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Materials Reliability Program: Evaluation of the Effect of Weld Repairs on Dissimilar Metal Butt Welds (MRP-114NP)

1009559

Final Report, July 2004

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PRODUCT DESCRIPTION

Background

Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 600 nozzles and penetrations in PWR plant primary system pressure boundaries has been a recurring problem since the mid 1980's. During the second half of 2000, cracks were discovered in Alloy 182 welds joining low alloy steel reactor vessel hot leg nozzles to stainless steel pipes at Ringhals 4 and VC Summer. Although cracking was the primarily axially oriented, at VC Summer, a short circumferential crack was also discovered in the ID region of the Alloy 182 weld clad. This circumferential crack arrested when it reached the low alloy steel base material. Although not a significant flaw in terms of structural integrity, the VC Summer circumferential flaw heightened the concern regarding circumferential flaws and their impact on structural integrity.

Objective

The purpose of this document is to assess the impact of circumferential cracking in repaired and unrepaired dissimilar joint locations made using Alloy 182 and also provides information for use in determining if the inspection interval needs to be adjusted from the current 10-year interval.

Approach

Fracture mechanics evaluations were performed to determine the potential for crack initiation and growth at as-welded (unrepaired) and repaired locations. The fracture mechanics analysis used weld residual stresses calculated for the repaired and unrepaired conditions for the RPV outlet nozzle and the pressurizer surge nozzle.

Results

Results of this evaluation indicate that if flaws initiate by PWSCC or some other reason (weld defect, grinding), for some repair sizes and at higher stress levels, significant growth may occur even at locations away from the weld repair. It is understood, given the residual stress in the weld repair, that if flaws initiated and there is a direct path of Alloy 182 through the pipe wall, that through-wall crack growth cannot be ruled out. This growth can be rapid, depending on the level of the applied loads, occurring in significantly less time than the current 10-year inspection interval.

However, the results support leak-before-break in that initiated flaws would tend to grow through-wall within the weld repair region, and, except for very high piping load cases, would grow through the wall beyond the edge of weld repair for only short circumferential distances.

The exception is the 360° weld repair case where through-wall growth could occur anywhere based on the analytical results. However, uniform initiation is highly unlikely, even when extensive grinding has occurred.

EPRI Perspective

This work was performed to provide insight into the behavior of PWSCC at Alloy 182 repaired locations. The results can be used to prioritize locations for further evaluation and used to determine if the inspection interval needs to be shortened.

ABSTRACT

Primary Water Stress Corrosion Cracking (PWSCC) in reactor pressure vessel nozzle to pipe welds was observed at VC Summer and at Ringhals 4 during the second half of 2000. During 2002 indications were discovered in a pressurizer surge nozzle butt weld at Tihange 2, although this has not been confirmed to be PWSCC. This report describes fracture mechanics analyses of Alloy 182 butt welds to assess the potential for crack initiation and growth to assess the impact of weld repairs. As-welded and repaired joints were considered in this evaluation. The evaluation included the RPV outlet nozzle and the pressurizer surge nozzle.

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1 INTRODUCTION

Recent incidences of cracking in Pressurized Water Reactor (PWR) Alloy 600 nozzles and penetrations has heightened the concern for potential of Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 182. In 2000, cracking in Alloy 182 was discovered at the VC Summer and Ringhals 4 plants. These incidences further increased the concern for the structural integrity of butt-weld locations in PWR primary system pressure boundaries.

At VC Summer, a through-wall axial crack was discovered by observation of boric acid crystals at the hot leg nozzle-to-safe end. Upon further examination, it was discovered that in addition to significant axial cracking, circumferential cracks were also present. The cracking of the VC Summer hot leg nozzle-to-safe end weld was caused by extensive construction repairs which created high welding residual stresses in a material and in an environment known to support stress corrosion cracking (SCC).

Experience in the Boiling Water Reactor (BWR) industry has also demonstrated that circumferential cracking can occur although axial flaws are expected to be more likely because the hoop stress is higher than the axial stress at dissimilar metal (DM) welds. The presence of circumferential flaws introduces a safety concern regarding the ability to inspect and detect (by volumetric examination or leakage) flaws prior to failure. As in PWRs, construction repairs in BWRs has been an important factor in observed cracking.

At dissimilar metal butt welds, cracking at unrepaired (as-welded) locations is not expected due to the favorable residual stress in the relatively thick walled sections. This is consistent with PWR and BWR experience, which indicates the repaired areas are susceptible to cracking. However, repairs made during installation can have a significant effect on the as-welded residual stress. Depending on how these repairs were made, finishing from the inside or from the outside diameters, crack initiation and growth can occur.

This report provides the evaluation for circumferential crack initiation potential and subsequent circumferential growth at Reactor Pressure Vessel (RPV) Outlet and Pressurizer Surge nozzles in DM weld locations where Alloy 182 weld metal is present. The cases evaluated are the as-welded condition and the repaired condition at single-V welds only. Repaired conditions include those finished from the inside diameter and those completed from the outside diameter.

Due to the many possible variations in the welding and randomness of the parameters (material, stress, geometry, weld parameters and geometry) the cases evaluated are considered representative cases and can be used to draw general conclusions regarding crack potential.

2
TYPICAL WELD REPAIRS IN PWR PIPE/NOZZLE WELDS

This section describes the results of an evaluation of the typical types of repairs that could be found in PWR pipes and nozzles. It relies on field experience and welding practices to identify the types of repairs that should be considered in the evaluation of potential cracking.

Weld residual stresses are significant factors influencing the likelihood for SCC in butt welds of both PWR and BWR nozzle-to-piping configurations. Residual stress patterns are determined by a number of factors that include:

- design of the weld,
- materials properties,
- initial welding methods, techniques and bead sequence, and
- repairs to the weld.

The first three factors listed above normally are considered when estimating the residual stress distributions associated with the weld. However, welding repairs can significantly distort expected residual stress distributions, and can create conditions that lead to shorter cracking times than would be expected for unrepaired welds. Magnitudes of tensile residual stresses required to support SCC are produced in typical butt welds of austenitic material, but the altered residual stress distributions produced by weld repairs often are associated with early incidents of SCC.

It is not unusual to find defects in butt welds that require repair. In fact, both shop and field welds may require one or more weld repair cycles prior to meeting American Society of Mechanical Engineers (ASME) code inspection requirements, especially in large welds. Often repairs were made during the overall welding sequence prior to acceptance inspection. Such repairs are commonly referred to as “in-process” repairs, and documentation is not required. Repairs performed, as a result of acceptance inspections (radiographic testing), would have been documented in Quality Assurance (QA) records. Information recorded in shop/field travelers, issue records for welding consumables, and inspection results can be used to identify and evaluate weld repairs. Knowledge of weld repairs can be useful for anticipating service performance and/or predicting behavior of existing defects.

Repairs are designed to restore the weld to meet or exceed design basis requirements. However, repair sequence, location, welding process, welding parameters, size of the repair, and post repair metalworking all contribute to final weld characteristics.

Surface grinding typically is used to remove surface blemishes and/or smooth and contour the surface of a weld. If grinding is abusive (heavy pressure and coarse grit tooling), a surface layer will be produced that is characterized by high tensile residual stresses and cold worked metallurgical structures. Typically, effects of heavy surface grinding are powerful, but normally are confined to the thin volume of material affected by grinding (1 to 7 mils depth). Surface laps and tears are produced based on the severity of grinding. As such, grinding exerts a great influence on crack initiation, but less for crack extension beyond the cold worked layer. Therefore both welded repairs and surface metalworking must be factored into predicting the initiation and growth of service induced defects. The following paragraphs describe representative repair scenarios that might be anticipated for butt welds to key PWR locations.

2.1 Weld Characteristics for Representative PWR Locations

Two locations have been identified to represent nozzle-to-pipe weld locations having a high potential for service-induced degradation. This selection is based on higher PWR coolant temperatures encountered at these locations and upon service experience. The locations are in the reactor cooling system (RCS) identified as the RPV recirculation outlet nozzle-to-pipe butt weld and the pressurizer surge nozzle-to-pipe butt weld. The details of the RPV recirculation outlet nozzle-to-pipe butt weld are described below:

- A typical PWR RCS pipe is 29” ID with a wall thickness of 2 ½”. The large ID of this weld provides the worker good access to the weld root so that manual weld repair can be performed from inside the component. Figure 2-1 provides a typical weld configuration designed without use of a make-up pipe spool or extension piece. As such this field weld likely would be the first weld completed during installation of the pipe segment. The other end of the pipe run would have been joined to the steam generator inlet nozzle normally making use of a pipe fit-up spool piece.

- The nozzle is fabricated as a low alloy steel (LAS) forging (SA 508 Class 2). The nozzle bore is clad with weld deposited stainless steel (typically Type 309L first layer followed by Type 308L for two more layers). The end of the nozzle is buttered with Alloy 600 weld metal (typically this is a manual application using E-NiCrFe-3 electrodes known as Alloy 182). The butter wraps the end of the nozzle and ties to the nozzle bore cladding as shown in Figure 2-1. The butter is applied in the fabrication shop so that post weld heat treatment (PWHT) can be accomplished in the shop furnaces prior to shipment to the site. Therefore, the field weld to this butter does not does not require PWHT. The cladding on the end of the nozzle typically is specified ½ inch minimum thickness after the nozzle end is machined for welding. This thickness provides sufficient margin for welding to the composite w/o PWHT (minimum 3/16” buffer to the LAS) to accommodate the need for potential corrective actions. The wrought piping material typically is specified SA 376 Type 304N or Type 316 stainless steel. Some manufacturers buttered the end of the dissimilar weld joint with Alloy 600 filler material to avoid making a field dissimilar weld. Note some suppliers specified wrought SA 376 stainless steel RCS piping while others specified SA 216 CF8 cast stainless steel pipe or stainless steel clad LAS piping. All configurations present unique welding challenges due to the large dissimilar weld and the constraint introduced by the stiffness of the heavy-walled components.

- Machine and/or manual gas tungsten arc welding (GTAW) or manual shielded metal arc welding (SMAW) processes were used depending upon the manufacturer and vintage of the plant. Filler material used with the GTAW process was ER-NiCr-3 (Alloy 82) and E-NiCrFe-3 (Alloy 182) electrodes for the SMAW process. In most cases a large volume weld joint geometry would have been designed to facilitate manual SMAW welds even though machine GTAW was specified. This was done to facilitate SMAW in case problems were encountered using the new (at that time) machine GTAW process. Otherwise a more narrow weld design (reduced volume) would have been specified to take advantage of the capabilities of the mechanized process. A 37 1/2 degree J-bevel design with a 0.055" – 0.065" land was typical.

  [Note: SMAW is a relatively thermally efficient welding process (about 75%) that melts filler material according to the electrical parameters established for the weld. GTAW is a cold wire-feed process that produces significant remelting of material already deposited. Typically subsequent weld passes remelt 40 to 75 percent of each bead unless special controls are taken to minimize remelting. This characteristic of GTAW adds to weld shrinkage and ultimately the magnitude of residual stress. Manual GTAW tends to have an even greater volume of remelt due to a mindset of welders that thin layers of added material (extra melting) avoids defects. Machine GTAW is more efficient than manual GTAW because of the capability to control both travel speed and wire feed speed. Generally GTAW weld conditions are characterized by thermal efficiencies between 40-60 % while manual GTAW thermal efficiencies typically run between 25-40%.]

- Weld roots were installed using either manual GTAW or machine GTAW and the root pass was generally followed by 2 or 3 hot passes adding minimum filler metal to facilitate maximum tie-in with minimum chance of defects. The root welding procedure could be either open butt or insert. Typically "K-type" rectangular cross-section inserts were used, but insert style selection was based on the preference and qualification of the installer. The weld root would have been pulled from the OD while maintaining an inert argon gas purge (low oxygen) on the inner surface. Purge dams often were used to minimize the volume of argon required, although some installers filled the entire pipe with argon to facilitate the purge. Normally an inspection would have been performed after the hot passes to make sure there were no root defects before filling the weld cavity. Once the root and hot passes were successfully applied, the cavity would have been filled using SMAW process in early plants and by machine GTAW in later plants as technology and reliability improved. Normally one or more intermediate radiographs would have been performed to provide opportunity to repair defects before completing the weld. This procedure was marginally effective for detecting sidewall indications because geometrical step changes at the sidewall makes it nearly impossible to obtain useful radiographs of the sidewall location. In most cases the weld roots would have been ground smooth to eliminate geometrical indications in the final acceptance radiographs. In general, flapping would have followed grinding to smooth the surface so far as practical.

For the purpose of this study it is assumed the original weld was completed using machine GTAW using ER-NiCr (Alloy 82) filler and welding parameters for 0.045" diameter filler wire and 30 KJ/inch heat input at a travel speed of 2.8" /minute to produce beads 1/8" thick and 3/8" wide. A welding efficiency of 60% is assumed (i.e. 40% remelt). In addition, a 1/8" K-type rectangular insert is assumed for the root fit-up. The root is pulled using machine GTAW w/o filler metal addition.

- Each manufacturer uses a different geometrical configuration for the pressurizer surge nozzle-to-pipe butt weld. In fact the configuration even differs for individual plants designed by the same manufacturer. The nominal diameter of the weld between the nozzle and the branch connection to the RCS piping varies between 10" to 14" nominal ID. Schedules 140 piping components are generally used to accommodate the temperature and pressure requirements. The 14" diameter is selected for this evaluation because the attendant wall thickness will produce the largest volume weld. Figure 2-2 displays a typical geometry having an ID of 14.32" w/cladding and a minimum cladding thickness of 0.19". The welding parameters and processes described above for the RCS nozzle are appropriate for the original field weld except for the smaller weld geometry.

2.2 Repair Strategies

Most butt weld defects tend to be associated with the lower portion of the weld (i.e. weld root and hot passes). This is the reason an intermediate inspection is performed of the root area. Typical defects found in the root volume are incomplete insert fusion, excessive push-through or suck-back, excessive oxidation, and incomplete sidewall fusion. Sidewall lack-of-fusion (LOF) is a common defect created during cavity fill. LOF is a planar defect that requires excavation and weld repair. Weld porosity and slag also are common defects that are found during cavity fill. Typical locations will be at or near sidewalls, but occasionally may be found between weld beads. Finally, undercut is a defect associated with the weld crown at top of the weld. The ASME Code defines acceptable and unacceptable defect sizes for all of these defects. Unacceptable conditions must be repaired. Repair scenarios identified in this review are differentiated on the basis of practical access to the inside of the component (ID size). Therefore original construction repairs on the large diameter RPV recirculation outlet nozzle-to-pipe butt weld will be approached from both the ID and the OD. Repairs to the pressurizer surge nozzle-to-pipe weld are typically approached from the OD but can be approached from the ID as well.

