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Materials Reliability Program: Primary System Piping Butt Weld Inspection and Evaluation Guideline (MRP-139NP)

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REPORT SUMMARY

This Materials Reliability Program (MRP) project identified butt weld locations susceptible to primary water stress corrosion cracking (PWSCC) and developed approaches for inspection, re-inspection, mitigation, and flaw evaluation.

Background

PWSCC of Alloy 600 nozzles and penetration locations in pressurized water reactor (PWR) plant primary system pressure boundaries has been a recurring problem since the mid 1980s. 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 (Sweden) and VC Summer (United States). At VC Summer, a through-wall leaking flaw was found in the Alloy 82/182 weld between the low-alloy steel reactor vessel outlet nozzle and the stainless steel primary coolant pipe. Although cracking was primarily axially oriented, at VC Summer a short and shallow circumferential crack also was discovered in the inside diameter (ID) region of the Alloy 182 weld clad beneath the low-alloy steel nozzle material. 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.

In 2003, a small leak was discovered from an Alloy 132 (similar to Alloy 182) butt weld on a pressurizer relief nozzle at Tsuruga 2 (Japan). This leak was from an axial crack in the butt weld between the low-alloy steel nozzle and the stainless steel relief valve line.

In Spring 2005, Calvert Cliffs Nuclear Power Plant (United States) identified indications in a 2-inch-diameter hot leg drain nozzle dissimilar metal weld. There were two (2) axial indications contained entirely within the weld and butter closely associated with the ID, located approximately 180° apart. There also was one (1) circumferential indication proximate to the ID extending approximately 100° in circumference, with one end oriented near one of the axial indications. The circumferential indication has been determined to be construction-related. The axial indications are being attributed to PWSCC.

Axial cracks without associated leaks have been discovered in butt welds at Ringhals 3 and 4, V.C. Summer, Tsuruga 2, and Three Mile Island Unit 1 (United States). The only circumferential crack reported to date was the short, shallow crack at V.C. Summer.

Objective

To provide generic inspection and evaluation (I&E) guidelines for PWR primary system piping butt welds.

Approach

MRP formed a focus group to develop PWR butt weld I&E guidelines. The group, comprised of utility and industry experts, reviewed available information including PWSCC experience and the MRP Alloy 82/182 Butt Weld Safety Assessment to develop this generic I&E guideline. This information was used to identify butt weld locations susceptible to PWSCC and to develop approaches for inspection, re-inspection, mitigation, and flaw evaluation.

Results

The I&E guidelines provide information on butt welds in primary systems, a discussion of susceptibility considerations, a “baseline” approach for the first inspection each plant will perform to new MRP requirements, and an approach for re-inspections.

The guidelines also contain a flaw evaluation methodology that provides guidance on performing flaw evaluations and assessing effectiveness of stress improvement (SI) processes.

EPRI Perspective

These guidelines are mandatory and serve to augment current regulatory requirements for inspecting Alloy 82/182 butt welds for PWR owners. The MRP Butt Weld Group plans to monitor results of all inspections closely so that new information obtained from these inspections can be factored into subsequent revisions of this document.

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INTRODUCTION

Recent incidents of cracking in pressurized water reactor (PWR) Alloy 600 nozzles and penetration locations have increased the concern for primary water stress corrosion cracking (PWSCC) of Alloy 82/182. In 2000, cracking in Alloy 82/182 was discovered by visual observation at the VC Summer and Ringhals 4 plants. These incidents 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 weld. On further examination, including non-destructive examination, it was discovered that in addition to significant axial cracking, a shallow circumferential crack also was present. A significant contributor to cracking of the VC Summer hot leg nozzle-to-safe-end weld was extensive construction repairs, which created high weld residual stresses in a material exposed to an environment known to support stress corrosion cracking (SCC).

Experience in the boiling water reactor (BWR) industry also has 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 the safety concern of pipe rupture. As in PWRs, construction repairs in BWRs have been an important factor in observed cracking.

At dissimilar metal Alloy 82/182 butt welds, cracking at unrepaired and unground (as-welded) locations is less likely 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 more susceptible to cracking. However, repairs made during installation can have a significant effect on the as-welded residual stress. Crack initiation and growth rate can be affected by how these repairs were made, for instance, finishing from the inside or outside or abusive surface treatments such as severe grinding.

Currently, these welds are inspected per American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section XI, which states that all welds must be inspected during each 10-year interval. This includes terminal ends, where most of the Alloy 82/182 welds are located. Recent risk informed-in-service inspection (RI-ISI) programs have eliminated some of the Alloy 82/182 weld locations from examination programs due to low risk and consequences. As more cracks were found, and recognizing the tight nature of SCC, the Materials Reliability Program (MRP) recommended in January, 2004, that PWR owners perform bare metal visual inspections (BMV) of all Alloy 82/182 weld locations in the primary system pressure boundary that are normally operated at greater than or equal to 350°F. These inspections should be performed within a facility’s next two refueling outages unless an equivalent examination was performed during the facility’s most recent refueling outage.

