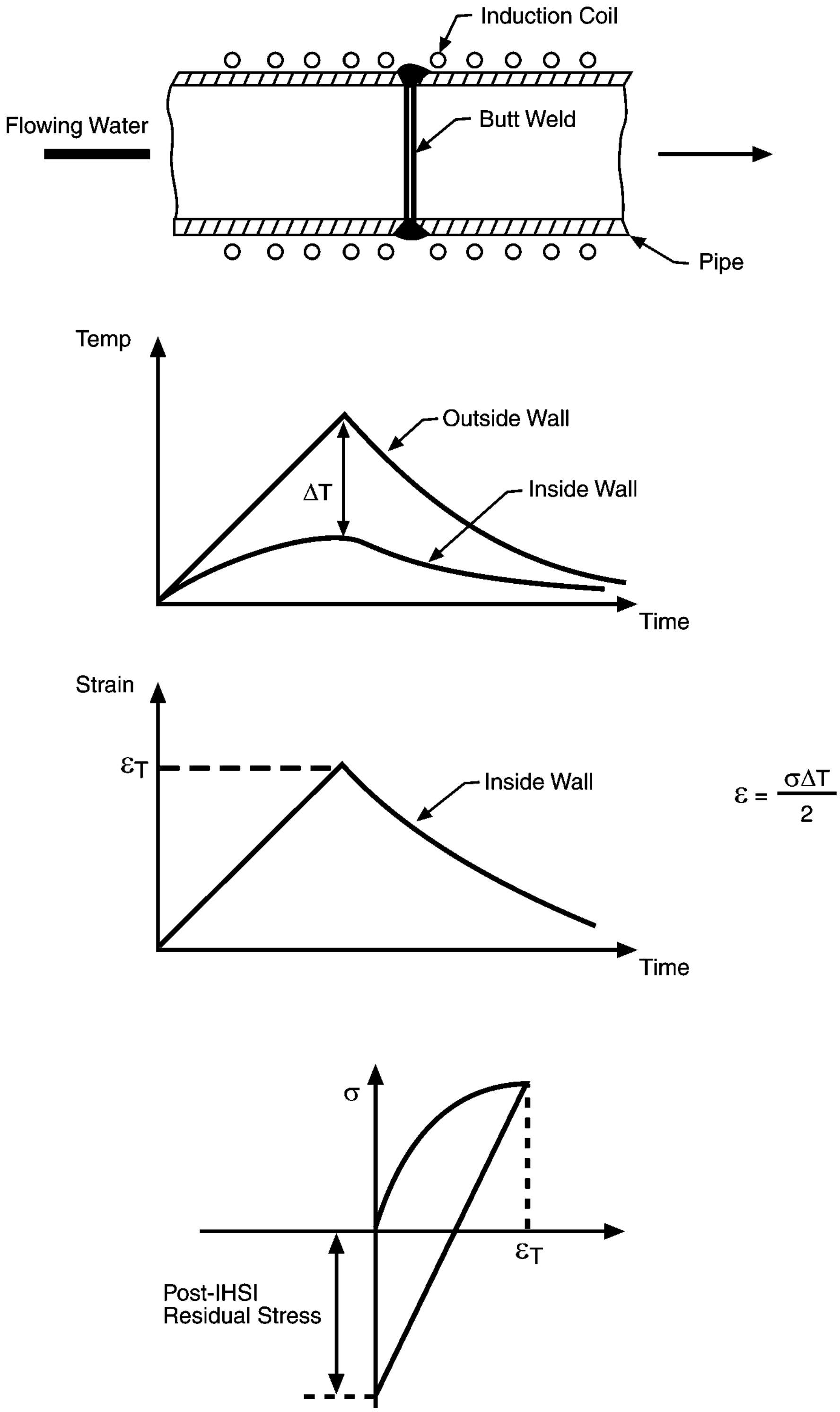
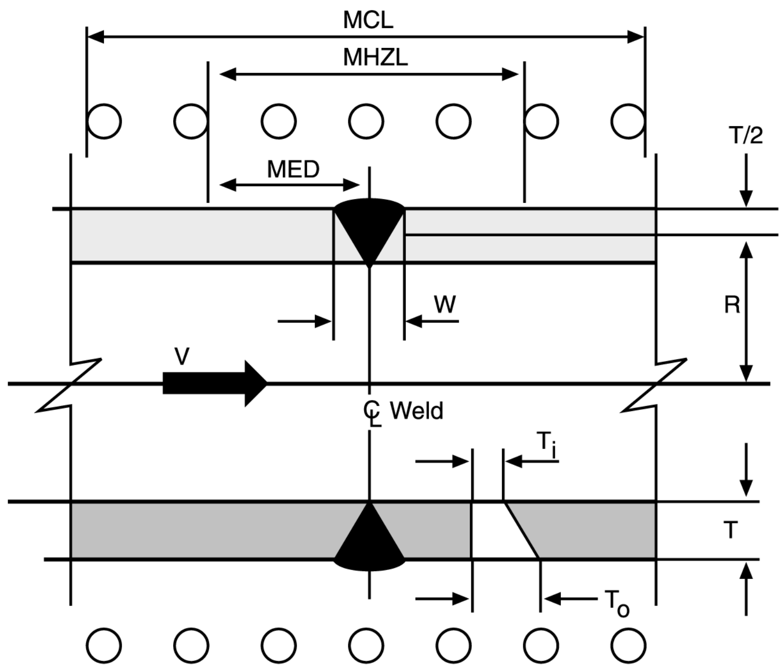


Figure 2-1
Schematic Illustration of the IHSI Process



T_o = Maximum Allowable Outside Pipe Surface Temperature ≤ 575°C	MCL = Minimum Coil Length = 3.0 √ RT	W = Weld Width
ΔT = Through-wall Temperature Differential = $T_o - T_i \geq$ 275°C	MHZL = Minimum Heating Zone Length = 1.5 √ RT	T_i = Temperature at Inside Surface
t = Minimum Heating Duration ≥ $0.7T^2 / \propto$	MED = Minimum Edge Distance ≥ Greatest of 0.6" or T/2 or W/2 + 1/8"	R = Nominal Radius of Pipe
∝ = Coefficient of Thermal Diffusivity	Ω = Power Supply Frequency Range = 3 to 4 KHz	V = Average Cooling Water ≥ 2 ft/sec

Figure 2-2
Summary of EPRI IHSI Process-Control Parameters

The principle for achieving compressive inner surface residual stress is to create a thermal gradient across the pipe wall thickness by heating the external pipe surface while flowing cold water through the inside of the pipe. Induction heating techniques were used for heating by making use of specially designed induction coils. The process variables and controls are relatively mature. The process has been shown to be an effective stress remedy for both large- and small-diameter piping. Coil designs are available for both straight pipe welds and fittings. The principle drawback to the process is the difficulty in ensuring that the desired thermal gradients have been established. The reason is that the defined thermal gradient across the pipe wall must exist completely around the pipe circumference.

Four different contractors have applied IHSI to approximately 4,000 IGSCC-susceptible weldments in more than 45 plants worldwide. Piping treatment included straightforward (generally axisymmetric without radical contour changes) weldment configurations and weldments having complex geometries and various interferences. As with most activities in an operating nuclear containment structure, the production rates associated with these projects were affected by adverse environmental conditions, which can greatly affect craft support labor productivity. In spite of these challenges, productivity rates rose due to improved engineering capabilities, better equipment, and more refined procedures.

The process has been shown to be effective and efficient. The U.S. Nuclear Regulatory Commission (NRC) recognized this in NUREG 313, Rev. 2 [2], by reducing the re-inspection frequency for weldments that had received an IHSI treatment.

2.2 Weld Overlays

Weld overlays are used as a standard repair option for IGSCC in BWR piping and are recognized as an effective IGSCC mitigation technique by the NRC in Generic Letter 88-01 [3] and NUREG-313, Rev. 2 [2].

Weld overlays were first applied in 1982 as a repair for IGSCC in stainless steel piping. The purpose of repairs of this type was to provide a new pressure boundary, essentially replacing the defected component in the area of the defect. The weld overlay repair technique for IGSCC flawed pipe welds is based upon application of weld metal to the outside pipe surface over and to either side of the flawed location, extending 360° circumferentially around the pipe. Although these repairs were accepted by the NRC as an effective IGSCC remedy, the initial regulatory position only recognized weld overlays as interim repair measures. Utilities were allowed to operate with weld overlay repairs so that they could develop and adequately plan for replacement.

Since the application of the first overlays, significant field, analytical, and experimental evidence has been assembled to demonstrate that weld overlays are effective long-term repairs. The technical basis includes:

- Weld metals typically used for weld overlay applications are inherently resistant to IGSCC [4–8].
- Weld overlay applied to a flawed component introduces a favorable compressive residual stress field [9–11].
- Advances in ultrasonic examination technology facilitated volumetric inspection of the weld overlay repaired components [12].
- Experimental work demonstrated the strength of weld overlays [13,14].

3
DISCUSSION

3.1 Induction Heating Stress Improvement

3.1.1 IHSI Qualification Programs

3.1.1.1 Japanese Qualification Program

The details of the Japanese qualification program are provided in the document prepared by IHI [15]. The Japanese program studied the effectiveness of IHSI on Type 304 stainless steel weldments in 4-inch (10.16-cm), 10-inch (25.4-cm), 12-inch (30.48-cm), 14-inch (35.56-cm), and 24-inch (60.96-cm) pipe sizes. These weldments included pipe-to-pipe, pipe-to-elbow, and pipe-to-forging (radical contour change) configurations. This program addressed the effect of heating duration, power frequency, and cooling water velocity versus through-wall residual stress distribution; through-wall temperature differential, coil length, and coil position versus inner surface residual stress; heating zone and coil length versus inner surface axial residual stress distribution; and maximum outside pipe surface temperature material sensitization effects. The presence and magnitude of residual stresses were confirmed using boiling magnesium chloride and strain gage techniques. This program also addressed the effectiveness of IHSI to produce beneficial residual stress improvement in weldments with pre-existing flaws. The pre-existing flaws (machined notches) ranged in size up to 25% through-wall and showed no crack propagation after IHSI treatment upon exposure to boiling magnesium chloride.

The Japanese studies determined empirically the process control parameters required to successfully implement IHSI. In addition, experimental results were verified analytically using nonlinear finite element analyses, effects of recirculation system operating temperatures and external application of axial stress were examined in terms of potential relaxation of beneficial residual stress, and the effects of repeated IHSI treatments on the state of residual stresses were studied. These studies verified the long-term effectiveness of IHSI as a residual stress-mitigation technique, determined the process-control parameters required to achieve these beneficial effects, and confirmed that no detrimental effects are produced by the process on either microstructure or mechanical properties.