It is noted that the repairs defined in this evaluation pertain to original construction. Capabilities at that time dictated the approach to repair. Today's modern machining and welding equipment is capable of accessing much smaller ID dimensions to perform remote repairs from the inner surface.

2.2.1 Large Diameter Nozzle-to-Pipe Weldment

Two ID repair scenarios are identified that require access to the inside of the component. These are based upon the types of field repairs documented in nuclear plant hardware. The first scenario considers extensive weld root repairs, and the second considers a limited length of ID repair excavated to a depth of mid-wall.

2.2.1.1 Repair Scenario 1 – 360^0 ID Repair of Defects Above the Weld Root & Hot Passes

This repair is particularly damaging because it enlarges the weld volume and finishes the weld on the surface exposed to the reactor coolant. In addition most of the deposited weld volume remains in-place to provide surfaces that are pulled in tension as the weld deposit solidifies and cools. Repair welding always alters the original residual stress distribution, but repairs applied directly to the ID are especially significant. This is because high residual tensile stresses are applied directly to the ID surface by contraction forces resulting from solidification and cooling on the ID surface. Thus, an ID root weld repair can be a particularly influential SCC damage mechanism. The completed weld repair will be ground to contour and smooth the weld root and newly welded interface. Figure 2-3 provides a schematic cross-section of the ID repair.

For the purposes of Scenario 1, it is assumed that significant defect indications have been identified on the buttered sidewall just above the hot passes and are located intermittently completely around the ID circumference.

The first step in the repair is to remove the ID root to a depth of ½" and blended to either side to a width of ¾". The root cavity is then welded out from the ID using machine GTAW (ID track mount), using 0.045 inch diameter ERNiCr-3 (Alloy 82) filler material. Welding parameters are assumed to create a heat input of 30 KJ/inch producing weld beads that are 0.25" wide and 0.125" thick. A 60% welding efficiency is assumed. Finally manual grinding contours and smoothes the finished ID weld surface.

2.2.1.2 Repair Scenario 2 – Limited Circumference ID Repair of Defects Located Mid-wall

This ID repair involves the repair of a defective area just below mid-wall along a 45^0 arc of the circumference (11.4" length). The flaws are assumed to lie along the buttered sidewall and are manually excavated by grinding from the ID to a depth of 1.25 inches and a width at the ID of 0.75". The repair cavity has a total length of 21.4" that (includes a 5.0" long taper (4:1) on both ends of the cavity. The bottom of the cavity is rounded to blend. The weld repairs are accomplished from the ID using a manual SMAW repair procedure. Figure 2-4 shows a schematic cross-section of the limited circumference ID repair geometry.

The SMAW repair weld will be accomplished using 1/8" diameter ENiCrFe-3 (Alloy 182) electrodes. Welding parameters and techniques are selected to produce weld beads 0.5" wide and 0.15" inches thick. The weld is deposited at a heat input of 18 KJ/inch at a 75% thermal efficiency.

2.2.1.3 Repair Scenario 3 – Deep 360^0 OD Weld Repair

An OD repair to the entire circumference is often the best approach to repair extensive defects. This method normally would be performed using machine GTAW welding since the original weld made use of this process. The cavity would be excavated to a depth consistent with the deepest defect using a clamshell OD mounted portable lathe. See Figure 2-5. The advantage of this method over severing the weld and starting over is that no root purge is required for welding and the most likely source for weld defects is eliminated. The weld is contour ground flush after welding to facilitate ultrasonic inspection. Weld evaluations performed on stainless steel pipe welding for BWR applications suggested that excavating the weld below the centroid of the weld mass, then rewelding, produced weld residual stresses similar to an unrepaired weld. The centroid of the weld mass is about 2/3 of the wall thickness above the ID surface.

The depth of the machined cavity for Repair Scenario 3 is 1.44" (slightly deeper than mid-wall) and spans the entire weld cavity. Machine GTAW parameters are set for a travel speed of 2.8 inches/min using 0.045" diameter filler wire. A heat input of 30 KJ/in is assumed with a 60% weld thermal efficiency. The weld bead sizes are 0.25" wide and 0.125" thick. The weld crown is finished by hand grinding and flapping to eliminate any undercut and remove the weld crown to facilitate inservice ultrasonic inspection.

2.2.1.4 Repair Scenario 4 – Short Through-wall Weld Repairs from the OD Surface

Localized through-wall weld repair from the OD surface is a difficult repair scenario because the weld root on the ID must be re-established from the OD. Access is limited. For this repair assume a repair cavity that is 7" at the ID and 27" at the OD and 1 ½" width and rounded at the bottom. Cavity is manually ground. The ends are tapered at 4 to 1 ratio (i.e. a 2.5 inch wall is tapered over a 10" length on each end of the cavity. See Figure 2-6. Manual GTAW open root technique (1/8" opening) will be used to simplify modeling. An inert argon purge is established on the inside of the pipe prior to welding the root and hot passes. Manual GTAW techniques are also used to complete the weld according to the following welding conditions.

The depth of the manually ground cavity for Repair Scenario 4 is 2.5" inches deep, 7.0" long on the ID and 27 inches long on the OD. Manual GTAW parameters are established to produce a heat input of 30 KJ/inch using E-NiCrFe-3 (Alloy 182) 0.045" diameter filler wire. A 40% weld thermal efficiency is assumed. The weld bead size is 0.30" wide and 0.1" thick. The weld crown is hand ground and flapped to eliminate any undercut and eliminate any weld crown that would limit in-service ultrasonic inspection.

2.2.1.5 Repair Scenario 5 – Short Mid-wall Repair from OD Surface

Local weld repairs are needed to correct defective conditions located above the weld root volume. Typically defects will be slag inclusions or sidewall LOF defects. Repair is approached from the OD by manually grinding lengths of the weld to incorporate as many individual defects as possible. For this case a total defect length of 7" is assumed along the weld fusion line on the nozzle butter side at a location just above mid wall. Therefore a cavity 17" long on the OD is excavated to a depth of 1.25" and a width of 1". This allows for a 5" taper (4:1) on each end of the repair cavity. The weld would be filled using manual GTAW according to conditions identical to Repair Scenario 4 above. See Figure 2-7. Finally the OD surface would be contoured smooth to permit ultrasonic testing and to eliminate the weld crown.

The depth of the manually ground cavity for Repair Scenario 4 is 1.25" inches deep, 7.0"long on the ID and 17 inches long on the OD. Manual GTAW parameters are established to produce a heat input of 30 KJ/inch using E-NiCrFe-3 (Alloy 182) 0.045" diameter filler wire. A 40% weld thermal efficiency is assumed. The weld bead size is 0.30" wide and 0.1" thick. The weld crown is hand ground and flapped to eliminate any undercut and eliminate any weld crown that would limit in-service ultrasonic inspection.

2.2.2 Repairs to Smaller Diameter Heavy-Wall Pipe-to-Nozzle Welds

Repair strategies to smaller diameter heavy-wall pipe/nozzle configurations are similar to those used for large diameter configurations (discussed above). One example is the steam generator surge line nozzles. The greatest differences for repairing smaller diameter heavy-wall pipe are that most repairs must be done from the OD, and any ID grinding would be limited and performed using long handled tools. This feature limits the opportunity for ID welding and minimizes the severity of grinding. ID grinding may result in grinding at the wrong location and smooth surfaces (freedom from defect initiation sites) likely will be difficult to obtain. The grinding tool will tend to bounce resulting in surface imperfections. The depth of cold worked surfaces would be limited to a 1 to 3 mils because it is difficult to exert heavy pressure on the grinding tool. A schematic of the original surge line weld is shown earlier in Figure 2-2. The same three OD repair scenarios discussed above apply to these smaller diameter configurations by scaling the cavities proportionate to the wall thickness difference.

2.2.2.1 Repair Scenario 6 – Near Mid-wall 360^0 OD Weld Repair of Surge Nozzle

This repair is conducted identically to that described in Scenario 3 above. The differences are in the dimensions of the repair. Figure 2-8 below provides the dimensions for the repair.

2.2.2.2 Repair Scenario 7 – Short Through-wall Repair from OD Surface of Surge Nozzle

This repair is conducted identically to that described in Scenario 4 above. The differences are in the dimensions of the repair. Figure 2-9 below provides the dimensions for the repair.

2.2.2.3 Repair Scenario 8 – Short Mid-wall Repair from OD Surface of Surge Nozzle

This repair is conducted identically to that described in Scenario 5 above. The differences are in the dimensions of the repair. Figure 2-10 below provides the specific dimensions for the repair.

2.2.3 In-Process Repairs

Significant repairs such as those described in Section 2.0 are expected to be documented in welding records. Other types of repairs, minor in comparison to those described in this section could also occur and are likely not documented. These types of repairs, called in-process repairs are very local types of repairs that would not have a significant impact on the final weld residual stress caused by repairs discussed in Section 2.0.

Appendix A contains additional discussion regarding in-process repairs.

2.3 Summary

This section has presented a summary of potential weld repairs in PWR pipe/nozzle dissimilar metal joint containing Alloy 182 weld butter. It has been demonstrated that the weld repairs can vary significantly in depth, length and location (finished on ID or on

OD). This assessment showed that significant repairs may be expected. Significant repairs such as those described, would be expected to be documented in welding records.

Since the cracking at VC Summer was caused by extensive repairs, causing high welding residual stress on the ID, the potential for initiation and propagation is a concern and is evaluated further in Section 3.