Based on field experience and the continued potential for PWSCC at dissimilar metal Alloy 82/182 welds, it has become evident that the examination frequency and the overall examination strategy for as-built DM welds require reassessment. As a result, MRP has made DM Alloy 82/182 inspection and evaluation guidelines a high priority. This inspection and evaluation (I&E) guideline covers primary system piping butt welds, including those 1” nominal pipe size (NPS) or greater exposed to temperatures at or above cold leg temperature. The basis for the size limit was that it covered the vast majority of butt welds considered susceptible to PWSCC. The basis for the temperature limit is that PWSCC susceptibility is partly a function of temperature. Butt welds of other sizes, classified in other code categories or exposed to lower temperatures, will be addressed in future industry guidance.

1.1 Objectives and Scope

This I&E guideline is a generic guideline to address the following:

- Butt welds (ASME categories B-F and B-J) in primary system piping that are 1" NPS or greater. Note that 1” to 4” weldments are included; however, they are not treated with equal volumetric nondestructive evaluation (NDE) rigor due to inspection limitations.
- Temperature greater than or equal to cold leg temperature.
- Locations on the piping for which examination is needed.
- Weld categorization to acknowledge mitigation, temperature, and inspection capabilities.
- Examination requirements for various weld categories.
- Extent of examination for each location.
- Evaluation procedures to determine acceptance of flaws, justification for mitigation actions, and changing examination categories.

The I&E guideline provides information on the piping geometries and weld locations for several weld categories. There is some discussion of susceptibility considerations that may influence the extent of examination and reexamination needed for various locations.

These guidelines present an MRP “baseline” approach for the first examination each plant will perform according to the new MRP requirements for piping welds as well as ongoing inspections following the initial examination.

1.2 Implementation Schedule

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Content Deleted – MRP/EPRI Proprietary Material

1.3 Examination Methodology Bases

The examination recommendations provided in this I&E guideline were developed using information from various sources. These sources included both technical analyses and status of current understanding of PWSCC in PWRs. Although PWSCC has been observed in thin-walled components such as steam generator tubing and pressurizer penetrations for many years, it is a relatively new phenomena in thicker-walled components in PWR plants. MRP has performed several studies regarding PWSCC in DM butt welds. The MRP-113 [20] butt weld safety assessment report and its referenced lower-level documents provide significant analyses regarding dissimilar metal butt welds. This information was used as part of the development for the examination recommendations provided in section 6.0 of this I&E guideline.

In addition to the significant amount of work performed to provide insight into the behavior of PWSCC in DM butt welds, plant experience, especially regarding inspections to characterize the condition of DM butt welds, is useful in assessing the examination schedule and requirements. Lessons learned from BWR industry experience with intergranular stress corrosion cracking (IGSCC) also is valuable in determining and developing examination schedules.

Section 4.4 of MRP-113 indicates that although there is a potential for PWSCC of Alloy 82/182 butt welds, the current experience indicates that the issue is limited in extent and severity. These conclusions are based on a significant number of non-destructive examinations performed to date, although not all have been performed using qualified techniques as required by ASME Code Section XI, Appendix VIII.

The MRP safety assessment also summarized conclusions from various analytical efforts to understand the behavior of PWSCC. The safety assessment used both deterministic and probabilistic methods to determine the structural significance of PWSCC. A key issue is the importance of weld repairs on the potential for PWSCC. In fact, incidents of butt weld PWSCC detected to date have been generally associated with significant weld repairs. Recognizing the potential importance of weld repairs to PWSCC, it also was recognized that documentation of weld repairs made during construction may not be complete.

The field experience of Alloy 600 and 82/182 weld materials indicates that locations exposed to higher temperatures are more susceptible to PWSCC than those at cooler temperatures. Therefore, as the examination schedules were developed, the examination of the hot leg and pressurizer welds was considered a higher priority than the cold-leg-associated DM welds.

Although the probabilistic predictions discussed in MRP-113 indicate there is not an immediate safety issue as measured by the impact on core damage frequency and that no changes to the current ASME Code are required, it is believed prudent, given the potentially high crack growth rates, to perform augmented inspections. It is evident that unlike IGSCC in BWRs, PWSCC in PWRs has been slower to initiate. The recent detection of through-wall flaws indicates that degradation is progressing and an augmented examination program is needed to identify locations of concern, if present. As more examination information becomes readily available, the examination requirements in this guideline can change to reflect the findings.

For all the above reasons, the basis for the inspection guidelines was weighted toward obtaining a baseline of the DM butt welds, which would address the following two conditions:

1) Determine how widespread significant PWSCC is
2) Determine the onset, if present, of increased initiation as plants age

Establishing baseline examination results for higher priority welds provides an early warning methodology for PWSCC in butt welds. Such an approach will assure defense in depth by maintaining a low probability of leakage.