3.1.1.2 EPRI Qualification Program

The details of the EPRI-sponsored qualification program are provided in [16 and 17], which were prepared by the GE. The EPRI program verified the effectiveness of IHSI on Type 304 stainless steel weldments in 4-inch (10.16-cm), 12-inch (30.48-cm), 16-inch (40.64-cm), 22-inch (55.88-cm), 26-inch (66.04-cm), and 30-inch (76.2-cm) pipe sizes. This program included the following weldment configurations as illustrated in Figure 3-1:

- Header-to-valve
- Riser-to-reducer
- Elbow-to-pipe
- Riser-to-sweepolet
- Cross-to-header
- Cross-to-tee
- Cap-to-header
- Pipe-to-pipe

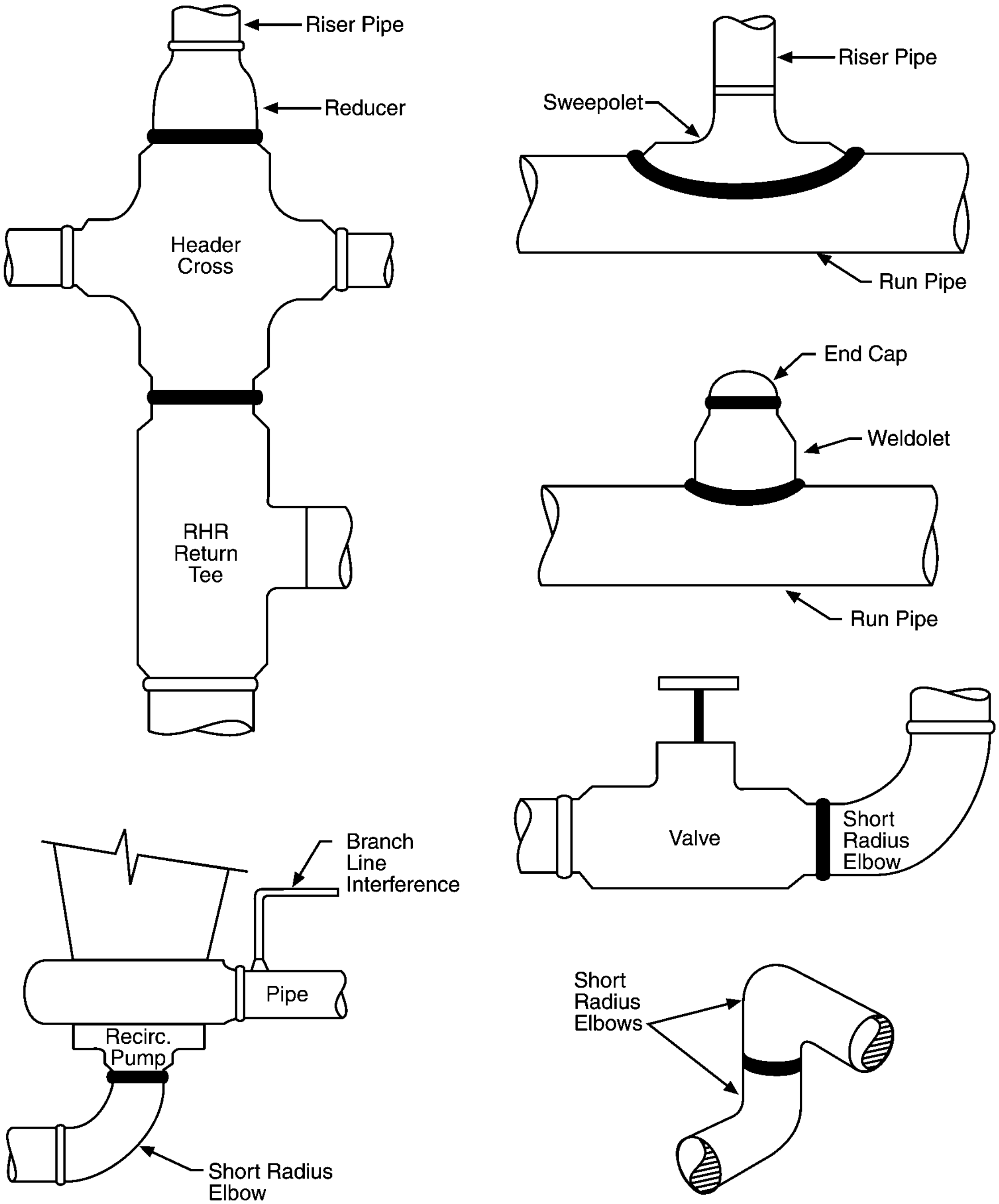


Figure 3-1
Complex Weldment Configurations

In addition to optimizing process-control parameters governing IHSI implementation, the program investigated the effectiveness of IHSI on both uncracked and IGSCC-flawed weldments. The effects of both horizontal and vertical weldment orientations were also considered. Residual stresses were measured using both strain gage and X-ray diffraction techniques, mechanical properties were tested, and microstructural investigations were performed to quantify the effectiveness of the IHSI process.

The long-term effectiveness of IHSI was part of the degraded pipe testing performed in GE's Pipe Test Laboratory [18, 19, and 20]. This testing included both uncracked and IGSCC-flawed weldments subjected to simulated BWR water and realistically applied cyclic stresses. Results suggested that IHSI completely prevented IGSCC initiation in unflawed weldments with applied cyclic stresses of up to 1.5 times American Society of Mechanical Engineers (ASME) Code allowable magnitudes and completely arrested preexisting IGSCC cracks having depths of up to 50% through-wall for cyclically applied stresses up to 1.0 times the Code allowable.

In addition to mockup testing, the EPRI-sponsored program included analytical residual stress verifications of the IHSI process for a range of pipe sizes and a variety of weldment configurations. The document prepared by the University of Tulsa [21] and EPRI report [6] provide details of these analyses. Elastic-plastic finite element techniques were used to verify that the recommended process-control parameters given in Figure 2-2 conservatively produce the maximum residual stress-improvement benefits for the IHSI process. Analyses discussed in [6] indicate that crack tip extension during the IHSI process is unlikely for the smallest cracks that can be detected by ultrasonic examination techniques due to the low plastic strains that occur in the crack tip region during the process.

3.1.1.3 Extension Programs

The use of IHSI has been extended by IHI, NUTECH, and others to weldment configurations, pipe materials, and specific plant conditions not originally addressed by either the Japanese or EPRI programs, as illustrated in Figure 3-1. Both IHI and NUTECH have developed IHSI treatment procedures for the nozzle-to-safe-end weldment having a thermal sleeve configuration, shown in Figure 3-2. IHI has developed two different techniques for the treatment of this type of weldment, as discussed in [22]. The first technique utilizes a phased heating process, which treats specific portions of the weldment in a three-step sequence. Because this technique was used at a domestic U.S. plant after recirculation system pipe replacement with Type 316 Nuclear Grade (NG) materials, the IHI qualification program also addressed the process-control parameters required to treat this replacement material. More recently, IHI has developed a nozzle-to-safe-end IHSI treatment technique utilizing an inside-the-reactor vessel cooling water injection nozzle to provide forced convection cooling in the thermal sleeve annular gap [23]. Both the three-step and injection nozzle techniques were qualified using full-scale mockups and analytical evaluations.

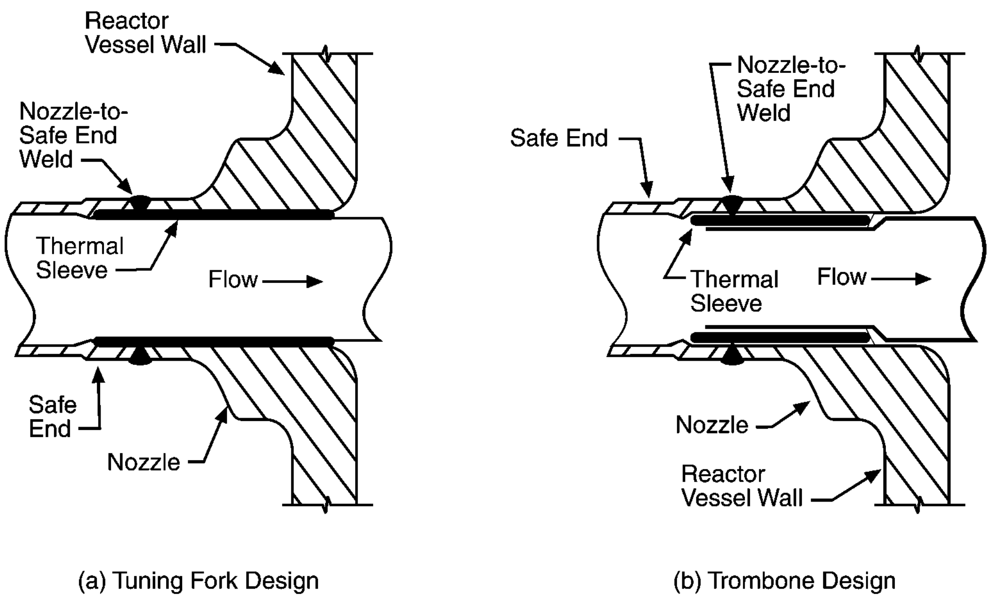


Figure 3-2
Typical BWR Nozzle-to-Safe-End Configurations

The nozzle-to-safe-end with thermal sleeve IHSI technique developed by NUTECH has been qualified on the four weldment geometries presented in Figure 3-2 and Table 3-1. As discussed in [24], NUTECH's technique modifies the process-control parameters developed in the EPRI qualification program to avoid the creation of a steam pocket at the top dead center position in the annular gap while still developing the through-wall temperature gradient needed to provide residual stress improvement. This modification is possible because the EPRI-qualified parameters contain significant conservatism. In addition to this technique, NUTECH has qualified IHSI process-control parameters for Type 316NG stainless steel [25] for piping weldments that are oriented both vertically and horizontally, without recirculation system cooling water flow [26], and for a 24-inch (60.96-cm) NPS cap located at the top of a ring-header cross. Sufficient cooling of the component inner surfaces was obtained by convection of the water while heating the outer surface of the component by induction. All of these qualification programs utilized full-scale mockups with extensive instrumentation. In addition, all of these qualification programs were backed up by nonlinear finite element analytical evaluations.

Table 3-1
Nozzle-to-Safe-End Geometries Used in the NUTECH Qualification Program

Configuration Number	Type	Nozzle/Safe-End OD (inches/cm)	Nozzle/Safe-End Thickness (inches/cm)	Annular Gap (inches/cm)
1	Tuning fork	13.875/35.24	1.175/2.99	0.378/0.096
2	Trombone	13.875/35.24	1.175/2.99	0.181/0.46
3	Tuning fork	13.88/35.26	1.327/3.37	0.25/0.64
4	Tuning fork	13.88/35.26	1.327/3.37	0.10/0.25

As part of an independent third-party evaluation for NUTECH, Structural Integrity Associates (SIA) examined the effect of repeated IHSI heat treatments on both uncracked and cracked weldments [27]. This evaluation also addressed the effect of relatively cooler areas under an IHSI coil and the effect of cool spot size on the creation of beneficial residual stresses. This evaluation utilized elastic-plastic finite element and fracture mechanics analysis techniques, resulting in both limitations and enhancements in NUTECH's utilization of the EPRI-qualified IHSI process-control parameters. Because repeated IHSI treatments may cause small crack tip growth in deep flaws (greater than 50% through-wall), a limit has been placed on the total number of heat treatments on any weldment until engineering evaluation can be performed. On the other hand, engineering evaluation of cool spot data can now be performed to determine the acceptability of a treatment without resorting to major coil modifications.

3.1.2 IHSI Field Implementation

IHSI field implementation experience has been well documented by a 1986 EPRI report [28] discussing challenges and improvements to the IHSI implementation process. IHSI has been applied to approximately 4,000 IGSCC-susceptible weldments around the world. A total of 45 plants were treated by one of four contractors. The treatments were performed on all types of weldment configurations, and it has been possible to accommodate a variety of interferences. As experience has been gained with implementation of IHSI, production rates have increased while craft support manpower has decreased. In-plant nondestructive examination (NDE) results have shown that IHSI can be an effective method with which to mitigate IGSCC in susceptible piping systems. It is recognized that precision ultrasonic testing (UT) sizing and characterization of IGSCC flaws is difficult, but techniques and equipment have improved significantly over the last two decades such that both in-plant characterization and sizing can be made with confidence.