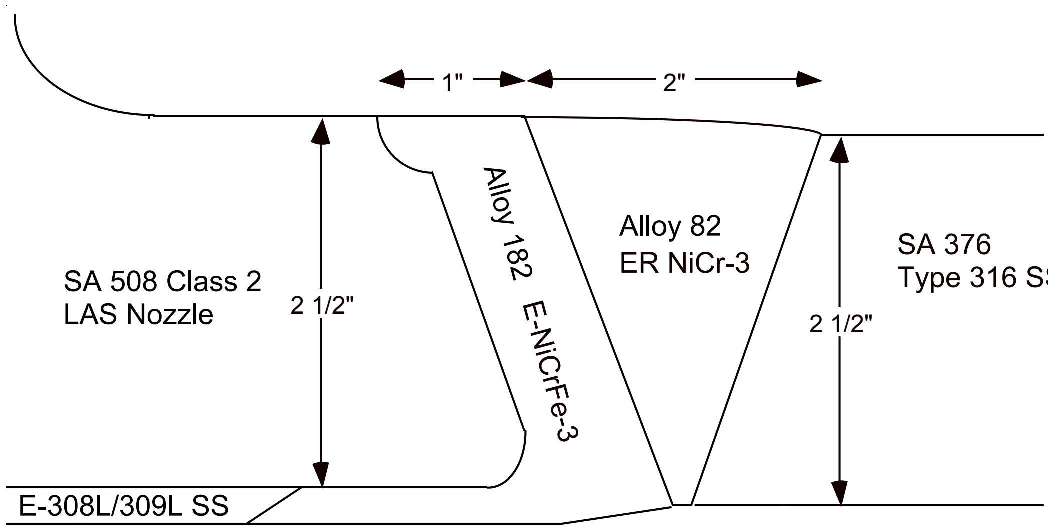


Figure 2-1
Original RPV Nozzle-to-Pipe Weld Configuration w/o Safe End

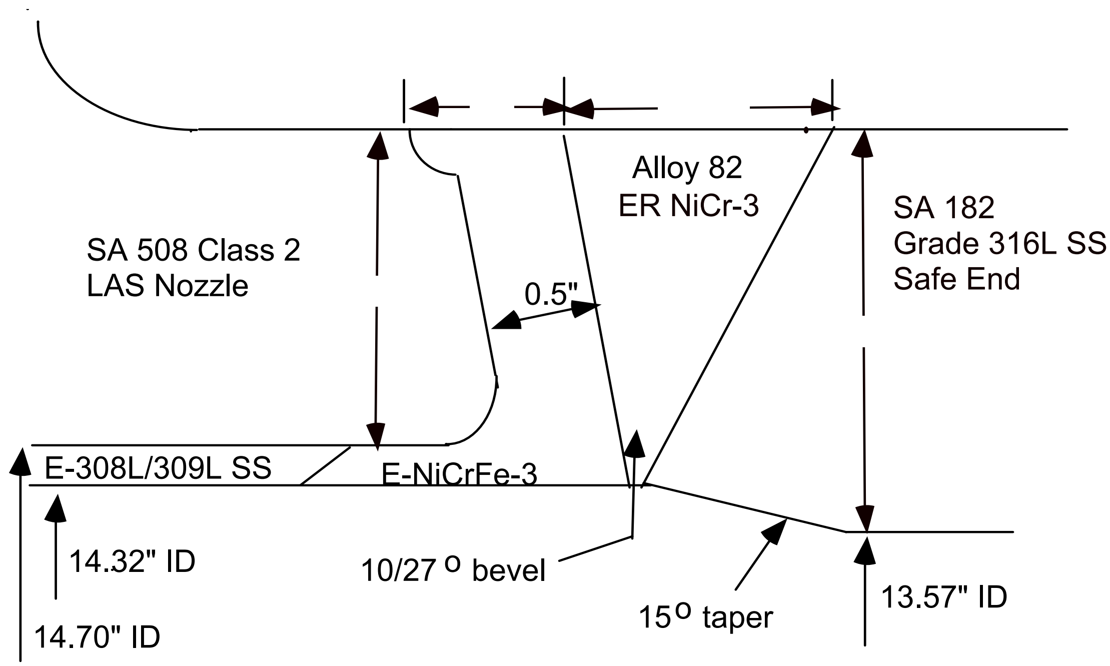


Figure 2-2
Original Pressurizer Surge Nozzle-to-Pipe Weld Geometry w/o Safe End

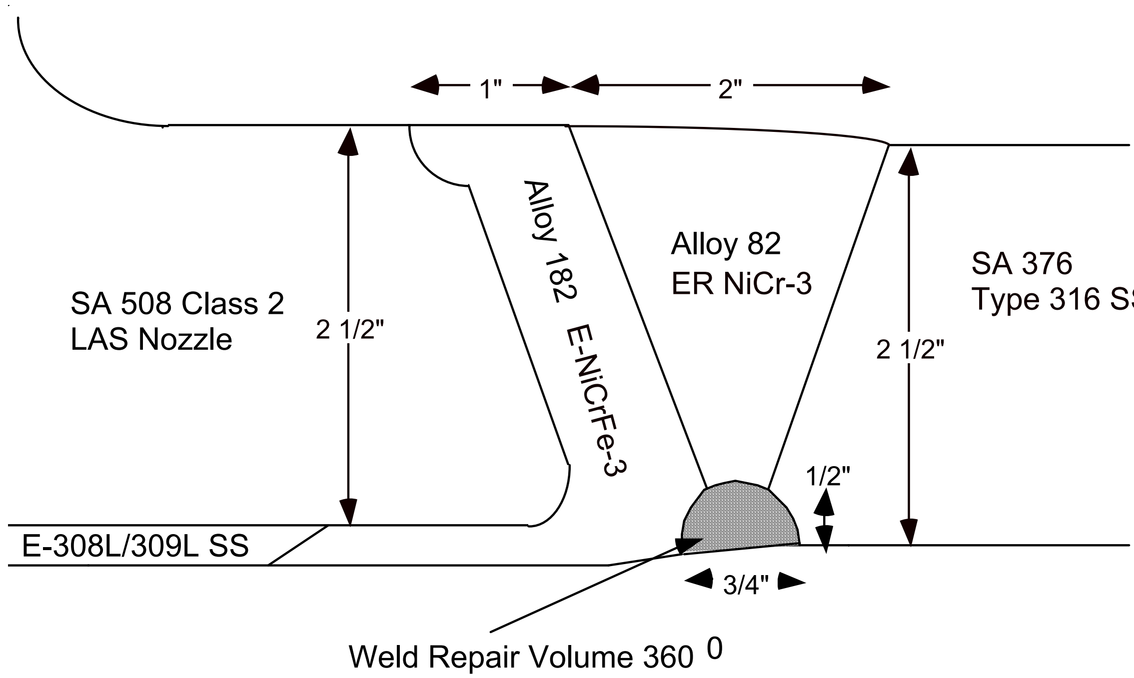
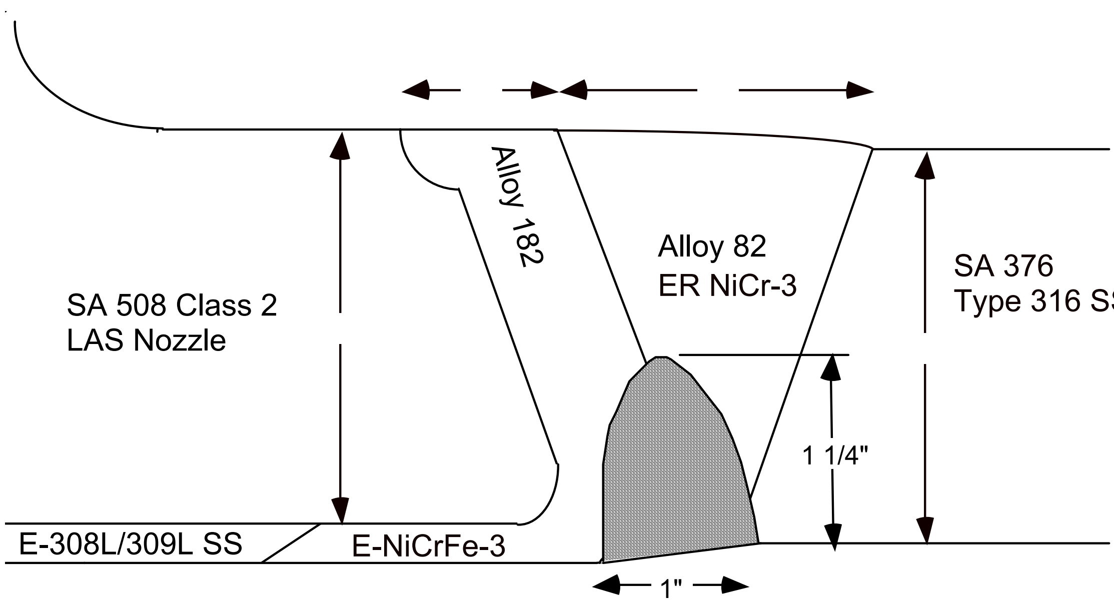


Figure 2-3
Schematic Cross-section of 360^0 ID Root Repair



Repair length is 21.4 inches long, 1 1/4 inches deep and 1 inch across.

Figure 2-4
Schematic Cross-section of Limited Length Mid-wall Weld Repair from ID