2

PWR PRIMARY SYSTEM PIPING DESIGN AND SUSCEPTIBILITY INFORMATION

2.1 Butt Weld Locations

This section provides a discussion regarding the various butt weld locations in primary system piping, typical designs, and susceptibility information. Alloy 82/182 dissimilar metal butt welds in plants designed by B&W, Combustion Engineering (CE), and Westinghouse (W), based on size and operating temperature, are listed in Table 2-1. These include those welds greater than or equal to 1" NPS in locations operating at cold leg temperature and higher. These locations, and the range of key parameters for each type of weld, are shown in Figure 2-1 through 2-3 for the three nuclear steam supply system (NSSS) designs. The table and figures do not include butt welds to instrument nozzles 1" NPS and less or butt welds in control rod drive mechanism (CRDM) nozzles, reactor pressure vessel (RPV) bottom head instrument nozzles, and core flood tank applications that operate at temperatures below the plant cold leg temperature. The following sections provide further information regarding key locations of interest for this I&E guideline.

2.2 Locations in Westinghouse Design Plants

Locations and details of Alloy 82/182 butt welds in Westinghouse design plants are provided in the Westinghouse safety assessment [1] and are summarized in Figure 2-1 for a typical 3-loop plant configuration. Westinghouse plants have stainless steel primary coolant piping. As a result, there are large diameter (DM) butt welds between the stainless steel piping and the low-alloy steel RPV and steam generators (SG). Most of the butt welds at RPV inlet and outlet nozzles are single-V Alloy 82/182 welds. Butt welds between the reactor coolant piping and the steam generator nozzles are stainless steel except for one plant, which has Alloy 82/182 butt welds at this location. Some of the replacement steam generators have Alloy 52/152.

Since the primary coolant piping is stainless steel, most of the smaller diameter branches from the primary coolant pipes also are stainless steel, eliminating the need for Alloy 82/182 welds at the branch connections.

The only other Alloy 82/182 pipe butt welds greater than or equal to 1" NPS, and operating at cold leg temperature and above, are between the low-alloy steel pressurizer and the stainless steel surge, spray, and safety/relief valve lines.

2.3 Locations in Combustion Engineering Design Plants

Locations and details of Alloy 82/182 butt welds in CE design plants also are provided in the Westinghouse safety assessment [1] and are summarized in Figure 2-2. The primary coolant piping in all but one of the CE design plants is low-alloy steel. Therefore, the only large diameter Alloy 82/182 butt welds are between the cold leg pipes and the stainless steel reactor coolant pump casing. There are two exceptions: the first has stainless steel primary loop piping and is assessed with the Westinghouse plants and the second (at a multi-unit site) has low-alloy steel reactor coolant pump casings.

Most branch lines to the low-alloy steel primary coolant piping are stainless steel, and there are Alloy 82/182 butt welds at the connection nozzles. This leads to a large number of smaller diameter Alloy 82/182 butt welds at the hot leg and cold leg piping branch nozzles.

The only other Alloy 82/182 pipe butt welds greater than or equal to 1" NPS, and operating at cold leg temperature and above, are between the low-alloy steel pressurizer and the stainless steel surge spray and safety/relief valve lines.

2.4 Locations in B&W Design Plants

Locations and details of Alloy 82/182 butt welds in B&W design plants are provided in the AREVA safety assessment [2] and are summarized in Figure 2-3. The primary coolant piping in B&W design plants is low-alloy or carbon steel. Therefore, the only large diameter Alloy 82/182 butt welds are between the cold leg pipes and the stainless steel reactor coolant pump casings.

The core flood lines are stainless steel, and there are Alloy 82/182 butt welds where these lines enter the RPV. This location operates at cold leg temperatures. There are Alloy 82/182 butt welds at the inlet to each of the two core flood tanks and at core flood tank pressure relief nozzles. However, these butt welds operate at essentially room temperature and are not considered further in this I&E guideline.

Most branch lines to the primary coolant piping are stainless steel, and there are Alloy 82/182 butt welds at the connection nozzles. This leads to a large number of smaller diameter Alloy 82/182 butt welds at the hot leg and cold leg piping branch nozzles.

The only other Alloy 82/182 pipe butt welds greater than or equal to 1" NPS, and operating at cold leg temperature and above, are between the pressurizer and the stainless steel surge, spray, and safety/relief valve lines.