3.1.2.1 In-Plant Weldment Configurations

Recirculation piping system weldments fall into two major groups:

1. Generally axisymmetric without radical contour changes:
   - Pipe-to-pipe
   - Pipe-to-elbow (long and short radius)
   - Pipe-to-reducer
   - Sweepolet-to-pipe (branch line)
   - Pipe-to-safe-end
   - Safe-end-to-elbow (long radius)
   - Pipe-to-valve
   - Pipe-to-pump
   - Pipe-to-cross
   - Pipe-to-end-cap
   - Valve-to-elbow (long radius)
   - Pump-to-elbow (long radius)
   - Weldolet-to-pipe (branch line)
2. Complex geometries and/or radical contour changes:
   - Nozzle-to-safe-end (with and without thermal sleeve)
   - Safe-end-to-elbow (short radius)
   - Valve-to-elbow (short radius)
   - Pump-to-elbow (short radius)
   - Valve-to pump
   - Tee-to-cross
   - Cross-to-reducer
   - Run pipe-to-sweepolet
   - Run pipe-to-weldolet
   - Elbow-to-elbow (both short radius and in the same or perpendicular planes)

Although some of the weldments shown in Group 1 above do not appear to be axisymmetric, the use of shifted heating zones and coils away from the non-axisymmetric component, as permitted by the EPRI-qualified process-control parameters, makes it possible to utilize axisymmetric coils. The weldments shown in Group 2 are more complex, as illustrated in Figure 3-1. Even the complex weldments have been routinely treated by IHSI by the use of carefully designed coils, shifted heating zones, and specially developed process-control parameters.

Implementation of IHSI also can be complicated by structural interferences that cannot be removed easily. A representative list of these types of obstructions follows:

- Branch lines
- Valve and blank flanges
- Flued heads
- Structural steel
- Pipe whip restraints
- Shear lugs
- Air ducts
- Other piping system components (such as sweepolets near header-to-end-caps)

Implementing organizations have found practical ways to accommodate all of these types of structural interferences. The IHSI process has been used for virtually all weldments encountered in BWR recirculation system piping.

3.1.2.2 Production Rates

The early implementation production rates and required craft level support improved with experience. It was noted over time that production increased and required levels of craft support decreased for all contractors implementing IHSI. The differences seen in production rates can be attributed to the following physical factors:

- Radiation levels
- Smearable contamination
- Airborne contamination
- Reduced interferences
- Drywell ambient temperatures

These physical factors heavily influence craft support personnel productivity rates because of limited stay times in radioactive environments. Such times can vary widely from plant to plant in any case. Also, the division of labor among various labor disciplines and organizations greatly influence overall productivity rates. IHSI productivity rates improved with experience in spite of these challenges.

The need for recirculation pumps to provide flowing water has been greatly reduced with the development of IHSI process-control parameters requiring no flow in the pipe. In-the-drywell craft support activities have been reduced by the use of shifted heating zones, improved IHSI coils (captured hardware for quick installation, field adjustable coil turns, a single coil which can treat adjacent welds, and so on), and enhanced engineering evaluations. Overall craft support productivity rates improved through use of composite crews where all personnel can perform all tasks. As productivity rates increased and craft support manpower levels decreased, IHSI steadily became an increasingly cost-effective alternative to the long-term resolution of IGSCC in BWR piping.

3.1.2.3 NDE Results

Some difficulties were encountered in the 1980s with flaw sizing before and after application of IHSI treatment where the piping contains IGSCC. Table 3-2 presents a list of post-IHSI IGSCC findings for a representative group of plants that have implemented IHSI. Although some of these plants appear to have new IGSCC indications since IHSI implementation, this table clearly illustrates the effectiveness of IHSI under actual operating plant conditions in the great majority of cases. Examination of the NDE results illustrates the difficulties associated with precise ultrasonic sizing/characterization of weldment flaws/indications. In many cases, the pre-IHSI UT examination of IGSCC-susceptible weldments was performed using manual UT techniques, whereas the post-IHSI examinations were performed using automated techniques. The result is an apparent increase in the number of IGSCC flaws, which argues against the effectiveness of IHSI. Instead, review of the NDE data illustrates the difficulties of UT repeatability. In addition to changes in UT techniques, the following considerations can influence inspection results:

- Differences in the interpretation of UT results by potentially different examiners from outage to outage.
- Difficulty in the examination of some weldment configurations due to their geometry, bi- or tri-metallic composition, and/or physical interferences.
- General difficulty in finding and sizing axial flaws.
- Human error during in-the-drywell examination, interpretation of UT data, compilation of the final UT results, or the analytical evaluation of the effectiveness of a stress-improvement process.
- Anomalies in the implementation of a stress-improvement technique.
- Improvements in UT techniques resulting in the discovery of flaws not observed using earlier techniques.

Table 3-2
IGSCC NDE Results (Post-IHSI)

Plant Designer	Commercial Operation Start Date	IHSI Implementation Date	Approx. No. of Welds Treated	"New" Post-IHSI Flaws	Comments
A	1972	1983	98	7	
B	1975	1984 1984	11 75	0 0	Pilot project
C	1972	1984	68	0	
D	1981	1984	197	0	
E	1984	1984	83	1	
F	1977	1984	80	22	Changed to automated UT
G	1975	1984	80	21	Changed to automated UT
H	1983	1984	72	0	
I	1981	1984	75	0	
J	1975	1985	107	0	
K	1975	1986	111	3	
11 Units			**1067**	**54 (5%)**	**Manual + automated UT**
				11 (1%)	**Excluding automated UT changes**

Even though "new" flaws have apparently been discovered after IHSI, in most cases, the "new" flaws have not resulted in a degraded weldment that would not meet ASME Section XI acceptance criteria for the intended operating period.

Concerns were identified in 1996 regarding the effectiveness the IHSI treatment in mitigating IGSCC. A workshop was convened at the EPRI NDE Center to review what appeared to be new IGSCC detected in IHSI-treated austenitic stainless steel weldments. An industry survey was conducted in BWR plants to determine if new IGSCC was reported from NDE examinations of treated pipe. Of the 21 plants surveyed, four reported new IGSCC. Reviews were conducted of the IHSI treatment and the inspection records by the affected utilities with EPRI assistance. The results of the review suggest that the IGSCC was present when the piping was treated and undetected by the UT examinations at the time, thus confirming the information presented earlier. The question of whether or not crack growth had occurred was not answered definitively. It was suggested that a new baseline examination be established for these weldments. The report further concluded that IHSI properly applied to uncracked pipe effectively mitigates IGSCC. The evaluation identified IHSI process parameters that are important to achieve effective mitigation. It is suggested that future in-service inspections be focused at weld locations that are difficult to treat because the IHSI process parameters are difficult to control. Further treatment of this subject is available in the EPRI report [29].

3.2 Weld Overlay

3.2.1 Technical Basis/Experience

Technical bases and experience with weld overlay repairs are summarized in the EPRI report *Justification for Extended Weld Overlay Design Life* [30], which was prepared by Structural Integrity Associates. The weld overlay repair technique for IGSCC flawed pipe welds is based upon application of weld metal to the outside pipe surface over and to either side of the flawed location, extending 360° circumferentially, as presented in Figure 3-3. The weld overlay repair performs the following functions:

- Provides structural reinforcement of the flawed location, such that adequate load-carrying capability is provided, either in the overlay by itself or in some combination of the overlay and the original pipe material
- Provides a barrier of IGSCC-resistant material to prevent IGSCC propagation into the overlay weld metal
- Produces a compressive residual stress distribution in at least the inner portion of the pipe wall that inhibits IGSCC initiation and propagation in the original pipe joint
- Prevents local leakage from small axial flaws

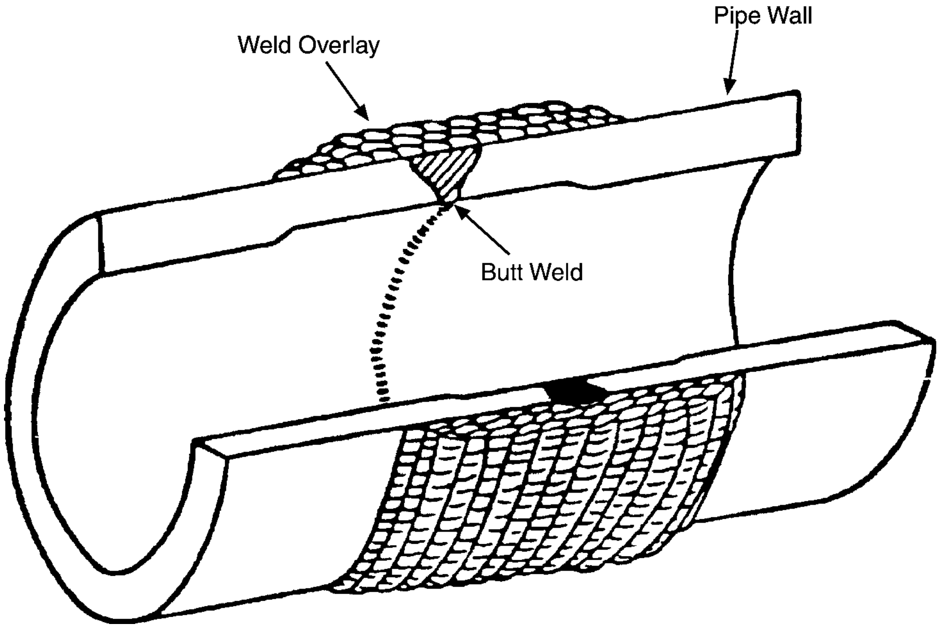


Figure 3-3
Weld Overlay Repair

Weld overlays for flawed stainless-steel weldments have generally been applied using the automatic gas tungsten arc welding (GTAW) process with Type 308L weld filler material. Application of weld overlays typically is performed with water backing on the inside of the pipe weld being repaired. This sequence produces a through-wall temperature gradient. The temperature difference across the pipe wall, coupled with the normally occurring shrinkage of the overlay weld metal, has been shown to produce a highly favorable residual stress distribution in the pipe wall [31–33].

All the above work supported the development of ASME Code Case N-504-1 [34], which provides the rules for design of weld overlays. The use of weld overlays as a long-term effective remedy for IGSCC flawed welds is recognized by the NRC in Generic Letter 88-01 and NUREG-0313, Revision 2. Generic Letter 88-01 provides the regulatory position on the use of weld overlays to repair IGSCC flawed weldments in BWRs. NUREG-0313, Revision 2 provides details of the design criteria and inspection requirements for various types of weld overlays. Three types of overlays are described in the following paragraphs.

1. Standard overlay – This overlay design is based upon the assumption that the original pipe wall supports no axial stress (as if the flaw were circumferential in orientation and extended entirely through the original pipe wall, 360º around the pipe). See Figure3-4 for this type of overlay.

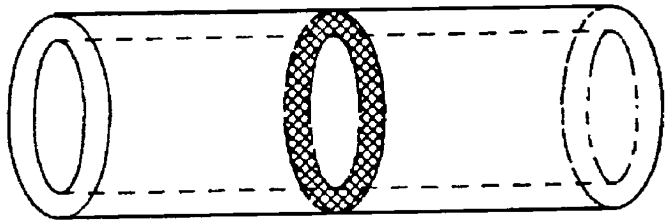


Figure 3-4
Design-Basis Flaw for "Standard" Weld Overlay

2. Designed overlay – This overlay design assumes that the flaw has finite length and/or depth (see Figure 3-5) so that some credit is taken for the strength of the remaining uncracked original pipe. This design depends on flaw sizing and the strength/toughness characteristics of the original piping weldment. NUREG-0313, Revision 2 also imposes limitations on the size of the original defect and on design methodology for overlays to fall in this category.