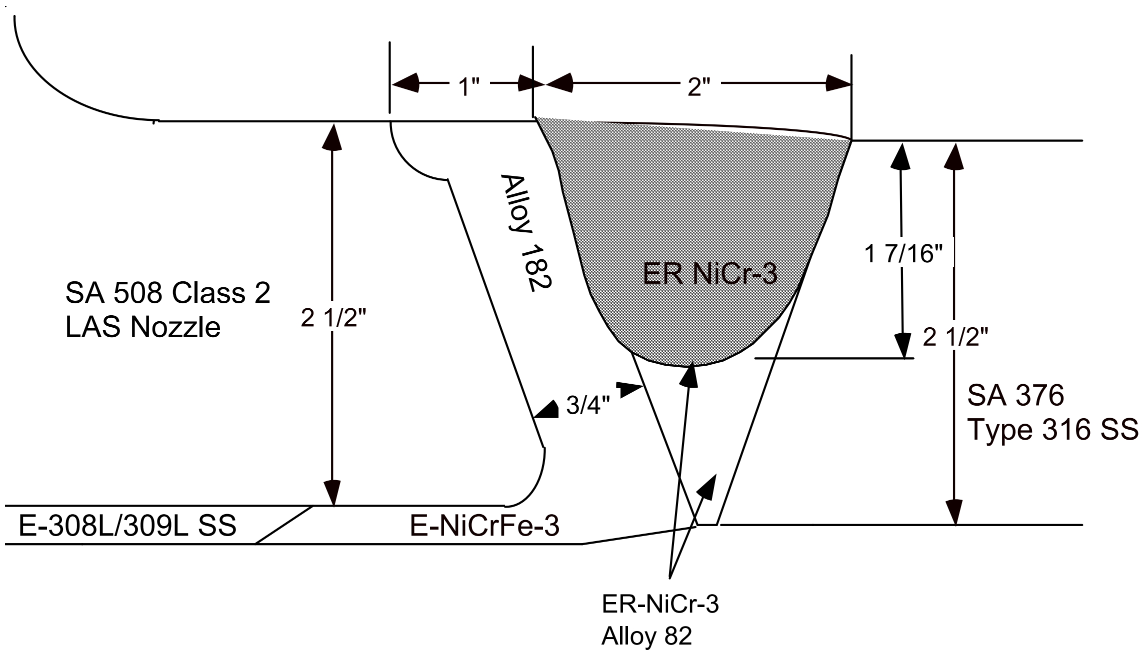


Figure 2-5
Schematic Cross-section of Deep 360^0 OD Repair

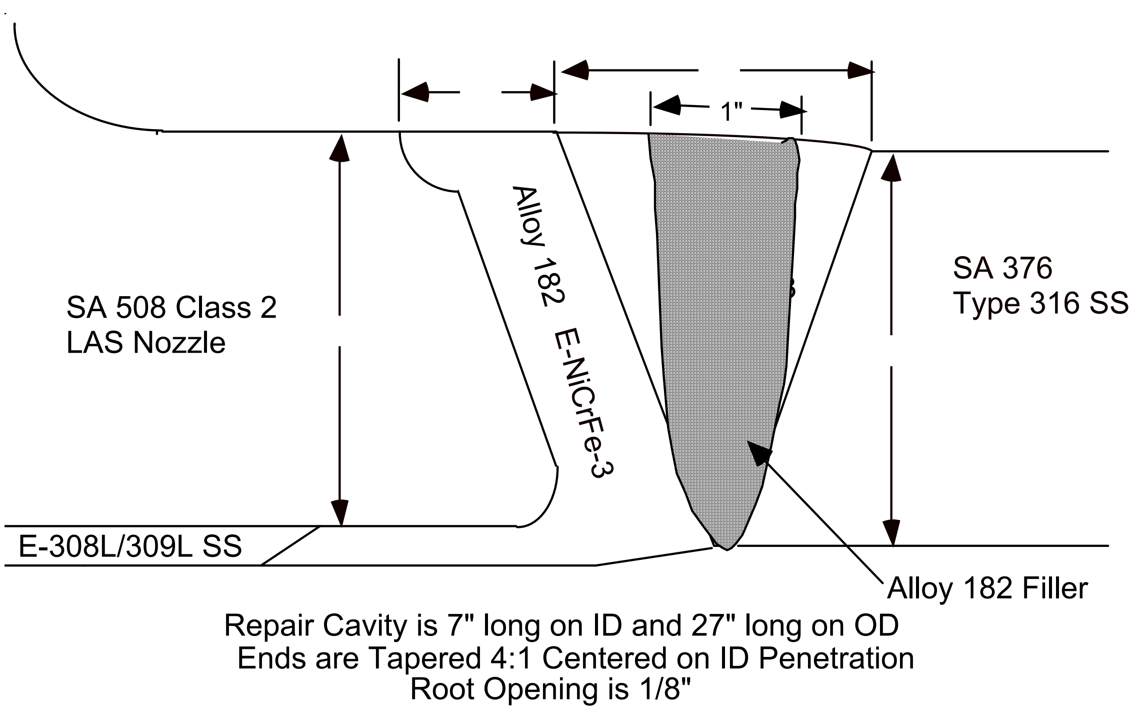


Figure 2-6
Schematic Cross-section for OD Repair of 7" Long Root Defect

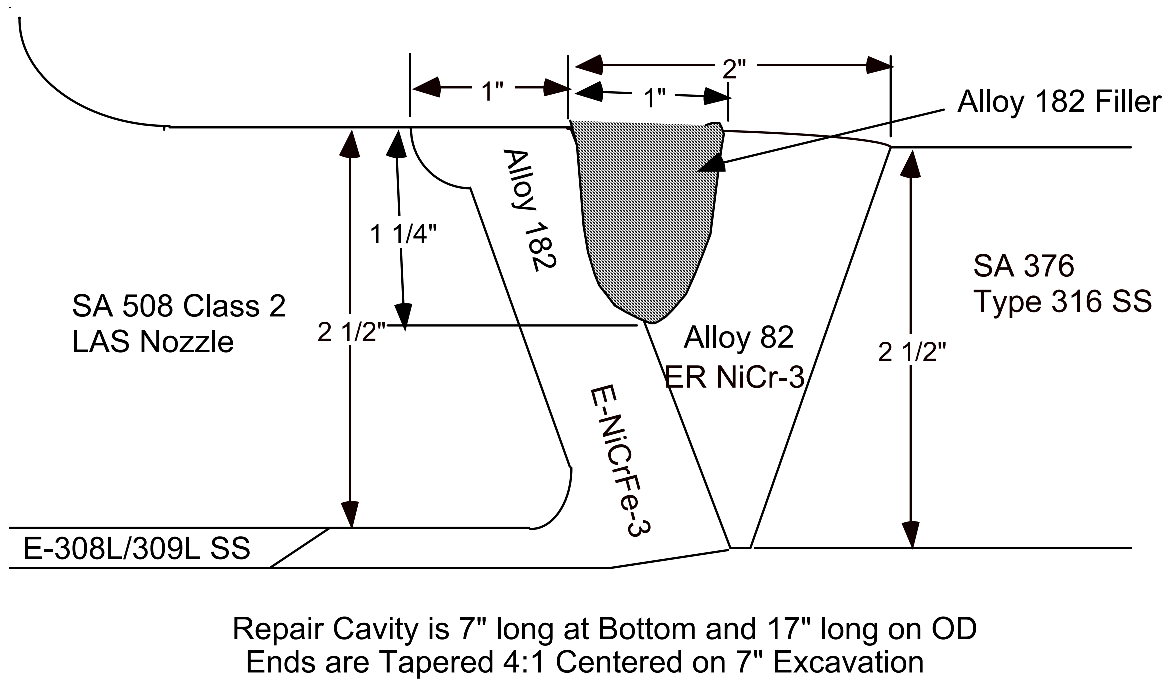


Figure 2-7
Schematic of Cross-section of Limited Length Repair at Mid-wall

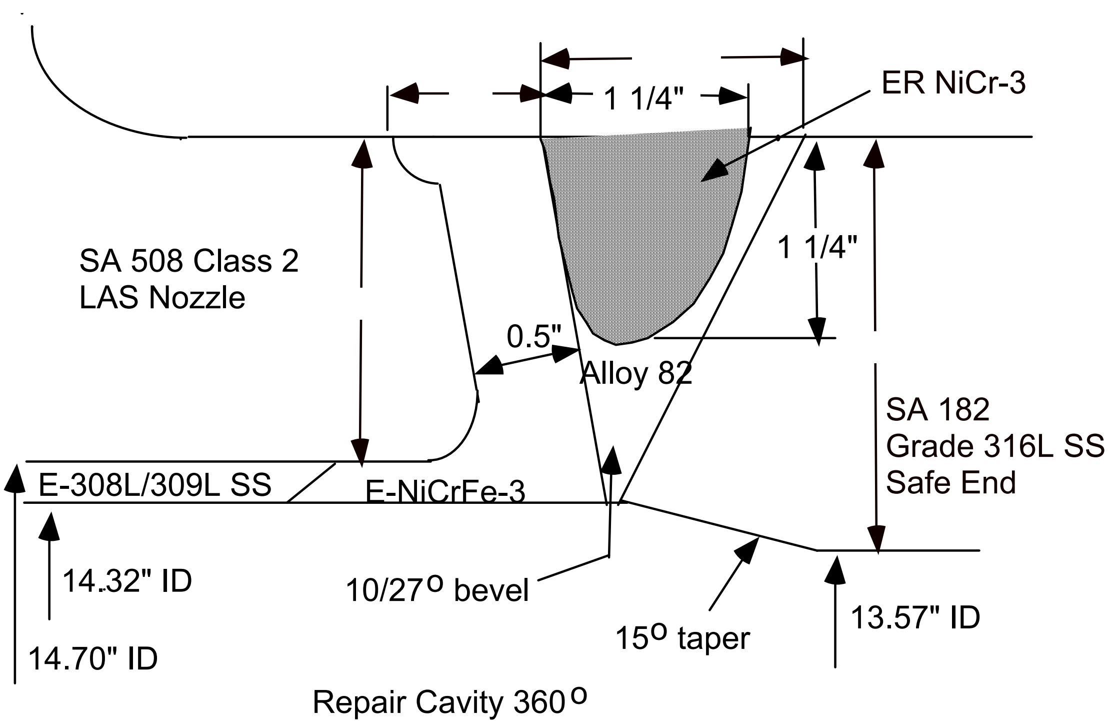
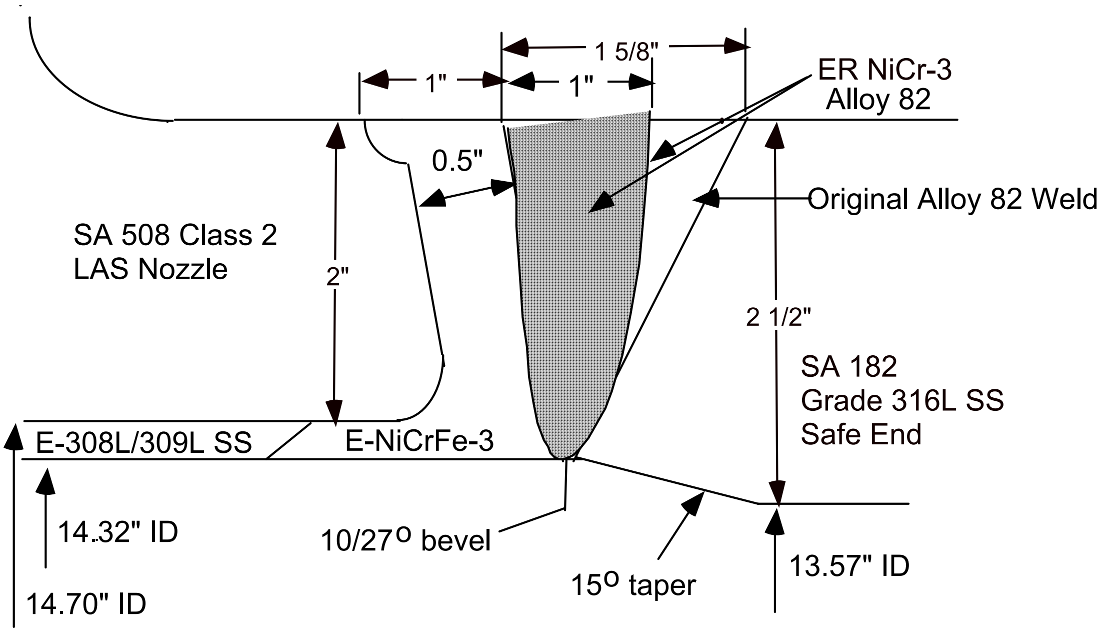
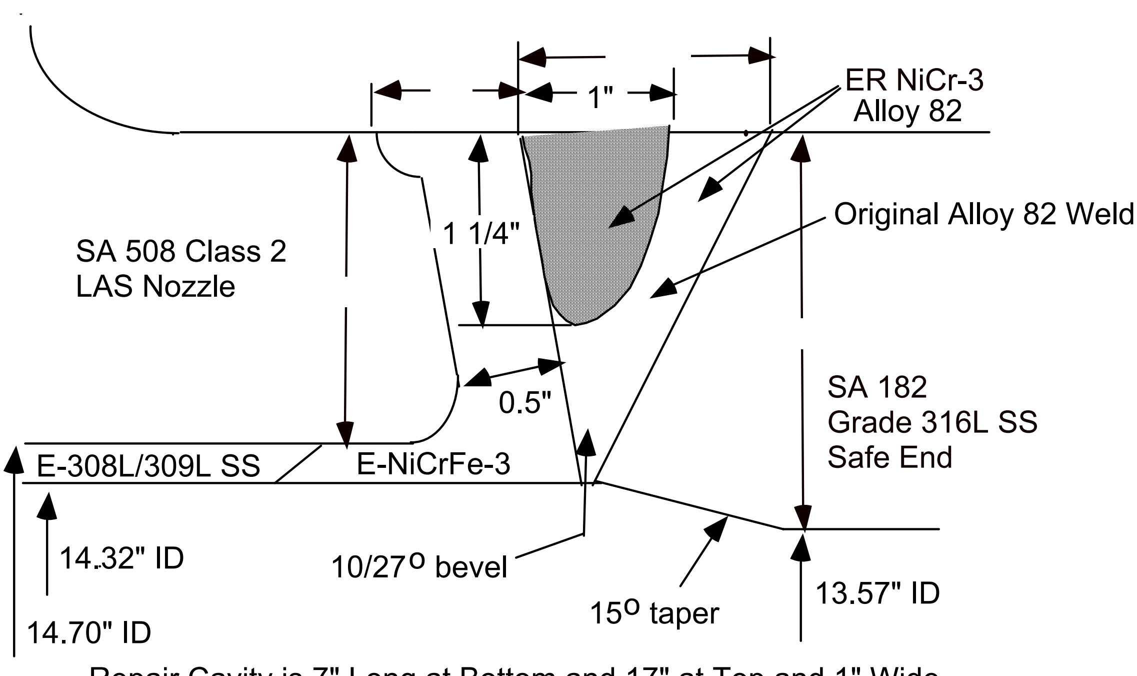


Figure 2-8
Schematic Cross-section of 360^0 Medal Repair to Surge Nozzle



Repair Cavity is 7" Long at Bottom and 24.6" at Top and 1" Wide
Both Ends are Tapered over 8.8" (4:1 taper)
Root opening is 1/8"

Figure 2-9
Schematic Cross-section of 7" Through-wall OD Weld Repair to Surge Nozzle



Repair Cavity is 7" Long at Bottom and 17" at Top and 1" Wide
Both Ends are Tapered over 5" (4:1 taper)

Figure 2-10
Schematic Cross-section of Limited Length Mid-wall Repair from OD of the Nozzle

3
EVALUATION OF PWSCC INITIATION AND GROWTH

This section presents the analysis and results to determine the potential for crack initiation and growth of circumferential flaws in the selected DM butt-welded nozzle locations (RPV outlet nozzle and pressurizer surge nozzle). The intent of the evaluation is to identify locations that may be susceptible to crack initiation and crack growth with respect to the size and position of the weld repair. The evaluation considers single-V as-welded locations and single-V weld repaired locations. Repaired locations include those that are completed from the inside surface and those completed from the outside surface.

Section 2 provided information regarding the types of repairs that may have occurred during construction. The findings in Section 2 showed that significant repairs could have occurred. Some of these were completed on the inside surface and others on the outside surface. The goal of this fracture mechanics evaluation is to determine the locations where crack initiation and growth could occur based on stress and stress intensity factor distributions. If crack initiation could occur at a specific location along the weld inside surface (based on the presence of tensile stress), then it was determined how deep the flaw would be expected to grow based on the through-wall stress intensity factor distribution. This information could be used to compare against leak-before-break and allowable flaw size margins in order to prioritize weld locations for further actions.

It is important to note that the residual stress distributions for repaired and un-repaired (as-welded) butt weld locations can differ significantly. For repaired welds, the residual stress also varies significantly based on which surface the weld repair was completed (ID or OD). Dominion Engineering Incorporated (DEI) in References 1 and 2 performed extensive analysis to determine the residual stress for various repair scenarios. This fracture mechanics analysis uses the stress results form References 1 and 2.

It is well established that welding causes residual stress in the local vicinity to the weld. Also, the weld residual stress decreases rapidly with distance from the weld repair (both circumferentially and axially). In order to incorporate the effect of the rapid decrease in weld residual stress with distance from the weld repair, through-wall stress distributions at various angular locations with respect to the weld repair were used in the fracture mechanics analysis. Figure 3-1 shows these locations as α_1, α_2, and α_3.

Based on PWR experience, there have been very limited incidences of cracking. Besides limited in the number of flaws observed, the size of the observed flaws has been limited. Thus, to determine the potential for crack growth, a small flaw is assumed at various angular locations relative to the weld repair line (see Figure 3-1). Field experience does not support the assumption that an entire weld repair is flawed, which would result in significant assumed flaws based on the findings of Section 2.0 for larger diameter, thick wall components.

3.1 PWSCC Initiation

PWSCC initiation can be caused by the synergistic effects of the three necessary contributing factors: susceptible material, aggressive environment and significant sustained stress. Another source for the presence of flaws is fabrication. Weld defects could serve as starter flaws for crack propagation. In addition, grinding on the weld root on the pipe inside surface could also introduce a cold worked surface with starter notches.

Regardless of how these flaws initiate, they will not continue to propagate unless there is a driving force for crack extension and the driving force must be sufficient to result in a stress intensity factor (K_I) greater than the threshold K_I for the Alloy 182 material. The stress intensity factor is a function of the through-wall stress distribution and is discussed further in Section 3.7.

3.2 Analyzed Configurations

This section summarizes the configurations that were considered in this analysis. As stated above, the as-welded condition was evaluated as well as the repaired condition. For the repaired condition, two configurations were considered, 1) repairs completed from the outside surface and 2) repairs completed from the inside surface.

As will be discussed later in this section, locations that were repaired and completed from the outside surface in thick intermediate diameter piping and thick large diameter piping contain beneficial weld residual stress with respect to crack growth, similar to that for the as-welded conditions. Thus, the focus of the analysis was on locations where the repair was completed on the inside surface.

As discussed in Section 2.0, repairs that were completed from the inside surface could vary in size and since a thorough search of field experience has not been performed, it is prudent to evaluate the general effect of the weld repair circumferential length on the potential for crack initiation and through-wall growth along the entire Alloy 182 ID surface. Thus, the following cases, defined by the circumferential length of the repair (in degrees) were evaluated for the RPV outlet and pressurizer surge nozzles.

1. 30° (8.3% of circumference)
2. 60° (16.7% of circumference)
3. 90° (25% of circumference)

4. 360° (full circumferential repair)

Figure 3-1 is a schematic of a circumferentially oriented weld repair of angular length θ.

For this analysis, the depth of the repair for the RPV outlet nozzle was 0.35 inches (15.2% of wall, same as the VC Summer repair) and for the pressurizer surge nozzle it was 0.55 inches (33% of wall).

3.3 Effect of Repair on Weld Residual Stress

Reference 1 and 2 present extensive analysis performed to determine the residual stress distributions for the RPV outlet nozzle and the pressurizer surge nozzle. The repair configurations selected for the analysis were based in part from the results of Section 2.0 of this report and the VC Summer incident.

The details of the residual stress analyses are not repeated here but can be found in Reference 1 and 2. As stated in Section 3.2, the circumferential length of the weld repairs were equivalent to 30°, 60°, 90°, and 360° of pipe circumference.

3.4 As-Welded Condition

Tensile stresses are necessary for crack initiation and propagation. If compressive stress is present on the pipe inside surface, then typically initiation will not occur. For crack propagation into the pipe wall, the stress distribution must be sufficient to continuously drive a flaw. Even if the stress is sufficiently tensile on the surface to initiate a flaw, if significant compressive stress exists within the pipe wall, crack arrest could occur. This is similar to a case where surface grinding has occurred. Cracking can initiate but arrests rapidly because the stress field induced by the grinding is very shallow.

Figure 3-2 and 3-3 show the residual stress in the RPV outlet nozzle and pressurizer surge nozzles for the as-welded condition. As can be seen from Figures 3-2 and 3-3, the axial residual stress is significantly compressive along the inside of the pipe in the vicinity of the Alloy 182 weld metal. Since compression is present in the material that is susceptible to PWSCC, crack initiation and subsequent propagation would not be expected at this location for the repair cases analyzed.

This is not unexpected since it is known that as pipe thickness increases, the weld residual stress decreases on the inside surface and can become significantly compressive in some cases. This behavior differs from BWR type piping. In BWR piping, dimensions are such that significant tensile stress on the pipe inside surface occurs and this tensile stress was a key factor in intergranular stress corrosion cracking (IGSCC).

Thus, as-welded, unrepaired butt-weld locations are not a concern for crack propagation and will not be considered further in the analysis.

3.5 Repaired Condition

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3.6 Applied Loading

In order to assess PWSCC initiation and crack growth, the total sustained stresses must be determined. For the locations being considered, the stresses are due to weld residual, pressure, deadweight and other applied piping loads including those due to thermal expansion. Note that for PWSCC, cyclic loading is not considered, as the contribution from fatigue is not significant. References 1 and 2 provide the weld residual stress and pressure stress at the locations of interest.

In addition to the weld residual and pressure loading, other sustained piping loads are present. These include those from deadweight and thermal expansion (RFE). These loads are sustained and must be included when performing the determination of crack initiation and crack growth. Due to the difficulty in obtaining plant specific piping loads, a parametric evaluation was performed. The applied piping loads were assumed to be 50%, 75%, 100% and 125% of the material design stress intensity (S_m). S_m is the design stress intensity for seamless high temperature steel pipe material SA-376 Type 304N which is equal to 17.6 ksi at 650°F, taken from [3]. Of this stress, 1 ksi was assumed to be an axial membrane load and the remainder was assumed to be an overturning moment.

In the analysis, three assumptions were made regarding the orientation of the applied moment and the orientation of the weld repair. In the first case, the applied moment was assumed to be aligned with the weld repair such that the maximum bending stress occurred at the center of the weld repair. In this case, the bending stress would decrease with angle from the center of the weld repair.

In the second case, the orientation of the applied moment was varied from 0 to 180 .

In the last case, the maximum applied bending stress was assumed to be applied to the entire section of the pipe (see Figure 3-6b). This is the bounding case.

3.7 Fracture Mechanics Evaluation

This section describes the fracture mechanics assessment using the applied loads described in Section 3.6. The purpose of this evaluation is to determine the extent of area where it may be possible for a flaw to initiate. If the flaw can initiate, the analysis also determines the depth to which the flaw could grow based on the through-wall stress intensity factor distribution at the specific angular location being analyzed. The process can be described as follows:

1) For a given nozzle and weld repair configuration, obtain the through-wall stress distributions at selected azimuthal locations (the αs in Figure 3-1).

2) If the stress is tensile on the surface, then it is assumed that the flaw can initiate (Note, this does not account for residual stress due to grinding).

3) If the flaw can initiate, then the depth to which the flaw could propagate is determined based on the through-wall stress intensity factor distribution. The potential crack depth is the depth when the stress intensity factor drops below the threshold stress intensity factor for PWSCC growth.

This process produces a "map" of angular locations where PWSCC initiation could occur and if it occurs, the depth to which a flaw could grow based on the through-wall stress intensity factor distribution. The important feature from this analysis is that it shows where a through-wall or deep partial-wall flaw could occur if initiated.

3.7.1 Stress Intensity Factor Calculation

The stress intensity factor is calculated at selected angles from the edge of the weld repair. The K_I solution considers the stress distribution through the wall due to the total sustained stress, which includes the weld residual and pressure stress, and the axial and bending stress due to the applied piping loads.

The K_I solution from Reference 4 is:

$$K_I = [\sigma_0 i_0 + \sigma_1 i_1 (a) + \sigma_2 i_2 a^2 + \sigma_3 i_3 a^3 + \sigma_{gb} F_b]\sqrt{\pi \cdot a} \tag{3-1}$$

where, a = crack depth measured from inside diameter surface, inches

i_0, i_1, i_2, i_3 and F_b are the influence coefficients for a given crack-depth-to-wall-thickness ratio, a/t. These are interpolated from the tables in [4].