2.5 Locations with Alloy 600 Safe Ends

There are two concerns at locations with Alloy 600 safe ends or pipes. First, experience at Palisades and the Navy Advanced Test Reactor (ATR) has shown the potential for through-wall circumferential cracks in the heat-affected zone of the Alloy 600 base metal. Second, if axial cracks develop in the Alloy 82/182 butt welds, the cracks can continue to propagate into the Alloy 600 base metal rather than arresting as would be the case for welds to low-alloy steel nozzles or stainless steel (SS) components. A survey of plant designs shows [1, 2] that the only locations with Alloy 82/182 butt welds to Alloy 600 safe ends in sizes greater than or equal to 1" NPS, and which operate at cold leg temperatures or higher, are the pressurizer spray nozzles in B&W design plants and several nozzles at Palisades. At the pressurizer spray nozzle safe ends in B&W design plants, the critical length of through-wall axial flaws is greater than the combined length of the Alloy 82/182 butt welds and the Alloy 600 safe end such that there is no risk of rupture. Any crack growth would slow when the crack reaches lower stressed regions, away from the welds. Cracking at these locations would be captured in the examination volume of interest.

2.6 Susceptibility Information

The following is a brief discussion of causes of PWSCC crack initiation in Alloy 82/182 butt welds, crack growth rates in Alloy 82/182 weld metal, the role of several key design and fabrication-related factors on crack initiation and growth, welding residual and operating stresses in Alloy 82/182 butt welds, and preferred flaw orientation.

2.6.1 Crack Initiation: Material Susceptibility, Tensile Stress, and Environment

As has been documented in many sources, nickel-chromium-iron Alloy 600/82/182 materials are susceptible to PWSCC in PWR plant primary coolant environments. Three factors must occur simultaneously for PWSCC to occur. These factors are discussed in the following sections.

2.6.1.1 Susceptible Material

Extensive work has been performed to determine the factors that affect PWSCC susceptibility of Alloy 600 base metals. This work has shown that two main factors are chromium content and annealing temperature. Specifically, to achieve good resistance to PWSCC, the annealing temperature must be high enough to result in carbides being deposited predominantly at the grain boundaries rather than distributed throughout the grains.

Laboratory test work by Bettis and KAPL has shown that, while the material microstructure is significantly different, Alloy 82 weld metal has about the same susceptibility to PWSCC as Alloy 600 base metal [3,4], assuming identical test conditions. Electricité de France (EdF) and Framatome conducted a comprehensive series of tests of weld alloys with chromium contents ranging from 14% to 30% [5]. The results of the four types of tests (bend tests in doped steam, constant extension rate tests, or CERTs, in primary water, reverse U-bends, or RUBs, in primary water, and constant load tests in primary water) were consistent and showed that susceptibility to PWSCC decreased as chromium content increased. This suggests that Alloy 182 (Cr 13-17%) will be more susceptible to PWSCC than Alloy 82 (Cr 18-22%) and Alloy 600 (Cr 18-20%).

In summary, Alloy 82 and 182 weld metals are known to be susceptible to PWSCC based on laboratory tests and previously summarized field experience, with Alloy 182 material being the most susceptible of the three due to its lower chromium content. The ability to distinguish the presence of Alloy 82 or 182 may be difficult based on available plant information.

2.6.1.2 Tensile Stress

Sustained high tensile stresses are required for PWSCC. There are two main sources of tensile stress: 1) operating condition stresses due to pressure, temperature, and other mechanical loads and 2) weld residual stress. Operating pressure, operating temperature, and external piping loads produce primary and secondary stresses. These stresses are included in the plant design calculations and must be maintained within the specified ASME Code Section III allowables. However, higher stresses are typically created during fabrication by shrinkage forces that develop as the weld cools. Welding stresses, commonly called welding residual stresses, are typically higher than the operating stresses and tend to be the dominant driving force for PWSCC initiation and crack growth. Welding residual stresses are not addressed in ASME Code Section III stress limits, but are addressed in Section XI.

For a typical PWR plant butt weld that is formed by application of weld beads from the outside surface, finite element stress analyses show high tensile hoop stresses in the outer part of the weld and lower hoop stresses approaching the inside surface. Axial tensile stresses also can develop on the inside surface. However, the magnitude of axial stresses tends to be relatively low in tension or compression in PWR welds that typically have a small diameter to thickness (D/t) ratio.

Paragraph 2.6.4 provides further discussion of welding residual and operating stresses in typical Alloy 82/182 butt welds, including the potentially detrimental effect of weld repairs.

2.6.1.3 Environment

Experience has shown that the water chemistry and temperature in PWR plant primary coolant systems contribute to PWSCC. The general experience is that, for materials of equal PWSCC susceptibility with equal applied tensile stress, the time to crack initiation is a function of operating temperature. Locations that operate at higher temperatures, such as in pressurizers, typically exhibit cracking sooner than locations that operates at lower temperatures, such as in the reactor coolant system (RCS) cold legs. For typical PWR plant pressurizer (653ºF), hot leg (600ºF), and cold leg (550ºF) temperatures and a thermal activation energy of 50 kcal/mole for crack initiation, the multipliers on time to PWSCC for hot leg and cold leg locations relative to pressurizer locations are 7.7 and 63.7, respectively. If predictions are based on crack growth rate data, the activation energy can be taken as 31 kcal/mole and the corresponding multipliers on time are 3.5 and 13.1, respectively.