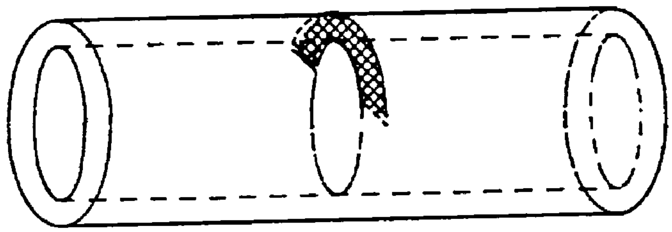


Figure 3-5
Design-Basis Flaw for "Designed" Weld Overlay

One subset of the designed overlay is the leakage-barrier overlay. This overlay design is not intended to provide significant structural reinforcement to the flawed location. Such overlays are applied to provide a leakage barrier to repair axially oriented or very short circumferentially oriented flaws for which there is no structural concern. Inherent in the design of these overlays is demonstration that the pipe wall is structurally adequate "as-is" and that the flaw growth is "arrested" due to the favorable residual stresses.

3. Limited service overlay – NUREG-0313, Revision 2 currently considers any weld overlays not conforming to the above definitions as "limited service overlays." These are considered as suitable for only a single fuel cycle of operation. If an overlay falls into this category, it is necessary to upgrade the overlay to one of the other design categories in order to justify long-term operation.

3.2.2 Design Methodology

The basis for the design of a weld overlay is a verified fracture mechanics evaluation providing justification for continued operation of a degraded component. As specified in NUREG-0313 and ASME Code Case N-504-1 [34], weld overlays are designed to the requirements of the ASME Boiler and Pressure Vessel Code, Section XI (Code) [35]. The Code bases for flaw evaluation are reviewed, and the flaw configurations and piping stresses used for the overlay design are defined. The steps for performing a flaw evaluation and overlay design are described in the following subsections.

3.2.2.1 Flaw Growth Evaluation

The allowable flaws described in IWB-3641 are end-of-evaluation period flaws. The evaluation of flaws found in service requires:

- A reasonable knowledge of the flaw size as determined by ultrasonic or other applicable examination methods
- The state of applied and residual stresses at the flawed location in the component
- The relationship of the crack growth rate to stress and the environment
- The ultimate load-carrying capability of the degraded component

Current flaw length and depth are determined from the results of the nondestructive examination. The applied stresses at the flawed location are obtained from the plant stress report or from system analytical studies. The state of residual stress at the location of the flaw in the component is determined from an evaluation of the original fabrication processes. In addition, any stress-improvement processes, such as MSIP or IHSI, that have been applied to the affected location and any existing weld overlay in the run of piping are considered.

The end-of-evaluation period flaw size is determined by extending the measured crack size by a length equivalent to the crack growth expected from corrosion over the evaluation period. The expected growth can be determined by considering the crack tip stress field, the crack growth rate for the material condition in the service environment, and the duration of the evaluation period.

Figure 3-6 provides crack growth rate information for the stainless steel and for nickel-based alloys in BWR environments published by SKI. It should be noted that the NUREG 0313 relationship for IGSCC crack growth rate in austenitic materials is also shown in Figure 3-6. This is the relationship published by the NRC for the purpose of evaluating crack growth by IGSCC in high-purity, high-temperature water found in BWR coolant systems. A stress-independent crack growth rate of 5×10^{-5} in/hr (12.7×10^{-5} cm/hr) is accepted by the NRC and is frequently used as a conservative estimator for IGSCC extension for BWR coolant systems.

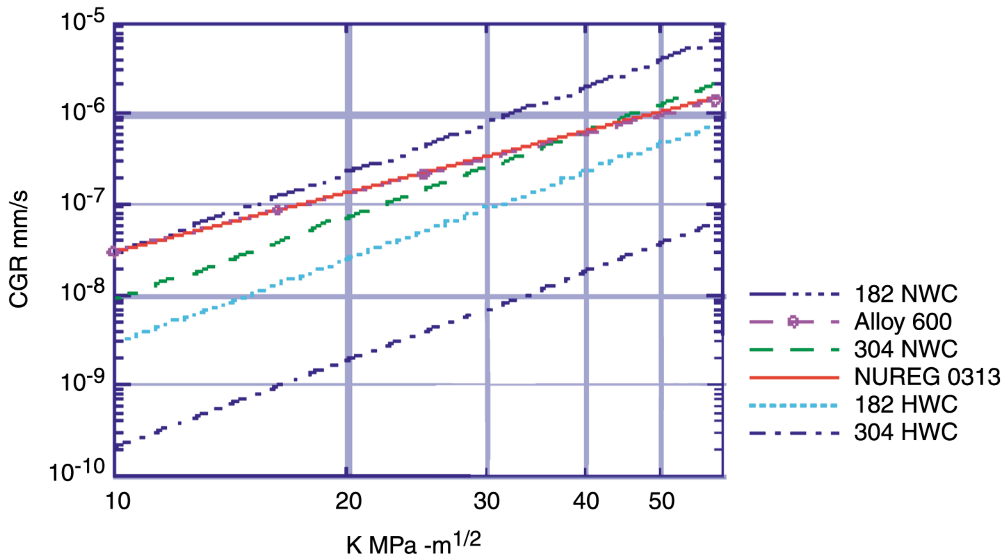


Figure 3-6
Typical Crack Growth Results in BWRs for Stainless Steel and Nickel-Based Alloys as Published by SKI

3.2.2.2 Allowable Flaw Size

Paragraph IWB-3640 of 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. Tables IWB-3641-1 and Tables IWB-3641-2 of the Code present the criteria in a matrix format. The allowable flaw depth is presented as a function of wall thickness. To determine the acceptability of a known flaw, it is necessary to enter these tables at the applicable stress ratio and read the allowable flaw depth as a percentage of the wall thickness. If the flaw in question is not predicted to exceed this allowable value during the evaluation period, the component is considered acceptable for service with no repair required. If the flaw exceeds the allowable value, or is predicted to do so in the evaluation period, a repair of the component (such as weld overlay) is required. The source equations for the Code flaw evaluation tables are presented in Appendix A of EPRI report NP-7103-D, *Justification for Extended Weld Overlay Design Life* [30].

The purpose of the weld overlay is to add additional material to the flawed component, so that the as-repaired component contains a flaw that is acceptable by the ASME Section XI criteria. That is, the ratio of the observed flaw depth to the sum of the component's original wall thickness and the additional overlay thickness is less than the IWB-3641-1 (or the IWB 3641-2) allowable value for the designated operating interval.

Tables IWB-3641-5 and IWB-3641-6 were incorporated into the Winter 1985 edition of the Code to account for reduction of fracture toughness in submerged arc and shielded metal arc welds by thermal embrittlement. The corresponding allowable flaw sizes for a given stress level are lower in the tables for these welds. For flaws in weldments produced by the submerged arc or shielded metal arc processes, the allowable end-of-period flaw size is determined from these tables in a manner analogous to that described previously.

3.2.2.3 Overlay Design-Basis Flaws

Three basic approaches are taken to establish a design-basis flaw for the weld overlay as outlined in Section 3.2.1 of this report. The approach taken depends on the confidence in the inspection data, desired life of the repair, inspectability of the repaired weld, radiation levels in the area, and schedule.

3.2.2.3.1 Postulated Through-Wall 360-Degree Circumferential Flaw

For purposes of design, the flaw is postulated to be completely through the original pipe wall and to extend fully around the pipe circumference. In essence, the original pipe is replaced by the overlay. This approach is the most conservative of the three and has been accepted as a long-term repair by the NRC. This is called a *standard* or *full structural* overlay.

Designing an overlay in this manner has several advantages:

- Accurate flaw sizing is not needed, and thus time for inspection and exposure of inspection personnel are limited.
- Questions regarding the integrity of the original pipe are eliminated because there are no issues regarding uncertainty of the flaw size.
- The overlay is generally fabricated using an automatic GTAW process, thus eliminating the need to account for lower toughness in the original weld if it had been made using a flux shielded welding process.

3.2.2.3.2 Finite Depth and/or Length of Flaw

For the purpose of design, the assumed flaw is related in size to the flaw that has been sized ultrasonically. An arbitrary factor often is applied to the observed flaw dimensions (for example, a factor of two) to add conservatism to the design-basis flaw to account for sizing uncertainty. Another common treatment is to assume that the flaw is completely through-wall but of finite length. In any case, this approach credits a remaining ligament of the original pipe in the overlay design. This type overlay previously has been referred to as a “designed overlay” in this report.

Designed overlays may yield slightly thinner overlays than standard overlays. This is desirable because welding time is reduced and the effects of the overlay on the overall piping system are minimized. The effectiveness of the designed overlay depends on the accuracy of flaw sizing and requires the designer to account for a lower toughness in the original weldment if it were made using a fluxing weld process. The NRC has limited the use of this type of overlay to flaw lengths that are 10% or less of the pipe circumference. Overlays mitigating longer flaws are defined as “limited service.”

3.2.2.3.3 Small Flaw, Acceptable Without Reinforcement

The design-basis for a small flaw that does not require structural reinforcement by weld overlay to meet the requirements of ASME Section XI, IWB-3641, focuses on mitigation of crack growth and/or prevention of minor leakage from axial flaws. The overlay associated with this type of flaw is thin, provides a barrier of material that is resistant to IGSCC propagation, and modifies through-wall residual stresses to produce a compressive stress field on the inner portion of the pipe wall. The latter factor will inhibit new crack initiation and will resist growth of the existing crack.

3.2.2.4 Overlay Design Stresses

ASME Section XI, IWB-3640 defines allowable flaw size as a function of the sum of applied primary membrane, primary bending, and in some cases, expansion stresses. Primary membrane stresses principally result from the system operational pressure. Primary bending stresses result from application of dead weight and seismic loads. Expansion stresses are secondary in nature and are only considered in flux weld applications per Tables IWB-3641-5 and –6 of IWB-3640.

The following stress components are used in Tables IWB-3641-1 and IWB-3641-2 for circumferentially oriented flaws in base material and on flux weldments:

- Pressure (P)
- Dead weight (DW)
- Seismic:
  - Operating-basis earthquake (OBE) for normal/operating conditions

    or

  - Safe shutdown earthquake (SSE) for emergency/faulted conditions

The stress combinations that are used in the IWB-3641 tables are:

- P + DW + OBE for normal/operating conditions (Table IWB-3641-1)
- P + DW + SSE for emergency/faulted conditions (Table IWB-3641-2)

For flaws in flux-shielded weldments, expansion loads are added to these terms that include the following additional stress components:

- Thermal expansion (TE)
- Weld overlay shrinkage effects (SHR)
- Seismic anchor movements (SAM)

The stress combinations that are used in the IWB-3641 tables for flux-shielded weldments are:

- P + DW + OBE + (TE + SHR + SAM_{OBE})/2.77 (Table IWB-3641-5)
- P + DW + SSE + (TE + SHR + SAM_{SSE})/1.39 (Table IWB-3641-6)

The ratio of these load combinations to the ASME Code allowable general membrane stress, S_m, for the material at operating temperature is used to determine the stress ratio needed to enter the appropriate IWB-3641 table.