σ_0, σ_1, σ_2, and σ_3 are the curve fit coefficients of the residual stress plus pressure distributions of the form $\sigma = \sigma_0 + \sigma_1 x + \sigma_2 x^2 + \sigma_3 x^3$, where x = distance from the inside surface.

σ_{gb} = global moment bending stress. The value of the global moment bending stress is assumed to vary from $0.5S_m$ to$1.25S_m$ in increments of $0.25S_m$.

The axial stress distributions are given for six circumferential locations with respect to the weld repair position. Figure 3-6 shows the orientation of the locations with the weld repair position.

For purposes of this calculation, the assumed circumferential crack has a depth-to-length ratio, a/2c, of 1/6 (see Figure 3-7), where c is the half-crack length.

3.7.2 Determining Potential Crack Growth

Potential crack growth was evaluated by first determining if the total sustained stress on the inside surface is tensile at the various circumferential locations, which indicates initiation might occur. If the total stress is compressive on the inside surface, then crack initiation will not occur. Note that this does not include consideration for residual stress due to local grinding. Local grinding would result in a very thin layer of tensile stress, possibly causing initiation of a flaw, but the flaw would be very limited in depth since the tensile stress decreases very rapidly.

If the stress is tensile on the inside surface, the next step was to determine the potential crack depth. This was performed by determining the depth where the stress intensity factor drops below the threshold stress intensity factor for PWSCC. Reference 14 reports that the threshold K_I for PWSCC was essentially zero.

3.8 Results

3.8.1 Stress Intensity Factor Distribution

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3.8.2 Potential Crack Depth

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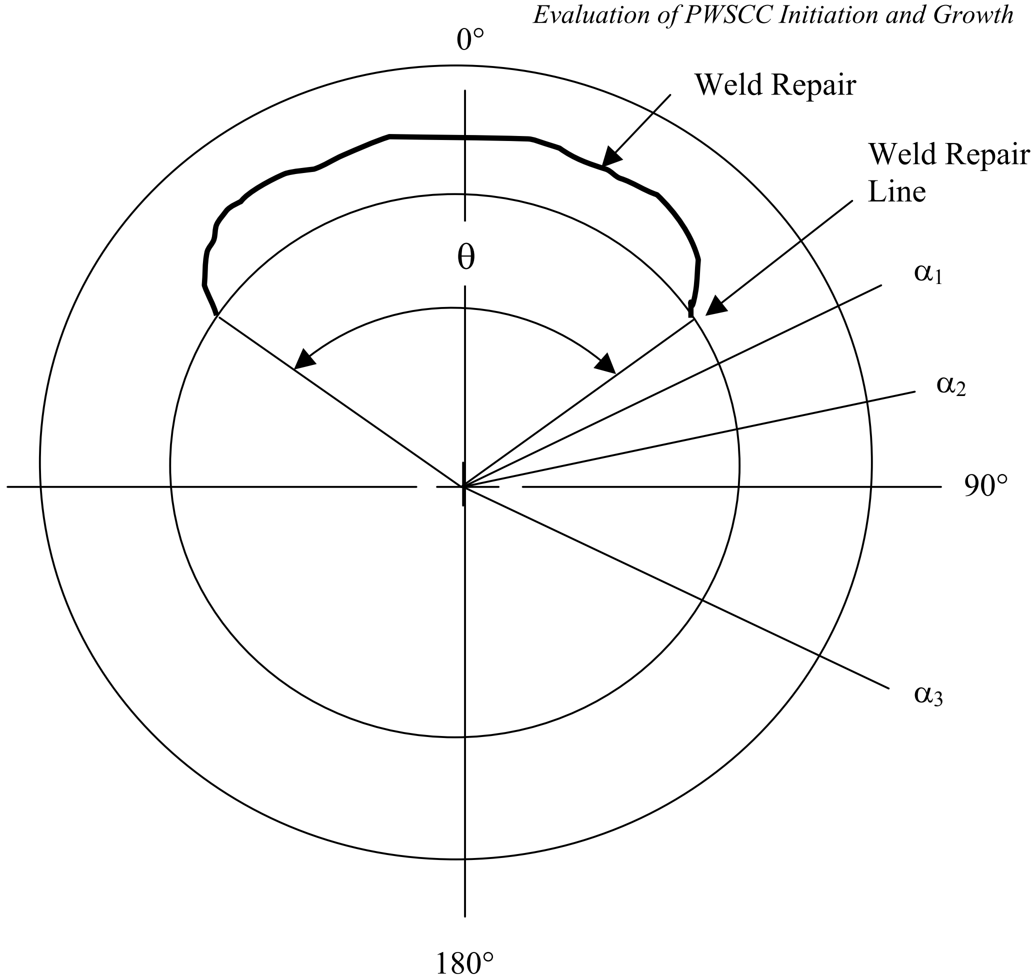

Figure 3-1
Circumferential Extent of Repair

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Figure 3-2
Residual Stress for As-welded RPV Outlet Nozzle

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Figure 3-3
Residual Stress for As-welded Pressurizer Surge Nozzle

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Figure 3-4
Residual Stress Along Inside Surface for RPV Outlet Nozzle Repaired from OD

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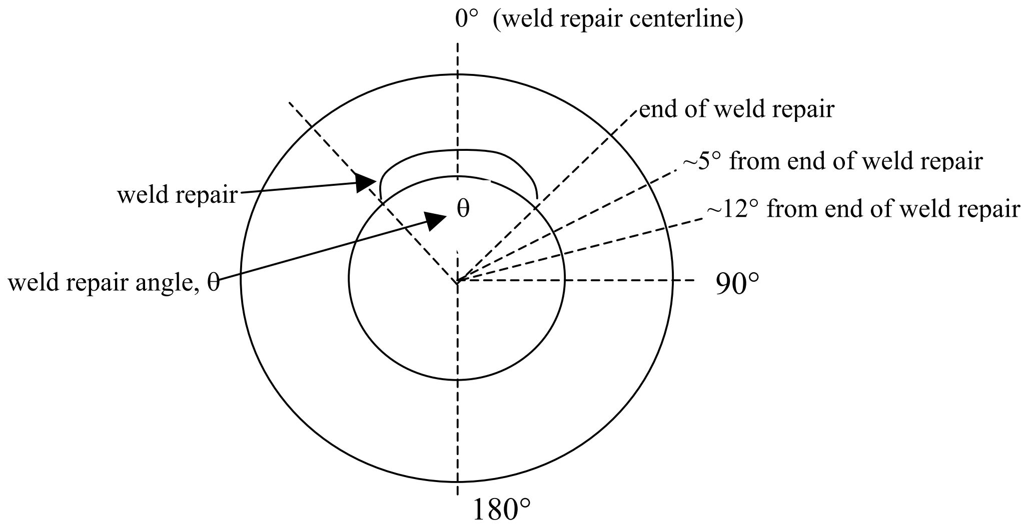
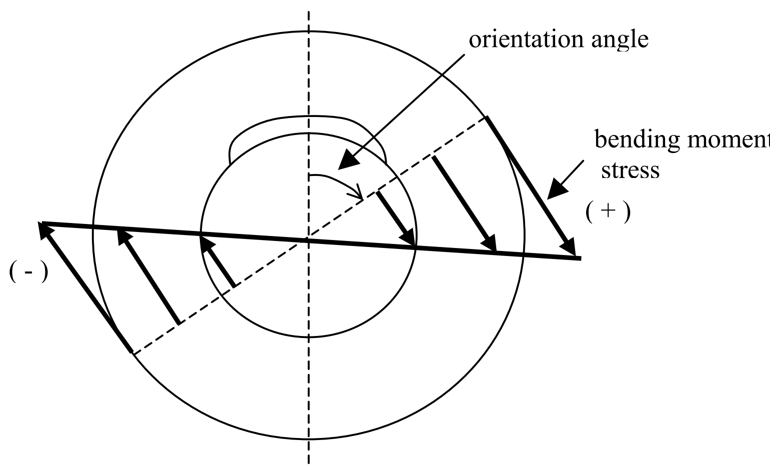
Figure 3-5
Residual Stress Along Inside Surface for RPV Outlet Nozzle Repaired from ID



a) Pipe Cross-Section Showing Weld Repair



b) Global Moment Orientation

Figure 3-6
Angular Locations Where Stresses Reported

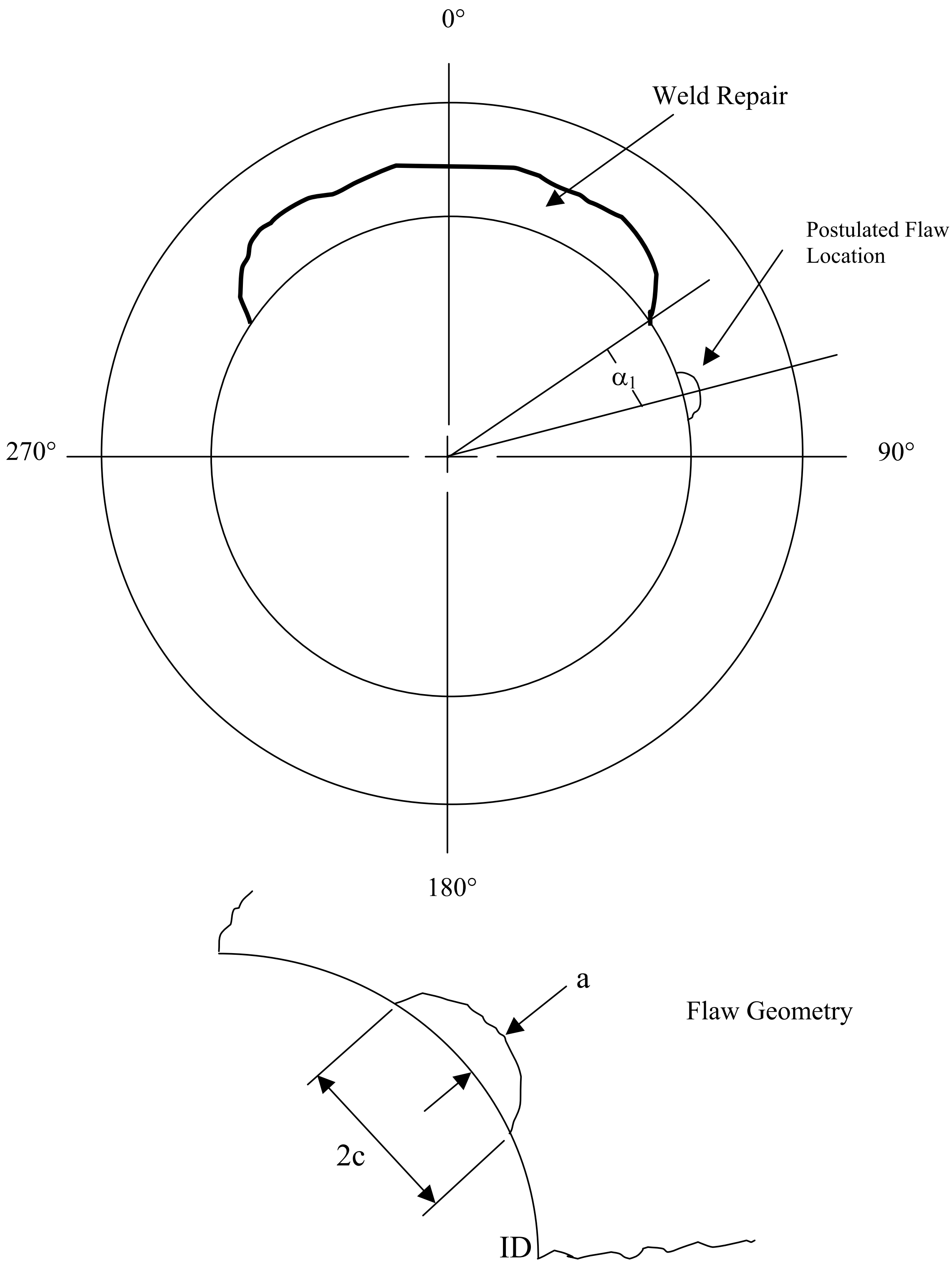


Figure 3-7
Schematic of Flaw Orientation and Geometry

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Figure 3-8
Stress Intensity Factor Distribution for RPV Outlet Nozzle, 30° Weld Repair, 0.5S_m for Maximum Bending Stress Applied Uniformly

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Figure 3-9
Stress Intensity Factor Distribution for RPV Outlet Nozzle, 30° Weld Repair, 1.25S_m for Maximum Bending Stress Applied Uniformly

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Figure 3-10
Stress Intensity Factor Distribution for RPV Outlet Nozzle, 360° Weld Repair, 0.5S_m for Maximum Bending Stress Applied Uniformly

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Figure 3-11
Stress Intensity Factor Distribution for RPV Outlet Nozzle, 360° Weld Repair, 1.25S_m for Maximum Bending Stress Applied Uniformly

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Figure 3-12
Stress Intensity Factor Distribution, Press. Surge Nozzle, 30° Weld Repair, 0.5S_m for Maximum Bending Stress Applied Uniformly

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Figure 3-13
Stress Intensity Factor Distribution, Press. Surge Nozzle, 30° Weld Repair, 1.25S_m for Maximum Bending Stress Applied Uniformly

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Figure 3-14
Stress Intensity Factor Distribution, Press. Surge Nozzle, 360° Weld Repair, 0.5S_m for Maximum Bending Stress Applied Uniformly

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Figure 3-15
Stress Intensity Factor Distribution, Press. Surge Nozzle, 360° Weld Repair, 1.25S_m for Maximum Bending Stress Applied Uniformly

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Figure 3-16
Stress Intensity Factor Distribution, RPV Outlet Nozzle, 30° Weld Repair, $0.5S_m$ Varying for Maximum Bending Stress Aligned with Center of Weld Repair

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Figure 3-17
Stress Intensity Factor Distribution, RPV Outlet Nozzle, 30° Weld Repair, $1.25S_m$ Varying for Maximum Bending Stress Aligned with Center of Weld Repair

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Figure 3-18
Stress Intensity Factor Distribution, RPV Outlet Nozzle, 360° Weld Repair, 0.5S_m Varying for Maximum Bending Stress Aligned with Center of Weld Repair

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Figure 3-19
Stress Intensity Factor Distribution, RPV Outlet Nozzle, 360° Weld Repair, 1.25S_m Varying for Maximum Bending Stress Aligned with Center of Weld Repair

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Figure 3-20
Stress Intensity Factor Distribution, RPV Outlet Nozzle, 30° Weld Repair, 0.5S_m Varying for Maximum Bending Stress Aligned with Center of Weld Repair