While the primary coolant hydrogen and lithium concentrations can affect crack initiation and growth, studies have shown only a small effect over the ranges through which these parameters can be adjusted within the EPRI *Primary Water Chemistry Guidelines* [6]. Zinc addition, on the other hand, has been used in a few plants and appears to have a beneficial effect to reduce PWSCC crack initiation. Zinc addition may be used in more plants in the future as a PWSCC remedial measure, including Alloy 82/182 butt welds, and as a means of reducing radiation exposure during refueling outages once more research is completed and plant data is evaluated.

2.6.2 Crack Growth Rates

MRP recently developed a deterministic crack growth model for Alloy 82/182 weld metal materials based on a statistical evaluation of the worldwide set of available laboratory test data for these materials using controlled fracture mechanics specimens [27]. Similar to the process used by MRP to develop a deterministic crack growth rate equation for Alloy 600 base metal [8], MRP screened test procedures, reviewed test results, produced a statistical model, and developed a recommended deterministic equation. An international panel of experts convened by EPRI provided detailed input to MRP during its evaluations of Alloy 600 and Alloy 82/182.

The general form of the MRP equation for Alloy 82/182 weld metal is as follows:

$$\dot{a} = \exp\left[-\frac{Q_g}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right]\alpha f_{alloy} f_{orient} K^{\beta}$$

where:

$\dot{a}$ = crack growth rate at temperature T in m/s (or in/h)
Q_g = thermal activation energy for crack growth
= 130 kJ/mole (31.0 kcal/mole)
R = universal gas constant
= 8.314×10^{-3} kJ/mole-K (1.103×10^{-3} kcal/mole-°R)
T = absolute operating temperature at location of crack, K (or °R)
T_{ref} = absolute reference temperature used to normalize data
= 598.15 K (1076.67°R)
α = power-law constant
= 1.5×10^{-12} at 325°C for $\dot{a}$ in units of m/s and K in units of MPa√m
(2.47×10^{-7} at 617°F for $\dot{a}$ in units of in/h and K in units of ksi√in)
f_{alloy} = 1.0 for Alloy 182 and 1/2.6 = 0.385 for Alloy 82
f_{orient} = 1.0 except 0.5 for crack propagation that is clearly perpendicular to the dendrite solidification direction
K = crack tip stress intensity factor, MPa√m (or ksi√in)
β = exponent
= 1.6

For comparison, earlier data in MRP-21 [7] for Alloy 182 weld metal was based on a smaller set of data available at the time and did not result from a systematic statistical assessment. Note that unlike the earlier MRP-21 curve, the apparent stress intensity factor threshold for the new MRP deterministic model [27] is taken as zero, meaning that crack growth is assumed to occur whenever the crack tip stress intensity factor is positive.

2.6.3 Effect of Design and Fabrication Practices on Initiation and Growth

Several design and fabrication practices have an apparent effect on crack initiation and growth in Alloy 82/182 butt welds. These are as follows:

2.6.3.1 Welding Processes and Material

Alloy 82 weld metal is uncoated wire that is used for manual or machine gas tungsten arc welding (GTAW) with a cover gas. Alloy 182 weld metal is supplied in the form of coated electrodes used for shielded-metal arc welding (SMAW). A main chemical composition difference between these two materials is that Alloy 82 material has 18-22% chromium and Alloy 182 material has 13-17% chromium. The higher chromium content of Alloy 82 material results in better resistance to PWSCC initiation and crack growth as noted in Paragraph 2.6.1.1.

Alloy 182 buttering was applied to the low-alloy steel nozzle or pipe, the buttering received a post weld heat treatment (PWHT) with the low-alloy steel component, then the final Alloy 82 or 182 weld was made to the stainless steel pipe or safe end. This design eliminated the need to stress-relieve the low-alloy or carbon steel nozzle/pipe after welding to the process pipe and avoided exposing the stainless steel material to PWHT temperatures where it could become sensitized. There were some variations of this basic configuration, especially for the case of reactor-vessel-nozzle-to-pipe welds in Westinghouse plants, and they are discussed in supporting nuclear seam supply system (NSSS) specific documents.

In most cases, the buttering was applied manually using the SMAW process with Alloy 182 weld metal. The butt weld root passes, and often 2 or 3 hot passes, were typically applied using manual or machine GTAW with Alloy 82 filler metal. The welds were then completed using the manual SMAW process with Alloy 182 filler metal in earlier plants or by GTAW using Alloy 82 filler metal in some later plants. Alloy 132, which has the same chromium content as Alloy 182, was used for the butt weld, including the repair in contact with the fluid, in the Tsuruga 2 pressurizer relief valve nozzle butt weld that developed a leak. For purposes of this guideline, Alloy 132 is treated as Alloy 182.