A more comprehensive explanation of weld shrinkage as well as comprehensive information on weld overlay qualification are found in EPRI Report NP-7103-D, *Justification for Extended Weld Overlay Design Life* [30].

3.2.3 Fabrication and Installation

This section of the report provides information regarding the weld overlay application factors that influence the effectiveness and quality of the weld overlay. The factors are:

- Welding process and equipment
- Weld-metal specification
- In-process welding requirements
- Repairs during weld overlay application
- In-process and post-overlay examination

3.2.3.1 Process and Equipment

The remotely controlled automatic (machine) gas tungsten arc welding process has been the most frequently used process for the application of weld overlays. The automatic welding machines can be equipped for remote optical monitoring and video recording of the weld process, as well as remote control of the operation to reduce radiation exposure to the operator while permitting close monitoring of the welding process. Location-specific engineering and modifications to standard equipment have improved both the efficiency of the welding and quality of the overlays. In addition, the improvements have further reduced personnel radiation exposure by minimizing the frequency of equipment re-adjustment and re-location while applying the overlays.

Welding head modifications often are used to facilitate improvements that reduce personnel radiation exposures. Some of these include the following features:

- Welding head extension devices to improve the span over which welding can be affected without resetting the welding track
- Incorporation of multiple welding heads and multiple wire-feed sources to facilitate welding in both directions

- Remote adjustments to the welding torch angle to facilitate welding in both directions
- Multiple cameras to facilitate welding in both directions
- Low-profile welding head and torches to address limited access
- Pendant controls to permit welders direct observation and control of the welding process from nearby locations having lower radiation levels

There are numerous suppliers of remote pulsed arc tungsten inert gas tungsten inert gas (TIG) pipe welding equipment worldwide. In the United States, two manufacturers dominate this market. These two suppliers are Dimetrics (Gold Track systems) and Arc machines. Both equipment systems are highly versatile and may easily be adapted to specific piping geometries. Both systems are used extensively by U.S. welding vendors for commercial pipe welding work. Typical welding systems feature clamshell drive tracks that mount directly over the exterior of the pipe and are locked manually into place by means of adjustable bolts and shims. The Gold Track system utilizes a rugged friction drive while the Arc system utilizes a gear drive. Both methods are proven in hundreds of applications, and there are advantages and disadvantages of each. The machine output capacity is normally 300 amperes, although greater machine capacities are available. Normally dry argon is utilized as a shielding gas, although argon-helium gas mixtures have been utilized to facilitate special welding requirements. Welding procedures employ pulsed arc current and specific parameters that have been established for the welding substrate and the weld filler material. Weld overlays have been applied in all positions, although the vertical and horizontal pipe positions are typical.

Machine welding produces very smooth surfaces; however, weld overlays are normally machined and/or surface ground after welding to facilitate post-weld dye penetrant and ultrasonic examinations. Such tests are required by ASME Code, and the surface finishes are specified in Code Case N-504-1. The machining is normally performed by means of a clamshell OD (outside diameter) mounted lathe. The typical lathe utilizes a hydraulic drive motor and is fitted with an indexing single point tool. The achievable finish is controlled by many machining variables, including rigidity of the lathe equipment. This means that the tooling must be rugged to maintain the required stability while reaching over the entire weld overlay deposit. In many cases, the machining will be followed by light grinding and flapping. Care must be taken to not smear the metal surface during metal working operations because a dye penetrant surface examination can produce false crack indications if the metal surface is smeared. Nickel-based fillers are particularly susceptible to surface smearing.

3.2.3.2 Weld Metal Specification

Low carbon (0.02 wt% maximum) Type 308L welding filler material meeting the requirements of SFA 5.9 of the ASME Code, Section IX, is typically specified for weld overlay repair of Type 304 piping and similar components. A minimum delta-ferrite content of approximately 8 FN, as determined by weld pad test, is generally specified. Material meeting these requirements has been shown to produce weld overlay deposits that are highly resistant to IGSCC propagation.

Other filler materials have also been used for weld overlay. In particular, nickel-based fillers are required when welding over nickel-based deposits such as ER NiCr-3 (Alloy 82) or E NiCrFe-3 (Alloy 182). ER NiCr-7 (Alloy 52), a 30% chromium nickel-based material, has been applied successfully to nozzle safe-end butters and weldments having nickel-based fillers. These filler materials can be difficult to weld, especially when applying a downhill welding progression. Interlayer oxides can form that produce ultrasonic indications having length and width but no measurable depth (akin to a thin lamination in the circumferential direction). A modification to the base Alloy 52 composition has been reported to minimize the potential for this problem, but use of an uphill welding progression has been used successfully and may be the best solution. The high chromium content of this filler material provides excellent resistance to stress corrosion.

3.2.3.3 In-Process Welding Requirements

Welding heat input typically will be limited in a welding procedure specification (WPS) to a maximum value of 30 KJ/inch (76 KJ/cm) [31]. It is recognized that with the pulsed TIG welding process, the wire feed and travel speed are independent variables, but the wire feed is normally fixed by good welding practice. Therefore, the heat-input calculations are adequate. The welding heat input of 30 KJ/inch (76 KJ/cm) has been shown both analytically and experimentally to produce residual stress distributions characterized as highly compressive in the inner volume of the repaired piping component.

Weld overlays may be applied with or without water on the inside of the pipe. Both methods produce compressive stresses on the inner volume of the pipe. The use of water backing will minimize the time required to stay below the maximum interpass temperatures. The heat of welding from the overlay deposit will not cause the inner surfaces to be sensitized, even for unstabilized grades of austenitic stainless steel. The thermal conductivity of austenitic stainless steel limits heat-affected zones to less than 0.25 inches (0.635 cm) for typical pulsed TIG welding.

3.2.3.4 Repairs During Weld Overlay Application

Metallurgical inclusions in the original circumferential butt welds or through-wall axial flaws (with their attendant “steam blowouts”) can cause defects in the weld overlay. Repair of these defects, either before or during the overlay application, has been performed successfully in the field. These repairs generally have been performed with water in the piping, thereby precluding the need for a drain down. One approach for repair of a leaking component is mechanical excavation of the flawed area to some depth below the outer surface of the original pipe and mechanically peening the flaw face closed. The excavation is then filled with an IGSCC-resistant filler material using small-diameter shielded metal arc electrodes to seal the leak (manual process). The repaired area subsequently is examined with liquid penetrant to verify that the defect is successfully sealed.

3.2.4 Inspection and Testing

Three types of examinations are usually performed while processing an overlay:

- Liquid penetrant examination of the base metal prior to application and examination of the subsequent layer
- Delta-ferrite measurement of the first welding layer
- Ultrasonic examination of the completed overlay to demonstrate proper metal bonding

Typically, liquid penetrant examinations are used to ensure that the surface to be welded is free from indications that could propagate as a result of the application of the overlay. The first layer in the overlay receives a liquid penetrant examination to ensure that any flaws in the base metal that were near the outer surface did not propagate into the overlay during welding. Care should be taken to completely remove all dye penetrant following examination.

Although it has been recognized that the weld metal typically used for weld overlay repair is highly resistant to IGSCC propagation, the concern of possible dilution of the weld metal by base metal exists in the initial layer. The concern is that high delta-ferrite weld metal in the innermost layer would be diluted during the welding process by mixing with the less resistant base metal, thus producing a composite material less resistant to IGSCC than the “undiluted” weld deposit.

In order to address this concern, delta-ferrite measurements of the first layer are taken with a magnetic instrument, usually a Severn gage. If the delta-ferrite content of the first layer is found to be sufficiently high (typically 7.5 FN or greater), this demonstrates that weld dilution is acceptable and that the layer can be included in meeting the specified design thickness.

The NDE of weld overlays involves two distinct aspects. The first is to demonstrate the quality of the weld overlay itself. The objective of this examination is to detect fabrication defects such as cracking, lack of bond, lack of fusion, inclusions, and porosity in the overlay. The second is to monitor the repair in-service to demonstrate that the flaw has not propagated into the overlay, thereby challenging the structural integrity of the repair and its capability to stop or contain IGSCC.

Although the ultrasonic inspection of austenitic stainless steel piping welds is well established, inspection of weld overlays offers additional challenges. These challenges include surface roughness of the weld overlay, UT signal attenuation and beam redirection as a result of the weld microstructure, and crack closure due to compressive residual stresses.

Surface irregularities in the overlay may impair routine examination of the overlay by liftoff of the transducer at these irregularities. Although the resultant surface of the overlay is reasonably smooth because it was welded using machine GTAW, some surface conditioning may be required. Criteria for surface finishing are:

- The flatness of the surface should be 1/32 inch (0.0794 cm) or less. This means that when a 1-inch (2.54-cm) straight edge is placed on the surface, it should not be possible to insert a 1/32-inch (0.0794-cm) diameter wire between the edge and the surface.

- The smoothness of the surface should be 250 micro-inch (0.000635-cm) RMS or better. This generally is accomplished by grinding and flapper wheel finishing. The adequacy of the surface finished is judged by visually comparing it to a set of standards.

Signal attenuation through the weld overlay generally precludes the use of ultrasonic shear waves. Examinations for bond are usually conducted using a zero-degree longitudinal wave. Examinations for planar indications such as cracks are usually done using 45- and 60-degree longitudinal wave transducers.

Additional information and qualifications can be found in reference [30].

3.3 Applicability of Well-Established Mitigation Processes to PWRs

Induction heating stress improvement (IHSI) and weld overlay for repair are two methods that have been proven effective in addressing stress corrosion cracking (SCC) in BWRs.

3.3.1 Induction Heating Stress Improvement

IHSI has been demonstrated to be effective in mitigating IGSCC in BWR piping by the extensive qualification programs:

- The tooling and process control for IHSI are well understood. Qualification for use on PWRs with thicker pipe walls and larger pipe diameters could be performed analytically because the analysis methods have been benchmarked for BWR qualifications, although there may be some limitations in application to very thick wall pipe.
- The treatment has been accepted as an effective mitigation method for IGSCC in BWR piping by the NRC in NUREG 0313, Rev.2. This is reflected as a reduction in re-inspection frequency for the treated piping. The mitigation method for PWRs relies on the same principle as that for BWRs: change of the stress field exposed to the environment from tensile to compressive.
- Operating experience with piping treated with IHSI further confirms the fact that IHSI is an effective mitigation method for IGSCC in BWR piping. Although IGSCC and PWSCC are different cracking mechanisms, the operating experience is believed valid for PWRs because high tensile stresses are needed for cracking to occur with either mechanism.
- Recent studies show that IHSI implementation in BWRs was effective. A few instances have been identified where the treatment was not effective, particularly where access for the induction coils had been limited by component geometry.
- NDE results that have indicated “new” cracks following IHSI may be due to NDE uncertainty and/or changes in examination methodology between inspections. Some cracking appears to have occurred at locations where the process was improperly implemented.

- The thicker wall thickness of the PWR piping components will make it more difficult to establish the requisite thermal gradient across the wall thickness. This capability should be demonstrated prior to application.
- Given the extensive use in a variety of piping applications in the United States, IHSI represents a potentially effective stress-improvement method in PWRs.