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Figure 3-21
Stress Intensity Factor Distribution, RPV Outlet Nozzle, 30° Weld Repair, 1.25S_m Varying for Maximum Bending Stress Aligned with Center of Weld Repair

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Figure 3-22
Stress Intensity Factor Distribution, RPV Outlet Nozzle, 360° Weld Repair, 0.5S_m Varying for Maximum Bending Stress Aligned with Center of Weld Repair

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Figure 3-23
Stress Intensity Factor Distribution, RPV Outlet Nozzle, 360° Weld Repair, 1.25S_m Varying for Maximum Bending Stress Aligned with Center of Weld Repair

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Figure 3-24
Potential Crack Growth vs. Angular Location from End of Weld Repair, RPV Outlet Nozzle, 30° Weld Repair for Maximum Bending Stress Applied Uniformly

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Figure 3-25
Potential Crack Growth vs. Angular Location from End of Weld Repair, RPV Outlet Nozzle, 60° Weld Repair for Maximum Bending Stress Applied Uniformly

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Figure 3-26
Potential Crack Growth vs. Angular Location from End of Weld Repair, RPV Outlet Nozzle, 90° Weld Repair for Maximum Bending Stress Applied Uniformly

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Figure 3-27
Potential Crack Growth vs. Angular Location from End of Weld Repair, RPV Outlet Nozzle, 360° Weld Repair for Maximum Bending Stress Applied Uniformly

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Figure 3-28
Potential Crack Growth vs. Angular Location from End of Weld Repair, Pressurizer Surge Nozzle, 30° Weld Repair for Maximum Bending Stress Applied Uniformly

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Figure 3-29
Potential Crack Growth vs. Angular Location from End of Weld Repair, Pressurizer Surge Nozzle, 60° Weld Repair for Maximum Bending Stress Applied Uniformly

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Figure 3-30
Potential Crack Growth vs. Angular Location from End of Weld Repair, Pressurizer Surge Nozzle, 90° Weld Repair for Maximum Bending Stress Applied Uniformly

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Figure 3-31
Potential Crack Growth vs. Angular Location from End of Weld Repair, Pressurizer Surge Nozzle, 360° Weld Repair for Maximum Bending Stress Applied Uniformly

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Figure 3-32
Potential Crack Growth vs. Angular Location from End of Weld Repair, RPV Outlet Nozzle, 30° Weld Repair Varying for Maximum Bending Stress Aligned with Center of Weld Repair

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Figure 3-33
Potential Crack Growth vs. Angular Location from End of Weld Repair, RPV Outlet Nozzle, 60° Weld Repair Varying for Maximum Bending Stress Aligned with Center of Weld Repair

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Figure 3-34
Potential Crack Growth vs. Angular Location from End of Weld Repair, RPV Outlet Nozzle, 90° Weld Repair for Maximum Bending Stress Aligned with Center of Weld Repair

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Figure 3-35
Potential Crack Growth vs. Angular Location from End of Weld Repair, RPV Outlet Nozzle, 360° Weld Repair for Maximum Bending Stress Aligned with Center of Weld Repair

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Figure 3-36
Potential Crack Growth vs. Angular Location from End of Weld Repair, Pressurizer Surge Nozzle, 30° Weld Repair for Maximum Bending Stress Aligned with Center of Weld Repair

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Figure 3-37
Potential Crack Growth vs. Angular Location from End of Weld Repair, Pressurizer Surge Nozzle, 60° Weld Repair for Maximum Bending Stress Aligned with Center of Weld Repair

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Figure 3-38
Potential Crack Growth vs. Angular Location from End of Weld Repair, Pressurizer Nozzle, 90° Weld Repair for Maximum Bending Stress Aligned with Center of Weld Repair

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Figure 3-39
Potential Crack Growth vs. Angular Location from End of Weld Repair, Pressurizer Nozzle, 360° Weld Repair for Maximum Bending Stress Aligned with Center of Weld Repair

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Figure 3-40
Potential Crack Growth vs. Moment Orientation, RPV Outlet Nozzle, 30° Weld Repair, 0.5S_m

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Figure 3-41
Potential Crack Growth vs. Moment Orientation, RPV Outlet Nozzle, 30° Weld Repair, 0.75S_m

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Figure 3-42
Potential Crack Growth vs. Moment Orientation, RPV Outlet Nozzle, 30° Weld Repair, 1.0S_m

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Figure 3-43
Potential Crack Growth vs. Moment Orientation, RPV Outlet Nozzle, 30° Weld Repair, 1.25S_m

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Figure 3-44
Potential Crack Growth vs. Moment Orientation, RPV Outlet Nozzle, 90° Weld Repair, 0.5S_m

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Figure 3-45
Potential Crack Growth vs. Moment Orientation, RPV Outlet Nozzle, 90° Weld Repair, 0.75S_m

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Figure 3-46
Potential Crack Growth vs. Moment Orientation, RPV Outlet Nozzle, 90° Weld Repair, 1.0S_m

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Figure 3-47
Potential Crack Growth vs. Moment Orientation, RPV Outlet Nozzle, 90° Weld Repair, 1.25S_m

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Figure 3-48
Potential Crack Growth vs. Moment Orientation, Pressurizer Surge Nozzle, 30° Weld Repair, 0.5S_m

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Figure 3-49
Potential Crack Growth vs. Moment Orientation, Pressurizer Surge Nozzle, 30° Weld Repair, 0.75S_m

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Figure 3-50
Potential Crack Growth vs. Moment Orientation, Pressurizer Surge Nozzle, 30° Weld Repair, 1.0S_m

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Figure 3-51
Potential Crack Growth vs. Moment Orientation, Pressurizer Surge Nozzle, 30° Weld Repair, 1.25S_m

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Figure 3-52
Potential Crack Growth vs. Moment Orientation, Pressurizer Surge Nozzle, 90° Weld Repair, 0.5S_m

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Figure 3-53
Potential Crack Growth vs. Moment Orientation, Pressurizer Surge Nozzle, 90° Weld Repair, 0.75S_m

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Figure 3-54
Potential Crack Growth vs. Moment Orientation, Pressurizer Surge Nozzle, 90° Weld Repair, 1.0S_m

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Figure 3-55
Potential Crack Growth vs. Moment Orientation, Pressurizer Surge Nozzle, 90° Weld Repair, 1.25S_m

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Figure 3-56
Potential Crack Growth vs. Crack Location, RPV Outlet Nozzle, 30° Weld Repair, 0.5S_m

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Figure 3-57
Potential Crack Growth vs. Crack Location, RPV Outlet Nozzle, 30° Weld Repair, 0.75S_m

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Figure 3-58
Potential Crack Growth vs. Crack Location, RPV Outlet Nozzle, 30° Weld Repair, 1.0S_m

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Figure 3-59
Potential Crack Growth vs. Crack Location, RPV Outlet Nozzle, 30° Weld Repair, 1.25S_m

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Figure 3-60
Potential Crack Growth vs. Crack Location, Pressurizer Surge Nozzle, 30° Weld Repair, 0.5S_m

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Figure 3-61
Potential Crack Growth vs. Crack Location, Pressurizer Surge Nozzle, 30° Weld Repair, 0.75S_m

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Figure 3-62
Potential Crack Growth vs. Crack Location, Pressurizer Surge Nozzle, 30° Weld Repair, 1.0S_m

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Figure 3-63
Potential Crack Growth vs. Crack Location, Pressurizer Surge Nozzle, 30° Weld Repair, 1.25S_m

4
BWR EXPERIENCE

Weld residual stress studies for very long or fully circumferential weld repairs completed on the inside surface have shown that significant through-wall cracking cannot be ruled out. However, this concern is predicated on the assumption that a very long or fully circumferential flaw was to initiate. At the Duane Arnold Energy Center (DAEC), a BWR, an essentially 360° flaw was found in 1978 and in fact a portion of the crack was found to be through-wall.

This section presents a discussion regarding the potential for a DAEC type incident in PWRs and also discusses the potential for 360° initiation due to grinding. Section 3 shows that given the sustained stress profiles, long flaws could occur based solely on stress and stress intensity factor considerations.

4.1 Comparison of Duane Arnold Safe-end Cracking to Alloy 600 PWSCC

The purpose of this section is to review the 1978 Duane Arnold Energy Center (DAEC) Alloy 600 recirculation nozzle safe end intergranular stress corrosion cracking (IGSCC) incident, the reduction in leak before break margins and to identify the similarities, if any, with repaired Alloy 600 PWR butt-welded piping.

4.1.1 Background

A slow increase in unidentified leakage was identified at DAEC on May 1, 1978 [5]. By June 14, 1978 the unidentified drywell leakage had increased from approximately 1 gpm to 3 gpm. At 00:55 am on June 17, 1978, an automatic reactor scram occurred due to problems in the reactor protection system relays during weekly control valve testing. DAEC decided to reduce reactor pressure, de-inert the containment, enter the containment and investigate the leakage. A survey of the drywell identified a leak in the vicinity if the N2A recirculation inlet nozzle similar to that presented in Figure 4-1. The actual source of the leak was made on June 17, 1978. The safe-ends on all eight recirculation inlet nozzles were visually, ultrasonically and radiographically examined. A 90-degree through-wall circumferential crack was observed on the N2A nozzle. Additional indications for 180 degrees on the inside diameter (ID) were identified. Cracks were identified on all of the remaining safe-ends.

4.1.2 Causal Factors for DAEC Safe-End IGSCC

The cracked DAEC safe-end was destructively examined at the Southwest Research Institute (SWRi) [5]. Results from metallographic examination indicated that the mode of cracking was IGSCC and existed 360 degrees around some of the safe end as sketched in Figure 4-2 based on a figure from Reference 5. General Electric Nuclear Energy (GENE) performed an independent evaluation and agreed with the SWRi evaluation [5]. The results of the examination yield several causal factors for the IGSCC at DAEC:

- The design of the safe-end was deficient for the intended application in that an electrochemical crevice was created where the thermal sleeve was attached to the safe-end with a partial penetration weld, Figures 4-2 and 4-3. The presence of a crevice results in premature IGSCC initiation in even high purity BWR-type environments [7]. When detrimental impurities such as sulfate and/or chloride are present, the detrimental effects of crevices are intensified. A discussion of the effect of crevices on IGSCC propensities are provided in the DAEC report and summarized in Figure III.B.2-9 [8] and in Figure 4-4 in this report. Small specimen test results for creviced and uncreviced Alloy 600 are shown in Figure III.B.2-4 of the DAEC report as updated in Figure 4-5 in this report.

- As noted above, sulfate accelerates IGSCC initiation and propagation [7-9]. Unfortunately, approximately 800 pounds of resin was inadvertently dumped into the DAEC pressure vessel during start-up in 1975 [10]. Although the system was cleaned up as best as possible at the time, any residual resin degrades into sulfate with irradiation. Sulfur was clearly identified in the crack tip of the cracked safe-end.

- High residual tensile stresses resulted from the shrinkage of the attachment weld as it cooled [5]. Estimates were made of the rate of cracking in the report based on the stress rule index [5]. It was reported that the creviced safe-end stress rule index (SRI) was 2.24 compared to 0.73 for the later design. This SRI was the highest in the BWR fleet. The result was confirmed by Battelle Columbus Laboratories (BCL) by a time history analysis that considered weld input parameters and utilized a temperature dependent material stress-strain curve and shown in Figure III.C.8-4 in the report [5]. The evaluation results indicated that above yield tensile stresses existed over the entire safe-end side of the crevice. The stress results are consistent with the location of the cracking.

- The susceptible region formed adjacent to the weld in the safe-end was caused by re-solutioning of the carbide phase and subsequent grain boundary precipitation. This was confirmed by the metallographic results from samples etched by phosphoric acid [5].

- In addition several weld repairs and associated grinding were performed on the weld. This would have contributed to both the premature crack initiation and propagation of cracking by further reducing the corrosion resistance of Alloy 600 due to additional heating from the weld repairs and the increase the yield strength. The cold working of the Alloy 600 from the grinding would also reduce the creviced material's IGSCC resistance.

4.1.3 Remaining Margin in the DAEC Degraded Safe-end

A leak-before-break (LBB) discussion was included in the DAEC report [5]. A calculation using net section collapse was performed for a 12-inch diameter pipe. The results of the calculation indicated that the critical through-wall circumferential flaw length was 20.7 inches. However, it appears that the calculation did not account for the 90% through-wall cracking that existed in the safe-end. In addition, there was no consideration for the properties of the flux welded Alloy 182 in the calculation. The ASME Code now requires that this reduction in toughness be addressed when flux welds are evaluated. With hindsight, it does not appear reasonable that a pipe with only 10% of the wall remaining would have a critical crack size of over 20 inches.

The crack length for a 5-gpm leak from the 12-inch diameter pipe at normal operating conditions was calculated as 7.4 inches. The existing crack in the safe-end (approximately 9 inches) leaked at a rate of 3.2 gpm. Qualitative arguments were made that additional leakage at high rates would be expected because of the high plasticity of the material. Studies were performed at Argonne National Laboratory (ANL) where leakage rates from actual IGSCC cracks were measured.

4.1.4 Applicability of DAEC Alloy 600 Safe End to Alloy 600 PWSCC

Section 4.1.2 of this evaluation presented the causal factors for the 1978 DAEC Alloy 600 recirculation inlet nozzle IGSCC. The focus in this section is to evaluate if a similar failure could occur in a PWR Alloy 600 butt-weld joint.

The typical stress distributions determined by modeling cooling of butt welds in large diameter piping greater than approximately 12 inch diameter (typically 1-inch in thickness or greater) welded from the outside have residual stress distributions that are "C"-shaped where tensile stresses are high on the ID and OD surfaces and compressive near the pipe mid-wall. This is in contrast to the case at DAEC where a thermal sleeve was attached to the ID of the safe-end by a partial penetration weld. An electrochemical crevice was formed between the pipe ID and the OD of the thermal sleeve at DAEC. Furthermore, the residual stresses from the attachment were highly tensile at the tip of the crevice.

IGSCC tests of uncreviced Alloy 600 in a BWR environment have shown that high tensile stresses are needed for crack initiation. In fact, no uncreviced Alloy 600 component has suffered IGSCC in the BWR. The only uncreviced Alloy 600 IGSCC identified in an operating BWR occurred on a pressurized tube test specimen that had a

90% through-wall crack after seven years of exposure at an applied stress ratio of 1.4. (See the solid point pinning the uncreviced Alloy 600 IGSCC curve in Figure 4-5.)