Based on the above, most Alloy 82/182 butt welds are expected to have at least some Alloy 182 weld metal in contact with the primary coolant where it can lead to PWSCC crack initiation. For example, most welds containing Alloy 82 weld root passes, or completed using automated Alloy 82 machine welds, will still have some exposed Alloy 182 weld metal in the buttering.

2.6.3.2 Weld Repairs

The Alloy 82/182 butt welds were inspected, and repaired if necessary, during fabrication. One of the supporting documents to the summary safety assessment report cites several repair scenarios [24]. Weld repairs can be performed from the inside surface or the outside surface. It is interesting to note that the two cases involving leaks from Alloy 82/132/182 butt welds (V.C. Summer and Tsuruga 2) and the 45% through-wall axial flaw at TMI-1 involved extensive weld repairs.

In many cases, plants do not have information on the actual repairs—inside diameter (ID) or outside diameter (OD) repairs—performed to Alloy 82/182 butt welds. However, some plants that do have these records indicate that repairs were common, including some welds being repaired multiple times, and that some repairs had a significant circumferential length. Weld repairs to the inside surface after completion of the full weld from the outside can result in high inside surface tensile residual stresses. However, from a practical standpoint, these types of repairs are not considered to have been widespread on welds less than 4" NPS due to the limited access from the inside. DM welds 4" NPS and larger, which are most likely to have had repairs to the inside surface, also are required to receive volumetric examinations at 10-year intervals per Section XI of the ASME Code unless the examination was eliminated as part of a RI-ISI program.

2.6.3.3 Machining Inside Surface After Welding

Some pressurizer surge line nozzles and nozzles with lesser diameters were machined on the inside surfaces after welding. This machining has the potential to remove crack starters at the weld root and improve inspectability. However, cold work due to machining on the inside surface and the heat input from turning operations can result in tensile residual stresses in the cold-worked material. The cold work and tensile residual stresses due to machining are typically limited to a shallow depth (typically 0.01" or less).

While machining can cold work the surface and create local tensile residual stresses, the resultant stress intensity factor may be too low to result in significant crack growth once the crack grows out of the cold worked layer.

It should be noted that this situation at the root of the butt weld, involving machining after welding, is significantly different from that in CRDM and bottom mounted instrumentation (BMI) nozzles where material is first cold worked to final dimensions by machining and then subjected to high strain during the J-groove welding process.

2.6.3.4 Welding and Grinding on Inside Surface

Fabrication records show that some larger size hot and cold leg piping butt welds were back-gouged on the inside surface and then welded and ground again on the ID surface. Welding on the ID surface after completion of the entire weld has potential to increase the inside surface tensile stresses and, thereby, increase potential for PWSCC. Further, grinding at this location could result in initiation sites due to the cold work and high thermally induced surface residual stresses.

2.6.4 Welding Residual and Operating Stresses

Weld residual stress measurements and studies have been performed to understand the potential for crack initiation and growth in Alloy 82/182. Studies also have been performed for cases of weld repairs of DM butt welds [9]. Results of these studies indicate that weld repairs can have a significant impact on the resulting residual stress and, in fact, cause a more severe condition with respect to crack initiation and propagation.

Results show that maximum hoop stresses typically exceed maximum axial stresses and that a weld repair to the ID surface after completing the main weld significantly increases both the axial and hoop stresses on the ID surface. Results also show that the significant increase in weld residual stress caused by weld repairs is typically limited to the region of the weld repair.

The general behavior of these stresses is expected to have a major influence on the flaw orientation as discussed further in the following section.

2.6.4.1 Flaw Orientation: Axial vs. Circumferential

Flaw orientation is a key factor in butt weld safety evaluations. In particular, axial flaws, which are limited to the width of the Alloy 82/182 weld metal, arrest when they reach low-alloy and stainless steel materials at each end. This has been confirmed by experience at V.C. Summer and Tsuruga 2 and also at Ringhals and TMI-1. It is noted that self-arrest at the weld interface does not occur for the case of Alloy 600 pipe or safe ends. Crack extension into the pipe or safe end cannot be ruled out.

Through-wall, part-circumferential flaws, although not yet seen to date in Alloy 82/182 weld metal in PWRs, can potentially grow to significant size before leakage would be detected by traditional online detection methods such as inventory balances. In most cases, significant structural margin exists even at the leak detection threshold [20]. Leakage associated with the critical size was greater than the maximum technical specification allowed leakage for all locations except one small diameter location.

Part-depth, 360° circumferential flaws, if they were to grow to significant depth, could pose a probability of rupture under upset conditions without advanced warning provided by leakage. Therefore, these flaws would pose the greatest safety concern.

The purpose of the following paragraphs is to review available information relating to possible flaw orientations.