3.3.2 Weld Overlays

The following are examples of how weld overlays have been successfully used:

- Overlays applied as described using the specified filler materials have been shown mitigate IGSCC in BWRs by changing the stress field from tensile to compressive and providing a welded layer that is highly resistant to IGSCC crack initiation. Using the appropriate filler material, the same results would occur for mitigating PWSCC in PWRs.
- The treatment has been accepted as an effective mitigation method for IGSCC in BWR piping by the NRC in NUREG 0313, Rev.2. This is reflected as a reduction in re-inspection frequency for the treated piping. The mitigation method for PWRs relies on the same principle as that for BWRs: change of the stress field exposed to the environment from tensile to compressive and use of a material more resistant to crack initiation and propagation.
- Operating experience with piping treated with weld overlays further confirms that weld overlay is an effective mitigation method for IGSCC in BWR piping. Inspection results have shown that cracking has not propagated into any overlay during BWR plant operation. Although IGSCC and PWSCC likely have different cracking mechanisms, the operating experience should apply to PWRs because high tensile stress and susceptible materials are common factors that contribute to stress corrosion cracking by either mechanism.
- Although the majority of weld overlays in BWRs have been needed to address IGSCC in austenitic stainless-steel piping components, the method has been used successfully for cracked nickel-based alloys and welds joined to low-alloy steels and/or austenitic stainless steels.
- Testing results from qualification testing for replacement piping and its associated filler materials as well as for steam generator tubing for PWR repair/replacement activities for the reactor coolant pressure boundary have shown that Alloy 690 and its appropriate filler materials are resistant to PWSCC initiation and propagation.

3.4 Weld Overlay for Stress Reduction

The concept of weld overlay as a means to effect a stress reduction in the inner surface material is similar to conventional weld overlay and MSIP. Weld shrinkage results in a constriction of the pipe directly under and to either end of the overlay applied. The deformation causes redistribution of the residual stress, causing the location at the area of interest to change from tensile to compressive. Residual stress improvement would be calculated by finite element analysis (FEA) techniques. The same design considerations for flexibility and existing flaws used in a standard overlay would be used. The process is as follows:

- The design of a weld overlay for stress reduction would specify bead placement, length, and location.
- The process would require conventional GTAW machine welding equipment for effective control of the welding parameters. The same filler materials used for weld overlays would be utilized.
- The process may be used on cracked or uncracked pipe locations with the same restrictions applied to either MSIP or ISHI.
- The use of automatic remote GTAW allows work in limited access and higher radiation locations.
- The process may be used near pumps or valves where IHSI and MSIP may be less effective because of coil problems or restrictions caused by the size of the clamps.
- The radial deformation produced by the overlay should not be limited by pipe sizes.

3.5 Pros and Cons of Well-Established Mitigation Processes for PWR Applications Including Weld Overlay Stress Improvement

Currently available mitigation processes exhibit a range of attributes that should be evaluated for each application. The following is a brief summary of the specific capabilities of three selected mitigation methods.

3.5.1 Induction Heating Stress Improvement

- Large-size equipment is required for the process. Cooling water and significant electricity service are required.
- Coil placement can be difficult for some component geometries.
- The process may afford more application flexibility than MSIP because the coils that must be placed should be easier to manipulate and position than the large hydraulic box clamps required for MSIP.
- The process does not restrict UT examinations. Small indications, if present, may be closed by the process, thereby reducing their reflectivity and potentially masking them. This same concern is applicable to any process that produces compression on the inner surface and tends to close flaws originating on that surface.
- Qualification of the process for PWR applications is needed. This could be accomplished analytically, but demonstration on the full size application would be desirable.

3.5.2 Weld Overlays

- The welding equipment required to support application of an overlay is smaller and more portable than equipment required either for MSIP or for IHSI. Delivery and manipulation tooling is available, and craftsmen skilled in the use of machine pipe welding are available. No special tooling or fixturing would generally be necessary for weld overlay application. Weld overlays can be applied at locations that are inaccessible for MSIP or IHSI.
- Weld overlay not only provides a new boundary of material that is selected so as to be resistant to PWSCC crack initiation and propagation but also produces favorable residual stress patterns.
- Weld overlays for butt-welded nozzle-to-safe-end locations would be designed to ensure that any residual tensile stresses would reside in non-susceptible material locations (low-alloy steel nozzle or solution annealed stainless steel safe-end).
- Weld overlays would be minimally thick and designed to facilitate UT examinations. The design thickness would be restricted to that needed to obtain a compressive stress field in the susceptible material exposed to reactor coolant. The thinner overlay, relatively fine structure of the weld, and smooth surface finish from the automated GTAW would minimize any additional UT examination difficulties.
- The weld overlay process is not only applicable for mitigation but for repair if necessary. If an overlay were used only for mitigation purposes, it is anticipated that two or three layers would be effective. If the overlay were used as "leak limiting" to mitigate axial cracking, the first layer would not be counted. Three layers, including the first layer, would be needed. If circumferential cracking were present, a full structural overlay would be needed. This logic is consistent with previous work approved by the NRC for BWRs.
- ASME Code Cases that have been approved by the NRC are available to support this work. It is anticipated that the ASME Code, within the next year, will issue additional code cases needed to perform weld overlays for BWR and PWR dissimilar metal and Alloy 600 weldments and components. NRC endorsement of these cases is anticipated shortly thereafter. Currently, these types of overlays require regulatory relief for dissimilar metal applications and from the 100-square-inch (645-square-cm) surface area limitation for ambient temperature temper bead welding.
- It is anticipated that the NRC would require some degree of computational analysis and demonstration work to qualify the process for PWR applications.

3.5.3 Weld Overlays for Stress Improvement

- The weld overlay process for stress improvement (WOSI) is a special application of conventional weld overlay technology. It has been conceptualized, but process parameters have not been developed nor has the method been qualified. It is anticipated that both computational analysis and physical demonstration/qualification would be required.
- Inspection requirements should be minimal, because the stress-improvement overlay has no function other than to alter residual stress fields. It would be reasonable to assume that only

the mitigated component would need in-service inspection and that an inspection frequency would need to be established.

- It is anticipated that the stress-improvement overlay could be designed to minimize interference with UT examinations. At a minimum, the same considerations discussed above for thinner overlays with regard to UT inspections would be applicable.
- The benefit of having a resistant material covering the cracking paths of a weldment susceptible to PWSCC would not characterize the stress-improvement overlay, but would provide residual stress improvement such as is derived with MSIP and ISHI mitigation remedies.
- It appears that special NRC approval would not be required for the stress-improvement overlay because applications would be accomplished by welding on the austenitic stainless-steel side of the weldment and also because the weld deposit would not be considered structural. All required activities are addressed and ASME Code years endorsed by the NRC or in code cases that have already been endorsed.

4 CONCLUSIONS

The results of this study provide the following conclusions:

- IHSI is a viable process for mitigating unfavorable residual stresses in PWR piping components. The process requires specific qualification for the piping sizes and thicknesses attendant to PWR applications.
- Weld overlay is a viable process for mitigating unfavorable residual stresses in PWRs. Overlays that are applied for mitigation or to prevent any potential leakage from axial defects would be thin, requiring only two or three layers. Given the nature of the weld application process, the overlay and weldment should be capable of being inspected by UT with minimal surface preparation, if any. Weld overlay not only improves the residual stress distribution but also provides a corrosion barrier of material selected to be resistant to PWSCC. The process would require qualification for PWR applications and approval from the NRC until the code cases currently being pursued are issued and approved.
- Weld overlay for stress improvement is a viable process for mitigating unfavorable residual stresses in PWR piping components. The weld overlay would be designed and located to minimize interference with UT of the weldment. Inspection of the overlay should be minimal because the overlay is non-structural. Future in-service inspection credit for the stress-improvement overlay would have to be established with the ASME Code and subsequently endorsed by the NRC.

5 RECOMMENDATIONS

The following recommendations are provided based on the results of this study:

- IHSI is a viable method to mitigate stress in certain PWR piping components. It is somewhat redundant to MSIP in that large equipment is required for implementation. Further, it is anticipated that qualification beyond computational analysis would be required. Therefore, because MSIP has already been demonstrated and applied in the field for several large PWR components, it is recommended that IHSI not be pursued at this time.
- It is recommended that weld overlay, including weld overlay for stress improvement, be pursued for the following reasons:
  - Weld overlays complement MSIP in that locations having restricted access could be treated.
  - The process is viable for locations having higher levels of radiation because machine GTAW equipment is utilized.
  - Weld overlays provide additional benefits over simple stress mitigation because a PWSCC-resistant weld deposit is placed around the circumference of the component. This provides a leakage barrier for axial defects. Full structural overlays placed over circumferential cracks could be repaired by welding if necessary.
  - Weld overlay may be applicable as a mitigation and/or repair method for penetration geometries such as control rod drive mechanisms (CRDMs) and pressurizer heater sleeves that are attached with “J” groove welds.
  - The weld overlay process has been incorporated in the ASME Code as an acceptable repair method.
  - The process has been reviewed and approved by the NRC for repair application in BWRs with credit given for limiting future inspection frequencies.
  - Weld overlay strictly for the purpose of stress improvement could be implemented within existing ASME Code rules endorsed by the NRC and thus should not need special case-by-case approval. NRC approval may be needed for issues related to inspection frequencies on mitigated weldments, provided that additional inspections had been imposed on certain susceptible butt welds.
- Qualification and analysis should be implemented as soon as practical to make this mitigation method available for field application.

6 QUALIFICATION TEST PROGRAM

Two stress-improvement concepts, mini-overlay (using Alloy 52 to provide a corrosion barrier) and WOSI, are recommended for qualification for PWR applications. Because recent service experience has identified problems with various pressurizer nozzles, it is recommended that two pipe sizes, 6 inch (15.2 cm) and 14 inch (35.6 cm), Schedule 120 or 160, be used for qualification. A carbon steel pipe would be buttered with Alloy 182, single "V" groove welded with Alloy 82/182 filler to a stainless steel pipe. Subsequently, the samples would be overlaid as appropriate by the GTAW process with either Alloy 82 or Alloy 52 wire, depending on the test sample being fabricated. A total of four samples would be made for each mitigation process. The butt welds to be used to evaluate residual stress patterns by strain gage measurements would be fabricated by welding the lower one-third of pipe wall, conditioning the ID (inside diameter) surface, attaching the strain gages, and then completing the sample. One welded butt joint would be used as a control; the other would be overlaid. The remaining samples would be used for control and overlay corrosion test coupons.

Prior to fabricating the test samples, analyses would be performed to define the overlay dimensions and placement for both the WOSI and the mini-overlay. Finite element analysis would be used to predict residual stress predictions in 3-D (ID and through-wall). The parameters would be reported to facilitate direct comparisons with stress and displacement measurements in welded test samples, thereby benchmarking the analytical results with those measured.

Task 1: WOSI: Analyses would be performed using an axisymmetric assumption for uncracked condition. Three different lengths of the "overlay" and three different widths would be evaluated. This task would use elastic analysis to find the best location for the center of the "overlay." The width would be varied. This task would provide some insight for the "mini-overlay" task (Task 2) because the volume directly below the WOSI could be investigated to determine the residual stress when the parameters are varied.

Task 2: Mini-overlay: Analyses of three different lengths, starting with the axial length as required for a leakage type of overlay from Code Case N-504 (two layers) (assuming uncracked condition) would be performed. Analyses of overlays of two different thicknesses would be performed.

Task 3: Task 1 would be performed for a cracked condition using final parameters from Task 1. The results from the analysis would identify the depth of crack that could be mitigated by the selected parameters.

Task 4: Task 2 would be performed for a cracked condition using final parameters from Task 2. The results from the analysis would identify depth of crack that could be mitigated by the selected parameters.