It would be expected that a poorly designed weld configuration similar to the DAEC safe-end might also suffer cracking in a PWR environment. If weld repairs were performed in a PWR from the pipe ID the residual stress distribution would be altered such that high tensile stresses could exist essentially through-wall. Significant repairs on the ID of a butt weld could result in a stress distribution that could initiate and drive a long circumferential crack both through-wall and circumferentially. Also, welding from both the OD and ID could result in an unfavorable tensile stress distribution through the pipe wall. In addition, welding with Alloy 600 filler material can be difficult. Defects such as fissuring and hot tearing are not uncommon and construction and in-service examinations may not identify these defects. Hot tearing, if open to the environment and of sufficient size, could serve as initiation sites for PWSCC.

The following is an item-by-item assessment of the DAEC causal factors as applied to the PWR butt-welded locations.

1. The severe crevice at DAEC and the associated high stresses at the crevice tip increase the likelihood of a 360-degree crack. Even if the PWR butt-weld location were repaired along the full circumference on the ID, it is not as likely that a full 360 degree flaw would develop since an electrochemical crevice is unlikely to be established in the deaerated PWR primary water environment [11]. Although the possibility of multiple initiation points cannot be eliminated, the same fully circumferential condition thus does not exist in the PWR butt weld case. However, if a thermal sleeve were attached in a similar manner to DAEC, it is possible that accelerated PWSCC could occur, due primarily to unfavorable residual stresses.

2. Sulfates are the most detrimental anion in the BWR environment [8] and were responsible for premature IGSCC of the Alloy 600 safe ends at DAEC. Although the presence of sulfates can increase crack propagation in deaerated, neutral environments, Figure 6 of Reference 12, these and other anions, such as chloride and fluoride, do not have a detrimental effect to the same degree on PWSCC of Alloy 600 in the buffered primary water environment [13]. Therefore, if proper cleaning controls are maintained prior to welding and EPRI PWR water chemistry guidelines are followed during start-up, operation and shutdown it is much less likely that sufficient impurities would be present to facilitate cracking in any crevice.

3. If a significant number of repairs and excessive grinding were performed on the ID of a butt weld in a PWR, high stresses and abnormal stress distributions may develop. In addition, significant grinding on the ID surface would cold work the materials and decrease time for crack initiation. However, it is not likely that cracks would grow in a uniform manner similar to the DAEC safe-end since the residual stresses associated with repairs and other bending loads would cause

cracks to propagate with aspect ratios high enough to produce leaks, i.e., LBB, before any encroachment were made on the critical crack size.

4.1.5 Conclusion

The likelihood of obtaining cracking similar to that observed at DAEC in PWR piping is considered remote, primarily because any PWSCC in Alloy 600 butt weldments and its associated weld filler metals would not be creviced. In fact, even if a crevice configuration was present, crevices are not as electrochemically detrimental in deaerated environments.

4.1.6 Recommendations

Based on the above discussion and conclusion, the following recommendations are suggested:

The fabrication practices for welding Alloy 600 safe-ends/butters should be reviewed to ascertain the suitability of welding practices for the specific components. The designs of thermal sleeve attachments should be compared to the DAEC design relative to partial penetration welds, crevice geometry, etc.

A survey of PWR owners should be performed to identify Alloy 600 components/weldments that have significant repairs or that have crevices and high residual stresses. These locations should be added to the owner's ISI program.

A program should be formulated to identify the required examinations. The examinations should be performed using methods demonstrated capable of reliably detecting flaws of the size of interest. Flaw size of interest should be determined from fracture mechanics and flaw growth considerations. Associated risk improvement should be determined to establish inspection and re-inspection frequencies.

4.2 Effects of Grinding on Initiation and Growth of PWSCC

As mentioned earlier, grinding of the inside surface near welds was a common practice during construction. Section 4.1 presented the justification why a DAEC type 360° flaw would not occur in a PWR. One other concern is the effect of extensive grinding on the pipe inside surface. If grinding can initiate flaws, there may be concern that if grinding were performed around the entire inside surface, a 360° flaw might initiate and grow.

Grinding, even if performed over the entire 360-degrees of circumference, is never uniform in depth or intensity. It is a function of the weld inside surface condition, and contour, and includes light or no grinding at some azimuths and heavy grinding at other azimuthal locations. The condition of the weld root also has a profound effect on the intensity of the grinding. Thus, although 360° grinding may have occurred, there is significant variation around the circumference in terms of the driving force for initiation and growth.

Field experience and laboratory results suggest that initiation of PWSCC is very difficult. It would be expected that initiation would be very limited, not at all similar to BWR experience, where electrochemical crevices can be present, giving rise to uniform crack initiation. As discussed in Section 4.1, no such crevice mechanism is known for PWRs.

Besides the non-uniformity of the grinding on the inside surface, there are other factors that would not favor uniform initiation at all grinding locations. Applied loading is non-uniform. Bending moments add to the overall load, and produce preferred locations for crack initiation. Field experience has also shown that weld residual stress, although predicted to behave smoothly in Reference 6, tends to demonstrate some variation on the inside surface of the weld, also contributing to non-uniform initiation.

Even if cracking were to initiate due to grinding, the cracking is expected to be minor. Any cracking that initiates due to grinding, will arrest near the ID surface, since the residual stress due to grinding is very local to the pipe surface (of the order if 10's of mils), and the weld residual stresses on these thick wall components will promote crack arrest.

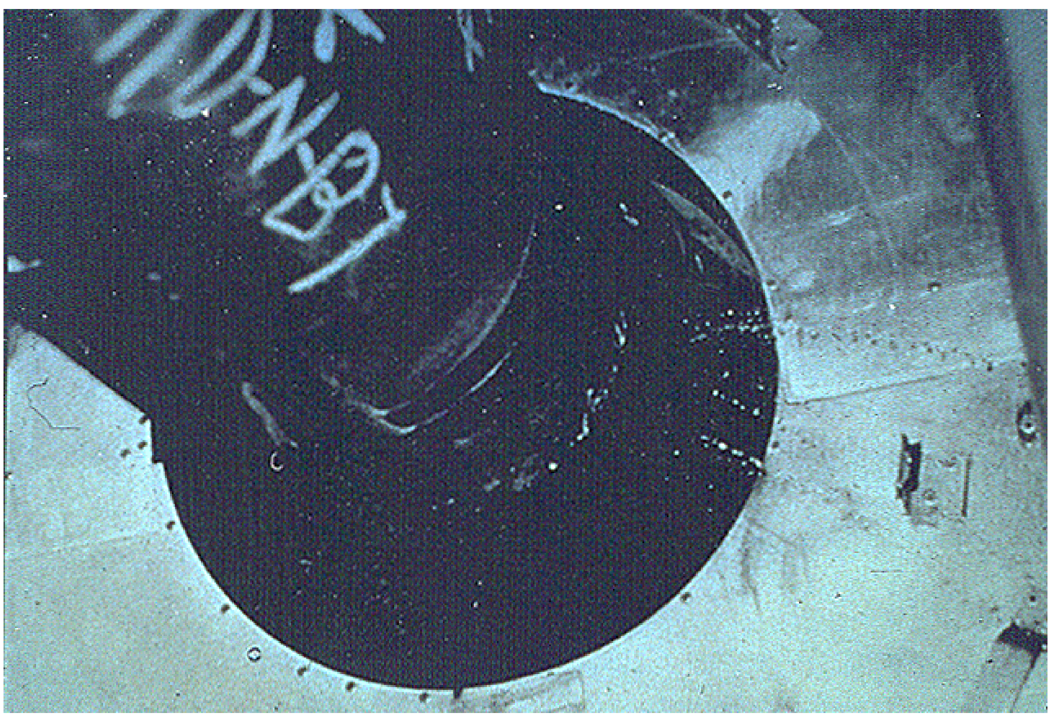

Figure 4-1
Leaking Alloy 600 Safe End at DAEC

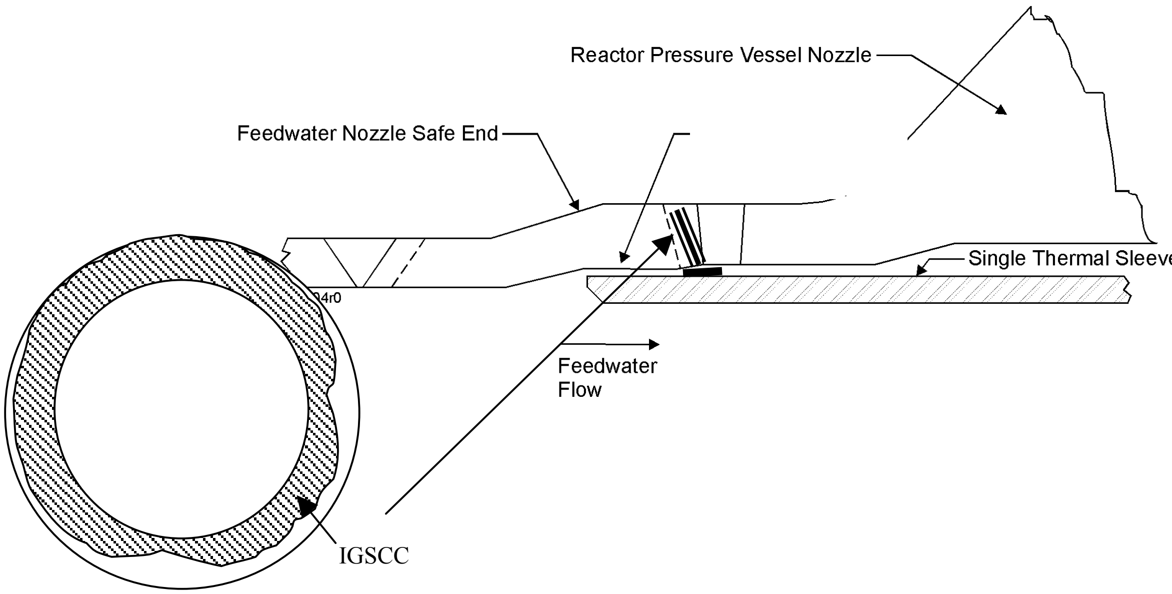

Figure 4-2
Schematic of the Circumferential IGSCC at Duane Arnold

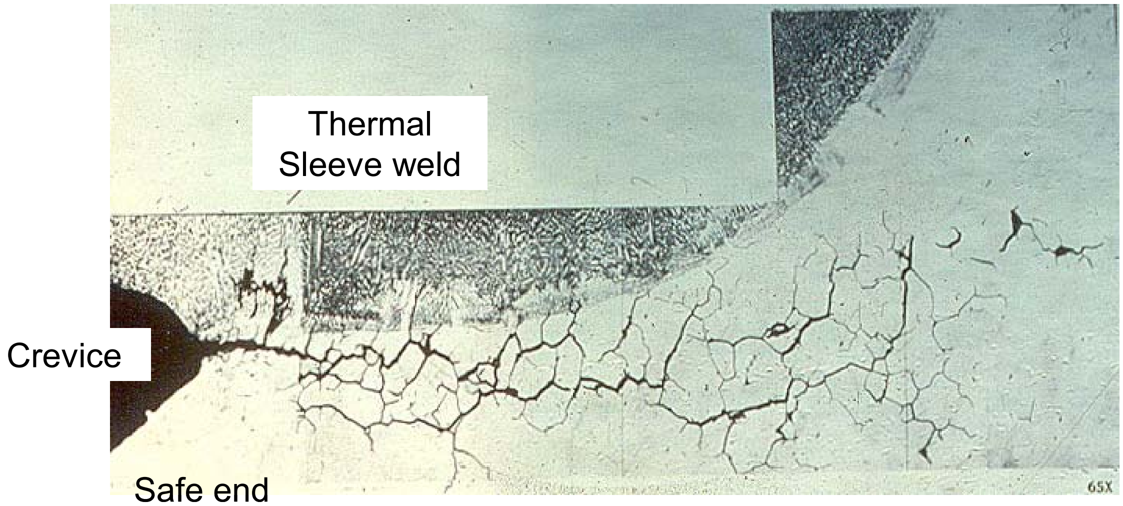

Figure 4-3
Duane Arnold Alloy 600 Recirculation Inlet Safe End Crevice with IGSCC

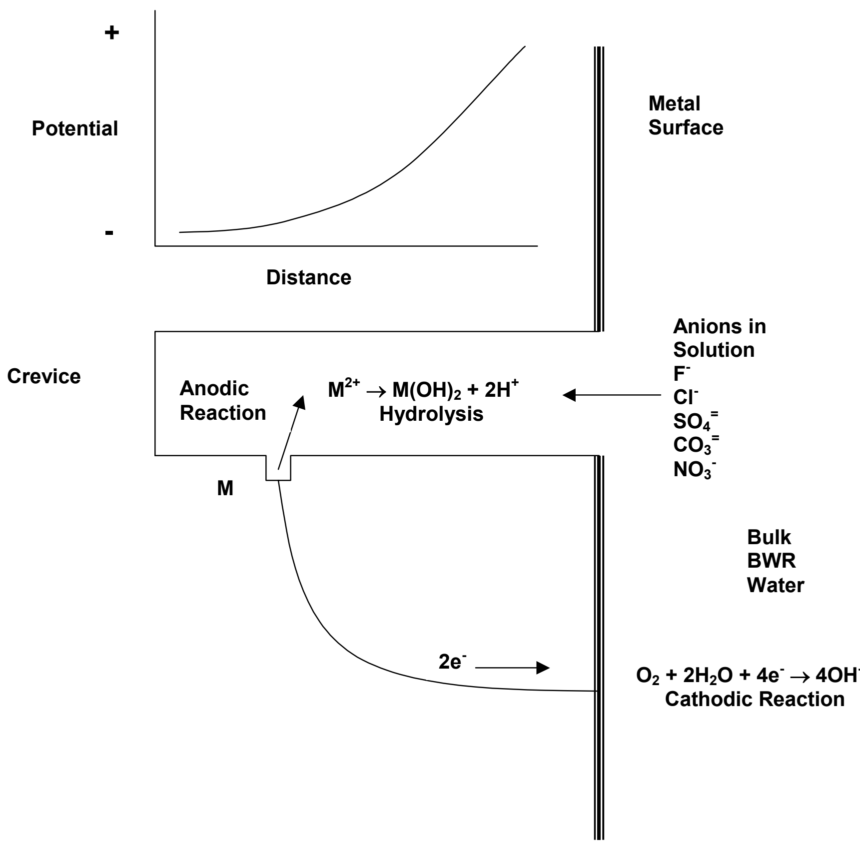

Figure 4-4
Crevice Effects in Oxygenated Environments

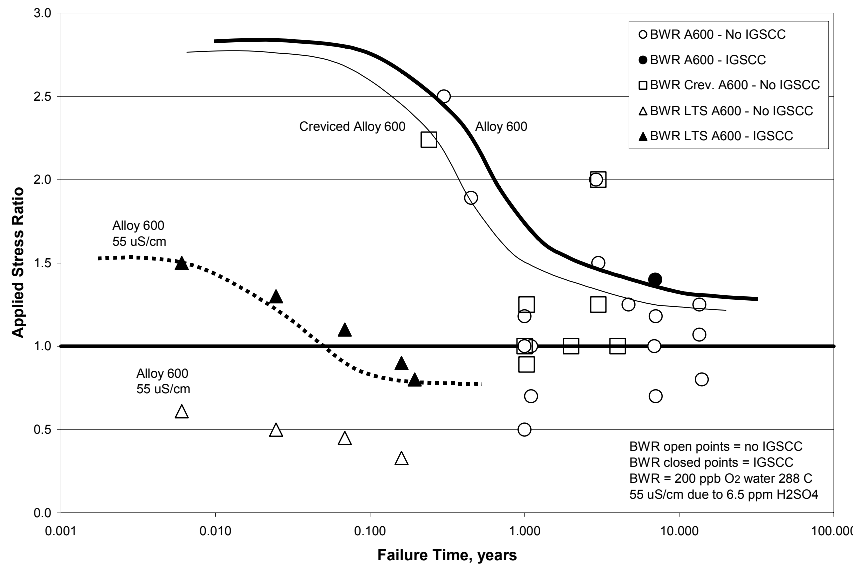

Figure 4-5
Effect of Crevices on IGSCC of Alloy 600 in BWR Environments [8][1]