2.6.4.1.1 PWR Field Experience

Cracking of Alloy 82/182 butt welds in PWR plants has been limited to V.C. Summer, Ringhals 3, Ringhals 4, Tsuruga 2, TMI-1, and possibly Tihange. All indications have been axial with the exception of a short (2-inch-long), shallow (≅ 0.2-inch-deep) circumferential crack in Alloy 182 of the same leg that had an axial flaw and leaked at V.C Summer. The shallow circumferential crack arrested when it reached the low-alloy steel nozzle base metal [20].

There have been two cases of part-circumferential flaws that extend through-wall in the weld-heat-affected zone of Alloy 600 base metal (Palisades [31] and ATR[32]).

2.6.4.1.2 BWR Field Experience

BWR plants experienced SCC of piping early in plant life, and flaw orientations can shed some light on the potential for circumferential cracks to develop in PWR-plant Alloy 82/182 butt welds.

MRP-57 [10] summarizes the cracking experience in BWR piping. The BWR data show that axial cracks can grow to significant length if not arrested by some resistant material transition such as low-alloy or stainless steel for the case of PWSCC in PWR plants. The data show that most circumferential flaws had arc lengths less than approximately 60º. Part-circumference weld repairs may be a contributing factor to this length. Some of these BWR circumferential flaws were associated with geometric features such as backing bars, which are unlikely to exist in PWRs.

The case of the 360º part-depth crack at Duane Arnold, a BWR, which also leaked, has received significant attention and is often used as an example of why 360º part-depth cracks cannot be ruled out [11]. Crack initiation and growth were attributed to the presence of a fully circumferential crevice that led to development of an acidic environment in the presence of oxygen or an oxidizing species in the normal BWR water chemistry. This set of circumstances was combined with high residual and applied stresses as a result of the geometry and nearby welds. The conditions that occurred at Duane Arnold do not apply for the case of Alloy 82/182 butt welds in PWR plants [20, 24].

2.6.4.1.3 Finite Element Stress Analysis

Finite element modeling shows that hoop stresses are predicted to exceed axial stresses at high-stress locations on the inside surface such that most cracks would be expected to be axially oriented. These results also show that through-wall stress distributions favor growth of axially oriented cracks such as those discovered at Ringhals, VC Summer, Tsuruga 2, and TMI-1. However, the analysis results show locations of high axial stress on the inside surface for the case of repaired welds that could possibly support initiation of circumferential cracks.

In summary, this review of PWR field experience, BWR field experience, and finite element stress analysis results suggests that most PWSCC flaws in Alloy 82/182 butt welds are likely to be axially oriented. Additional work on this subject has shown that deep circumferential flaws are likely to be limited to the arc length corresponding to repairs from the inside surface or the area affected by deep repairs from the outside surface.

Table 2-1
Locations Involving Alloy 82/182 Pipe Butt Welds[1]

Location	Westinghouse Design Plants	Combustion Engineering Design Plants	Babcock & Wilcox Design Plants
Reactor Vessels			
- Inlet & Outlet Nozzles	Yes	No[2]	No
- Core Flood Nozzles	N/A	N/A	Yes
Pressurizers			
- Surge Line Nozzles	Yes	Yes	Yes
- Spray Nozzles	Yes	Yes	Yes
- Safety & Relief Valve Nozzles	Yes	Yes	Yes
RCS Piping Loop			
- SG Inlet & Outlet Nozzles	No[4]	No[4]	No
- RCP Suction & Discharge Nozzles	No	Yes[3]	Yes
RCS Branch Line Connections			
- HL Pipe to Surge Line Connection	No	Yes	Yes
- Charging Inlet Nozzles	No	Yes	Yes
- Safety Injection and SDC Inlet	No	Yes	Yes
- Shutdown Cooling Outlet Nozzle	No	Yes	Yes
- Pressurizer Spray Nozzles	No	Yes	Yes
- Let-Down and Drain Nozzles	No	Yes	Yes

1. Table does not include butt welds in instrument nozzles 1” NPS and smaller or welds that operate at less than 550°F (CRDM nozzle to flange butt welds, BMI nozzle to pipe butt welds, core flood tank nozzle butt welds).
2. One CE design plant has Alloy 82/182 welds and is evaluated with the Westinghouse design plants.
3. One CE design plant does not have Alloy 82/182 RCP suction and discharge nozzle welds.
4. One Westinghouse design plant and one CE design plant have Alloy 82/182 butt welds at this location.