The residual stress at the ID of the control samples would be determined by strain gage measurements of the as-welded pipes. Strain gage measurements would be made after the fabricated weldments are overlaid to determine the residual stress at the ID. In addition to the strain gage measurements, all overlay welding would be monitored by measuring diametric displacement (constriction) at four equally spaced azimuths around the inner circumference (0–180, 45–225, 90–270, and 135–315 degrees) for four equally spaced axial locations under the overlay (both ends and two intermediate locations). The measured results would be compared with the results from the analysis.

Corrosion testing of the as-welded pipe samples and the overlaid (WOSI and mini-overlay) pipe samples would be performed in a sodium thiosulfate solution (Polythionic acid) to obtain a qualitative measure of the expected improvement in resistance to cracking in the overlaid samples at the ID of the weld.

The results from the program outlined above are considered appropriate to provide a technical basis for ASME Code and regulatory justification.

7
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A
EXAMPLE INDUCTION HEATING STRESS IMPROVEMENT APPLIED AT A U.S. NUCLEAR GENERATING STATION

ABSTRACT

This report documents the implementation of Induction Heating Stress Improvement (IHSI) on the IGSCC-susceptible welds of the reactor recirculation, core spray, and isolation condenser piping systems at the a U.S. Nuclear Generating Station. The IHSI process produces a state of compressive stress on the inside surface of the pipe in the weld region, thereby eliminating stress as a major factor causing intergranular stress corrosion cracking (IGSCC).

Forty (40) welds in the recirculation, core spray, and isolation condenser systems were treated by IHSI using specifications and plant unique procedures developed by a contractor. Following the initial equipment set up, IHSI was performed between November 14 and December 5, 1988. This was followed by a period for IHSI equipment demobilization.

Table of Contents

1.0 INTRODUCTION

One of the most effective remedies for mitigating the occurrence of intergranular stress corrosion cracking (IGSCC) in the heat-affected zone of austenitic stainless steel piping welds is Induction Heating Stress Improvement (IHSI). The IHSI process produces a state of compressive stress on the inside surface of the pipe in the weld region, thereby eliminating stress as a major factor contributing to IGSCC.

Various reports published under the auspices of the Electric Power Research Institute (EPRI) have demonstrated the effectiveness of IHSI in mitigating the occurrence of IGSCC in stainless steel welded pipes (References 1 to 4). Based on the studies contained in these reports, IHSI has been successfully applied to the piping systems of many boiling water reactors in the U.S. and elsewhere.

In order to provide protection against IGSCC, a U.S. utility elected to treat welds of various susceptible piping systems by IHSI. During the 1986 refueling outage, a total of sixty-four (64) welds in the stainless steel recirculation piping system received IHSI treatment. These welds are shown in Figure 1-1.

During the 1988 refueling outage, a total of forty (40) susceptible welds on the recirculation, core spray, and isolation condenser piping systems received IHSI treatment. All of the treated welds during this outage are identified in Figures 1-1 through 1-3. A summary of the IHSI process parameters used for treatment are shown in Tables 1-1 and 1-2.

Table 1-1

Summary of IHSI Process-Control Parameters

Parameter	Value
Maximum Pipe Wall Outer Surface Temperature	575˚C (1067˚F)
Minimum Through-Wall Temperature Differential (ΔT)	275˚C (495˚F)
Minimum Width of Zone Heated to ΔT Minimum	$1.5\sqrt{RT}$ (See Notes)
Heating Duration	
a. Welds in horizontal pipe runs with no cooling water flow:	
Maximum Heating Duration	$t = 0.7\ T^2/a$ (See Notes)
Minimum Heating Duration	0.75 t
b. Welds in pipe runs with flow and welds in vertical pipe runs without flow:	
Maximum Heating Duration	No limitation
Minimum Heating Duration	$t = 0.7\ T^2/a$ (See Notes)
Frequency of Power Supply	3 KHz ±10%
Minimum Induction Coil Length	$3\sqrt{RT}$ (See Notes)
Minimum Distance from Center of Weld to Boundary of Zone Heated to ΔT Minimum	Maximum of T/2 or W/2 + 1/8" or 0.6" (See Notes)

Notes:

R = Mean Pipe Radius (inches)
T = Maximum Pipe Wall Thickness in the Weld Heat-Affected Zone (HAZ) (inches)
a = Thermal Diffusivity (in^2/sec.)
W = Width of Weld (inches)

Table 1-2

Summary of IHSI Process Control Parameters
for Nozzle-To-Safe End Weld With Thermal Sleeve

Parameter	Value[1]
Maximum Pipe Outer Surface Temperature	575˚C (1067˚F)
Minimum Pipe Outer Surface Temperature	435˚C (815˚F) (See Note 2)
Minimum Width of Zone Heated to ΔT Minimum	$1.5\sqrt{RT}$
Minimum Distance from Weld Center to Boundary of Zone Heated to (ΔT) Minimum	0.6” (15mm) or T/2 or W/2 + 1/8" (whichever is greater)
Maximum Heating Duration	$t = 0.56\ T^2/a$
Minimum Heating Duration (See Note 3)	$0.49\ T^2/a$
Frequency of Power Supply	3 KHz ±10%
Minimum Induction Coil Length	$3\sqrt{RT}$

Notes:

1. R = Mean Pipe Radius (inches)
   T = Maximum Pipe Wall Thickness in the Weld Heat-Affected Zone (HAZ) (inches)
   W = Width of Weld (inches)
   a = Thermal Diffusivity (in^2/sec.)