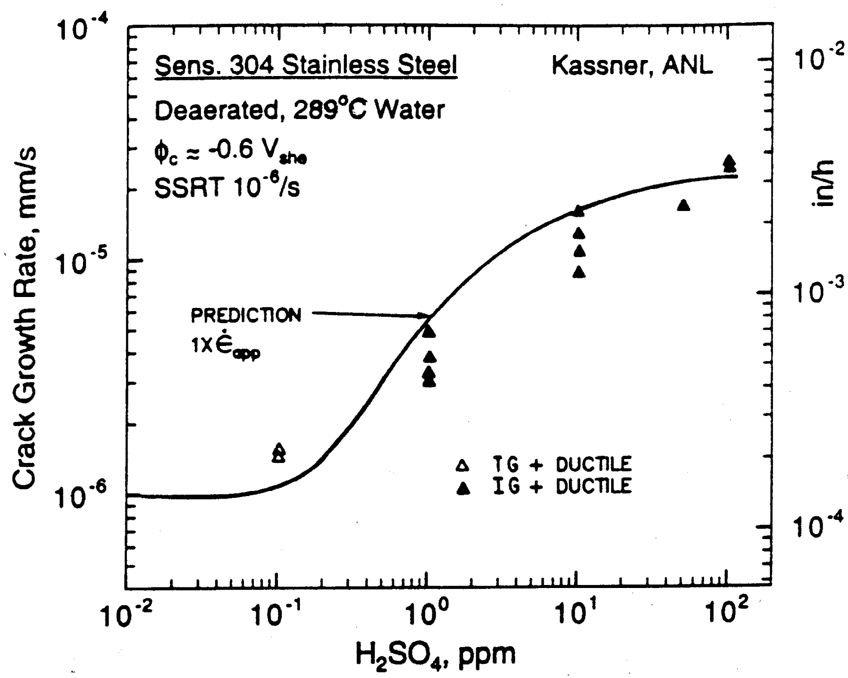

Figure 4-6
Effect of Sulfate on Crack Propagation Rates in Deaerated Water [12]

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[1] The general shape of the Alloy 600 time-to-failure curves are based on sensitized stainless steel data where the uncreviced Alloy 600 curve is pinned by the single pressurized tube result. Since creviced Alloy 600 would be expected to crack after shorter exposures periods, the creviced curve is sketched to the left of the uncreviced curve.

5
CONCLUSIONS

An analysis has been performed to evaluate the potential for PWSCC initiation and growth in the Alloy 182 weld butter for ID repaired RPV outlet and pressurizer surge nozzles.

Residual stress and operating pressure and temperature results were calculated in a separate report (References 1 and 2) and combined with parametrically selected piping moments. Results were obtained for weld repair lengths of 30°, 60°, 90°, and 360° of the pipe circumference and maximum bending stress of $0.5S_m$, $0.75S_m$, $1.0S_m$, and $1.25S_m$. Three assumptions were also made regarding the applied bending moment. The first assumed that the maximum bending stress occurred at all azimuthal locations (applied uniformly across the pipe section) and the second assumed that the maximum bending stress was aligned with the center of the weld repair. The third case, which is an extension of the second case, assumed the maximum bending stress at various orientations away from the center of the weld repair.

Results of this evaluation indicate that if flaws initiate by PWSCC or some other reason (weld defect, grinding), for some repair sizes and at higher moment stress levels, significant growth may occur even at locations away from the weld repair. It is understood, given the residual stress in the weld repair, that if flaws initiated and there is a direct path of Alloy 182 through the pipe wall, that through-wall crack growth cannot be ruled out. This growth can be rapid, occurring in significantly less time than the current 10-year inspection interval. Thus, to meet current ASME Code requirements that no flaw can be greater than 75% of the pipe wall, or the allowable flaw size – whichever is smaller – the inspection interval would need to be reduced.

However, the results support leak-before-break in that initiated flaws would tend to grow through-wall within the weld repair region, and, except for very high piping load cases, would grow through the wall beyond the weld repair for only short distances. The exception is the 360° weld repair case where through-wall growth could occur anywhere. However, uniform initiation is highly unlikely, even when extensive grinding has occurred.

Operating plants can use these results to prioritize DM nozzle-to-piping locations for inspection or proactive mitigation.

6 REFERENCES

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A
UNDOCUMENTED ID REPAIRS IN PRIMARY LOOP, NOZZLE-TO-SAFE END AND HEAVY WALL NICKEL BASE WELDS

1.0 Scope

Concerns exist on the possibility that significant repairs could have been made from the inside diameter of certain weldments in an “in process” mode during other welding and therefore be performed without documentation. Such repairs would have the potential of creating unfavorable and unknown residual stress conditions. This discussion reviews large bore nozzles and/or primary coolant piping (to SG, RCP, and RPV) weldments that have sufficient access for work or repairs to be conducted from the inside diameter of the weld. The discussion is relevant for wrought, cast, forged and clad components.

2.0 Discussion

It is first necessary to define in process repair (IP): work accomplished during the normal course of weld completion. For example, upon completing a weld bead, a welder notices some trapped slag between weld beads or at a sidewall, a crater crack at a stop, or some undercut. He decides, properly, to remove the abnormality by grinding before proceeding. In the course of the removal, another or other indications are found. He continues excavation to remove the defects – real or perceived. Upon removal, the excavated cavity is welded up and the weld completed.

The aforementioned example could occur when welding from the OD only. It would be very unusual for such to occur if welding from the ID without documentation and have a through-wall situation to the OD result. If repairs were to be made from the ID, they would likely follow a construction radiograph, and thus be documented, as noted later in this paper (Section 3.3).

Since most primary loop welds were conducted with manual GTAW/SMAW, flaws would be intermittent, not continuous around the circumference, and thus the probability of significant repair or welding encompassing large portions of the circumference would be unlikely.

If occurring, repair would be more than likely localized. If adjacent to the base metal in the original weld groove, removal and repair would result in an increase of weld groove cross-section in the immediate area. Such a change should/may be visible on final RT but probably wouldn't be questioned if there were not any rejectable indications present. Further, such a condition may not be identified unless the film reviewer compared the final film to any interim shots. A repair or work that remained within the confines of the original weld groove would be very difficult to detect, especially if all work was done from the OD.

To detect additional work done from the ID, it would be important to have both interim and final RT film. Film type and actual sensitivity would also play an important role in whether one could see any differences in overall geometry. Differences would typically exhibit themselves as a reduction in surface irregularities whereas final film that showed "nothing" and interim film showed weld bead irregularities and contours. One could surmise that cosmetic grinding was done at some point on the ID.

If, however, a flaw was observed on final film and it was determined to be a root condition plus access to the ID was available, it would normally be addressed from the ID. Such a case should be documented as part of the welding record.

3.0 Potential Areas for In Process Repair

Areas where in process repairs could occur and potential for documented/undocumented activity are outlined as follows:

3.1 Fit-up

During fit-up, the weld groove faces and geometry are reviewed for conformance with drawings. As a minimum, a visual examination is conducted to verify dimensional criteria. On Class 1 grooves, an NDE surface examination (Magnetic Particle or Liquid Penetrant) was required. If any rejectable indications were identified in the base metal(s), the NDE inspection would trigger a repair operation. Any weld repair necessary and subsequent NDE should have been documented as part of the welding record.

3.2 Root & Hot pass(es)

On heavy wall weldments (2-4" thick), such as those found in a PWR primary loop or various nozzle connections, many installers performed interim volumetric (RT) inspections after the root and at least the hot pass was deposited. It made good economic and technical sense to perform these interim inspections to identify and fix any problems prior to depositing an entire weld groove. Some firms actually performed a volumetric examination after each inch of deposit.

If indications were identified that required removal and subsequent welding, the event would have been documented. Where access was available, it was not unusual for imperfections or defects to be addressed from the ID. Such items would have typically been cosmetic (bead/root profile, machining marks, etc.), lack of fusion or inadequate penetration related. Because only a limited amount of metal would have been deposited, the extent of repair would be limited. Further, some or these repairs were the direct result of gravitational effects and their relative position around the circumference – but not all the way around. Such indications were often seen in the bottom (4:00 to 7:00) or very top (11:00 to 1:00) of a 5/6G weldment (weld axis vertical or canted), but not continuous within any given region.

If an in process repair occurred that created a through-wall condition, it should have triggered documentation. Rework of a root would normally require a new fit-up inspection, purge verification (stainless steel welds), and evidence and instructions for the necessary welding procedures and drawing GTAW wire for the open root condition.

In most cases, follow-up volumetric inspection would have been conducted to establish that the area was free of unacceptable indications or to assist in the interpretation of the film. Film from such interim inspections, however, was not always maintained in the document package once the final weld was found to be acceptable. Weld history-type records recording details of welding, if conducted, should be in the package.

3.3 Fill Passes

In process repair of localized defects or abnormalities is considered a normal part of the welding operation, especially in the fill passes or beads. Such repair is usually restricted to a small volume of the deposited weld metal. One may not see any evidence on final volumetric examination of heavy-wall weldments due to the type or film or source used or where the repair was made. An exception would be where base metal was repaired and the overall or original geometry of the weld groove width may have been altered. Even with good sensitivity, final radiography of thick weldments oftentimes lacks great detail – especially where all surfaces (ID and OD) are ground smooth (for inservice inspection). It is not unusual to have difficulty finding the boundaries of a completely defect free (within the film and technique sensitivity) weld that has been ground smooth.

There were some instances where root and hot pass welding of primary loop piping presented such problems that they were removed and rewelded from the ID. This particular case was documented.

It probably has had little effect on the operational performance of weldments, but it should be mentioned that weld metal was oftentimes deposited in an unbalanced sequence to adjust or maintain alignment of the large primary loop piping and components. Unbalanced sequencing of weld metal (OD) and associated shrinkage was quite effective – far more than come-a-longs or jacking. This unbalanced welding would have little effect on the final state of residual stress because these deposits were only a minor portion of the completed weldment volume.

3.4 Clad Pipe

Some primary loop designs utilized low alloy steel pipe clad (welded or roll-bonded) with stainless steel on the wetted surface. Cladding in the root area was typically completed/restored from the ID. An in process repair of stainless clad would have been minimal in depth and thus relatively benign from a residual stress standpoint, but could have possibly encompassed the entire circumference if disbonding of the cladding was discovered.

If , during clad restoration from the ID, a defect in the carbon or low alloy steel base material or weld were discovered, it is possible that repair could have been made on an in process basis. However, such a repair would have more than likely been due to root and/or hot pass irregularities and would be localized rather than extensive in nature. Given the level of attention given to primary loop and RPV nozzle welds, it is unlikely that any repair of any significance would have been made without oversight and documentation.

3.5 Final/Baseline Acceptance

If something was done from the ID on a completed weld, it may be difficult to ascertain on thick sections due to radiography sensitivity issues. Anything extensive, either in depth or circumference, would probably have been obvious (to inspection) and documentation would have been generated before or because of the work. Localized touch-up or welding for cosmetic reasons could have possibly occurred under the guise of in process repairs and went undocumented as a specific operation. But, in order to withdraw weld metal from an issue station, one had to have a specific job or weldment, depending on the quality program.

3.6 Balance-of-Plant

Many unusual things could and did occur in balance-of-plant welding in the very early facilities. Welders who came off fossil or petro-chemical work did not necessarily exhibit attention to detail and quality assurance/control that nuclear construction demanded. Early quality programs also did not mandate or implement the same level of detail or control over operations that is implemented today. In fact, much of the early work was done to existing piping codes such as B31.1 because ASME III did not exist yet. These early plants have provided many years of satisfactory service in spite of the fact that they didn’t have the benefit of modern codes, quality programs and regulatory requirements. Even though balance-of-plant welding may have been conducted similar to a fossil or petro-chemical facility, primary loop and vessel connection welds enjoyed a much higher level of attention and scrutiny.

4.0 Summary

Since most primary loop welds were conducted with manual GTAW/SMAW, flaws would be intermittent, not continuous, around the circumference, and thus, the probability of significant repair or welding encompassing large portions of the circumference would be unlikely.

If occurring, repair would be more than likely localized. If adjacent to the base metal in the original weld groove, removal and repair would result in an increase of weld groove cross-section in the immediate area. Such a change should/may be visible on final RT but probably wouldn't be questioned if there were not any rejectable indications present. Further, such a condition may not be identified unless the film reviewer has a need to compare the final film to any interim shots and is looking specifically for these in-process repairs. A repair or work that remained within the confines of the original weld groove would be very difficult to detect, especially if all work was done from the OD. However, an ID repair of the root and hot pass prior to continuation of the groove welding would not produce a final weld residual stress distribution significantly different than produced for an unrepaired weld.

If something was done from the ID on a completed weld, it may be difficult to ascertain on thick sections due to radiography sensitivity issues. Anything extensive, either in depth or circumference, would probably have been obvious (to inspection) and documentation would have been generated before or because of the work. Localized touch-up or welding for cosmetic reasons could have possibly occurred under the guise of in process and went undocumented as a specific operation. However, such a repair would have more than likely be due to root and/or hot pass irregularities and would be localized rather than extensive in nature. Given the level of attention given to primary loop and RPV nozzle welds, it is unlikely that any repair of any significance would have been made without oversight and documentation.