2. Assumes static water head at nozzle between 40 and 75 ft.

3. On the average, heating rate must be linear or greater than linear, tapering to steady-state at power-off.

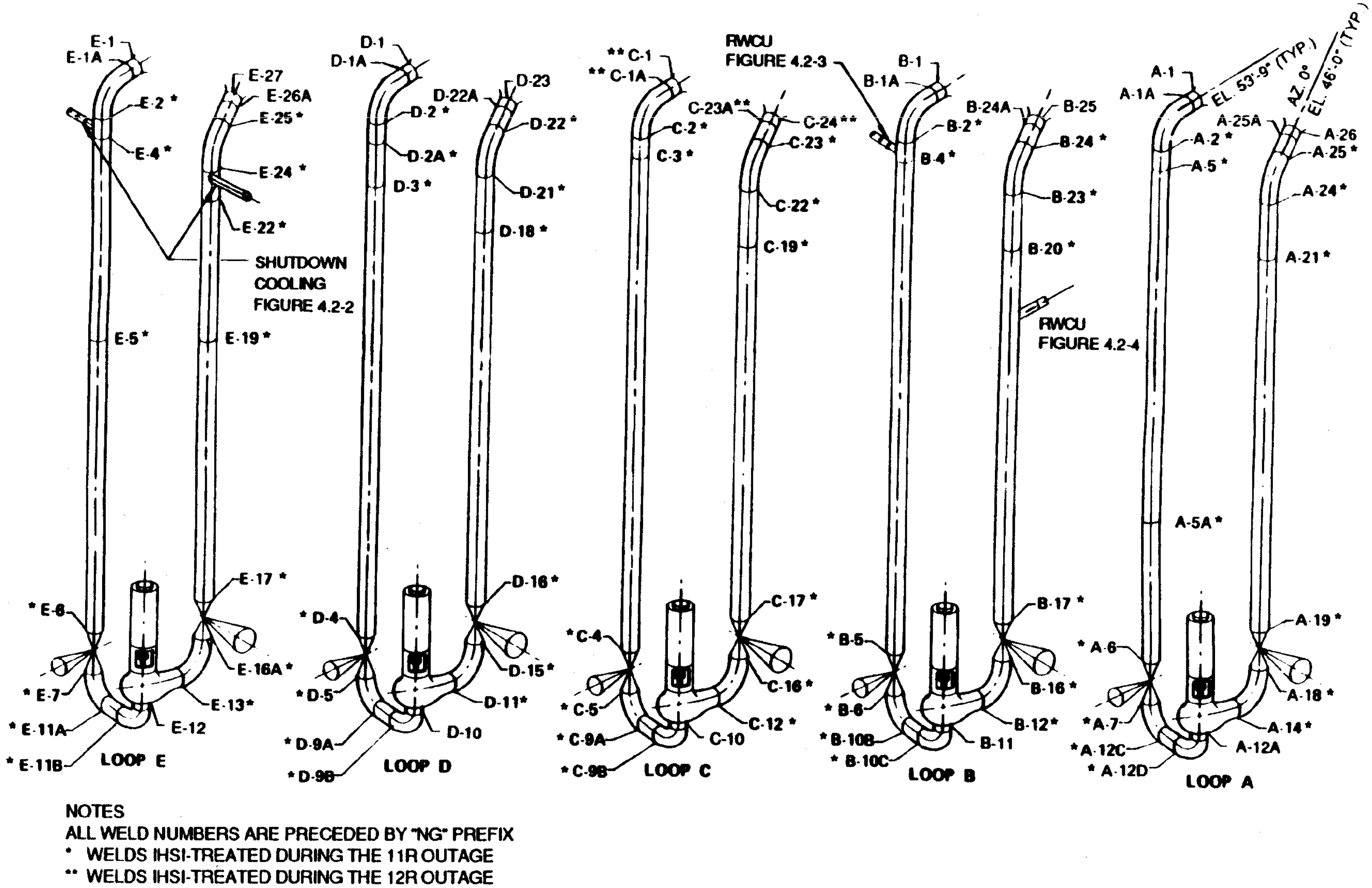

Figure 1-1. A U.S. Nuclear Generating Station Reactor Recirculation System

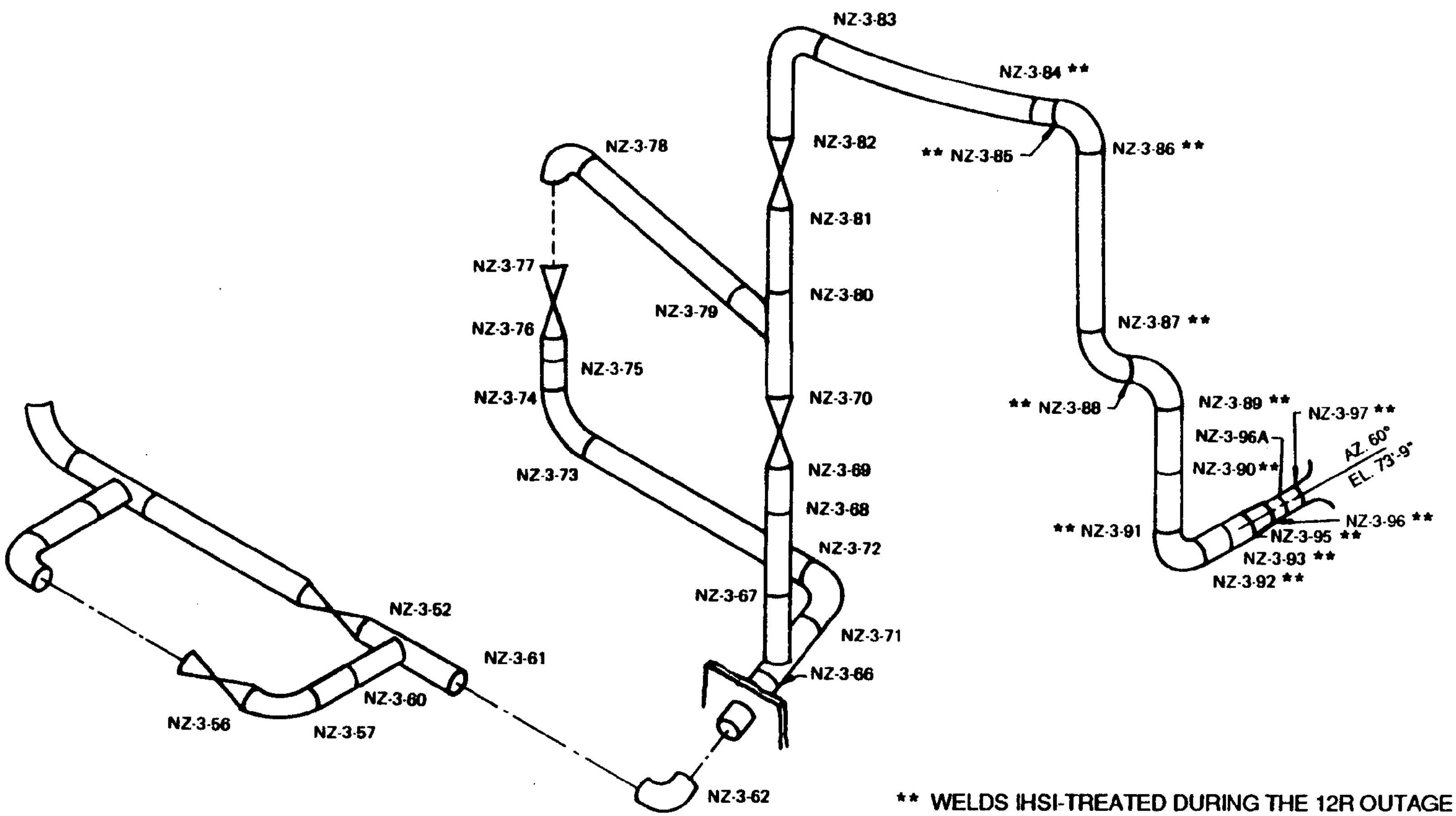

Figure 1-2. A U.S. Nuclear Generating Station Core Spray System

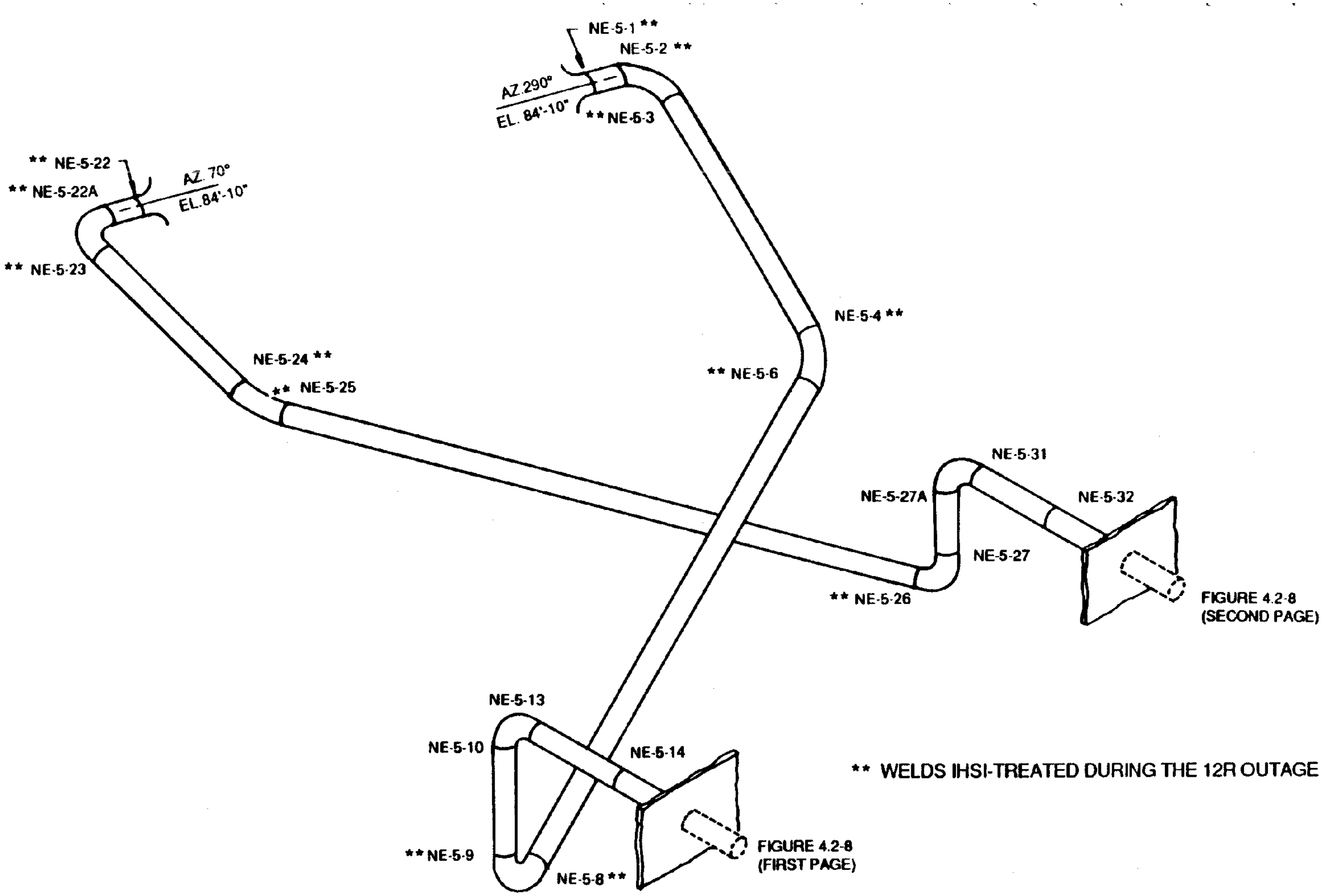

Figure 1-3. A U.S. Nuclear Generating Station Isolation Condenser Supply Lines (Inside Drywell)

2.0 IHSI IMPLEMENTATION

An on-site IHSI implementation program was started at the plant site. The various phases of the site implementation are described briefly below. The contractor provided the IHSI equipment, management of the project, and technical direction. Craft labor support was also provided by the contractor by subcontract to an IHSI equipment vendor.

Mobilization

The initial contractor team arrived at the plant site to begin the application process. Survey of the piping welds to confirm induction coil requirements was performed as scaffolding/lighting installation and pipe insulation removal made welds accessible. Set up of IHSI equipment involved the use of two heat sites (heat sites are cables and hoses used to connect the coil to the power supply and the pump station) in the drywell to treat 40 welds. This equipment was located in the drywell with care to minimize interference with other activities. A weld heating sequence was developed to permit efficient utilization of the equipment. To accommodate changes in plant conditions and/or system availability the weld heating sequence was revised on site as needed.

Training

Prior to the start of IHSI implementation, meetings were held with the utility and the IHSI core vendor to enable the contractor personnel to explain the IHSI process requirements to the plant personnel, Quality Assurance, Rad Con and other managers/supervisors at the utility. Specialized “hands—on” training for craft personnel was also performed for thermocouple attachment, IHSI coil installation, and cooling water hook—up to the coils and control unit assemblies. Sections of pipe were used in the training sessions to simulate the actual pipes in the plant. These training sessions were held throughout the duration of the project to assure that new and/or replacement personnel were formally trained.

Attendance lists were maintained for all sessions, along with thermocouple welder certification records, to document that personnel were adequately trained for their appropriate tasks in the IHSI implementation.

IHSI Work Packages

An IHSI work package (IWP) was prepared for the IHSI treatment of each weld. These IWPs were prepared prior to the start of IHSI activities on a given weld and contained an individual Cover Sheet, Process Control Traveler, Thermocouple Setting Instruction Sheet, Operators Master Checklist, and the IHSI Heating Record. Prior to use, each IWP was reviewed and approved by the contractor IHSI project personnel, and submitted to the utility to establish any desired notification points. They were then issued to the implementation team by the contractor Site Superintendent.

Thermocouple Layout and Installation

Locations for placement of thermocouples that measure the temperature of the IHSI treatment area were marked on the pipe according to the individual thermocouple setting instruction sheets which were a part of each IWP. After the layout was checked, thermocouples were attached to the pipe by a capacitive discharge (CD) welding process. Thermocouple attachments were inspected prior to the weld being approved for coil installation.

Coil Installation

The IHSI coils were initially installed according to shift supervisor instructions based on manufacturer's recommendations. After ensuring correct coil position, hoses and electrical leads were connected to the coil. The complete coil installation was inspected to assure the coil and all electrical and water connections were ready for test heating.

In addition to connecting the hoses and electrical leads, the heat site switch box, including the warning strobe light, the thermocouple junction box, a communications system and a fire extinguisher were placed near the weld.

<u>Test Heats</u>

IHSI test heats were performed at weld locations to verify satisfactory coil location and equipment operation. During a test heat, the maximum temperature of the pipe was limited to 250ºC ± 50ºC (482ºF ± 90ºF). All test heats were run in accordance with the "IHSI Heating Manual" and were recorded on the "Operators Master Checklist" in the IHSI work package (IWP). In addition, temperature recorder strip charts for all test heats were included in the IWP. Coil adjustments were made based on temperature spread of the thermocouples, if required prior to regular heating. For certain welds, as allowed by procedure, the power supply operator had the option during a test heat, if the equipment operation and thermocouple readings were satisfactory, to continue the test heat through completion of a regular heat cycle.

<u>Regular Heats</u>

After the performance of a satisfactory test heat, if any, a regular IHSI heat was performed on the pipe weld. As was done for the test heats, regular heats were run in accordance with the "IHSI Heating Manual" and recorded on the "Operators Master Checklist" in the IWP. Of the total of 40 welds, 21 required more than one regular heat cycle. In any case, the number of regular heats performed on a particular weld was limited to five without written permission from the contractor Site Superintendent. None of the welds required more than five regular heats. Temperature recorder strip charts for all test and regular heats were included in the IWPs. When the IHSI treatment was completed, the "IHSI Heating Record" was completed to document satisfactory IHSI treatment.

Thermocouple Removal

Following IHSI treatment, the water and electrical leads were disconnected from the coil and the IHSI coil was removed. The thermocouples and hold-down clips were removed from the pipe and their locations were marked. The locations were then “flapped” and remarked to prepare the attachment locations for a dye penetrant (PT) NDT examination.

Dye Penetrant Examination

At the completion of the IHSI process, the thermocouple and hold-down clip attachment locations were examined by the utility by dye penetrant (PT) examination to document that the thermocouple material had been fully removed and that the capacitive discharge welding had not caused surface indications on the pipe.

Completion of IHSI Weld Packages

The IHSI Shift Supervisor and Field QA Supervisor reviewed the IWPs for correctness and completeness. Attached to the IWPs were the temperature recorder strip charts for all IHSI test heats and regular heats and any calculations or engineering evaluations required to complete the IWP. The completed IWPs were then submitted to the utility.

Demobilization

After treatment of the last weld, all the IHSI equipment was removed from the drywell for decontamination and packed in crates.

3.0 RESULTS AND CONCLUSION

IHSI was successfully implemented on forty (40) welds on the recirculation system at a U.S. Nuclear Generating Station. All but ten of the welds met all of the process control parameters (Tables 1-1 and 1-2). The 10 welds which did not meet the process control parameters are considered to have been effectively treated based on engineering evaluations performed. It is therefore concluded that all welds were effectively treated by the IHSI process.

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