Application	Reference Number in Figure below	Typical Temperature (°F)	Typical ID (inches)	Typ. Number (3 Loop Plant)
Pressurizer				
- Surge Line Nozzle	1	653	10	1
- Spray Nozzle	2		4	1
- Safety/Relief Nozzles	3		5	4
RCS Hot Leg Pipe				
- Reactor Vessel Outlet Nozzles[3]	4	600-620	29	3
- Steam Generator Inlet Nozzles[4]	5		--	--
RCS Cold Leg Pipe				
- Steam Generator Outlet Nozzles[4]	6	550-560	--	--
- Reactor Vessel Inlet Nozzles[3]	7		27.5	3

1. Figures only show locations in pipes greater than 1" NPS and operating at temperatures greater than about 550°F.
2. Plants with original reactor vessel closure heads have CRDM nozzles with Alloy 82/182 nozzle-to-flange butt welds (4" diameter).
3. There are no Alloy 82/182 RPV nozzle welds in Westinghouse 2-loop plants and some early Westinghouse 3-loop and 4-loop plants.
4. One plant has Alloy 82/182 butt welds between the reactor coolant piping and steam generator nozzles.

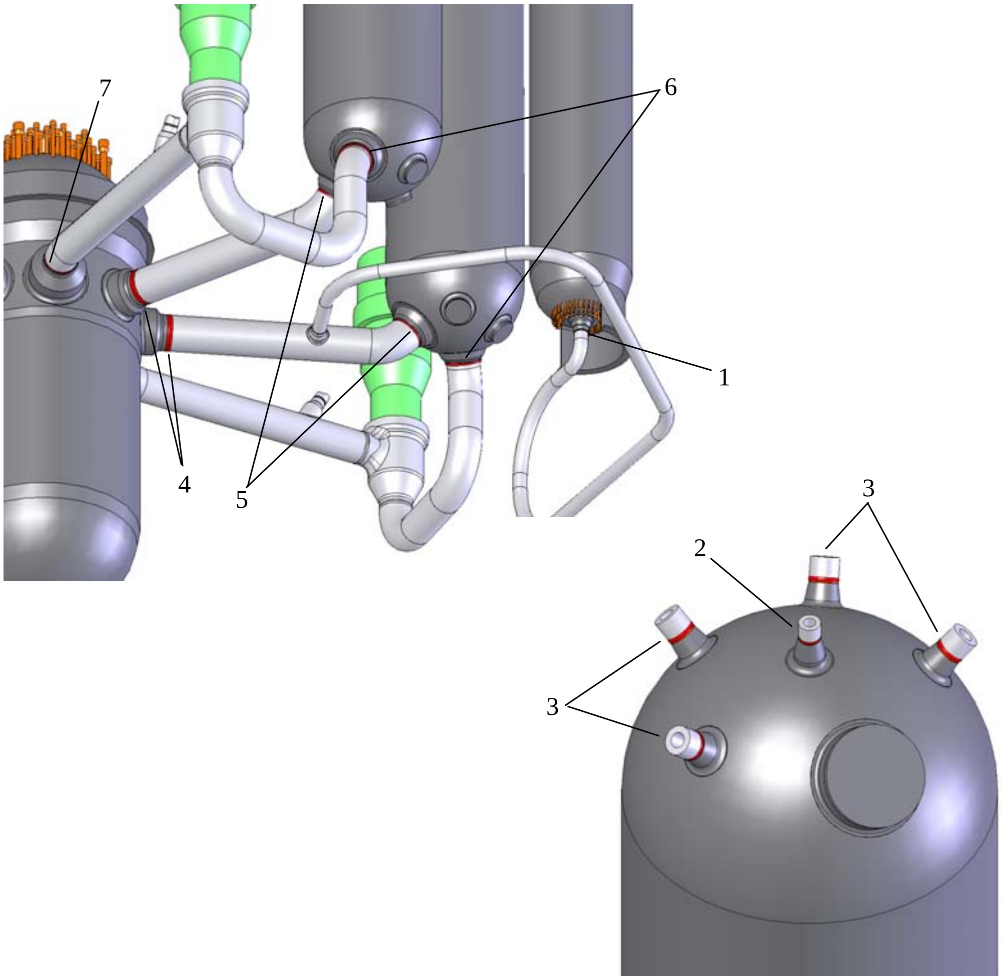

Figure 2-1
Typical Locations of Alloy 82/182 Butt Welds in Westinghouse Design Plants

Application	Reference Number in Figure Below	Typical Temperature (°F)	Typical ID (inches)	Typical Number
Pressurizer		643-653		
- Surge Line Nozzle	1		10	1
- Spray Nozzle	2		3	1
- Safety/Relief Nozzles	3		5	2-3
RCS Hot Leg Pipe		600		
- Surge Line Nozzle	4		10	1
- Shutdown Cooling Outlet Nozzle	5		10	1
- Drain Nozzle	6		2	1
RCS Cold Leg Pipe		549-560		
- RCP Inlet Nozzles	7[3]		30	4
- RCP Outlet Nozzles	8[3]		30	4
- Safety Injection	9		10	4
- Pressurizer Spray Nozzles	10		2.25	2
- Letdown/Drain Nozzles	11		1.3	4[4]
- Charging Inlet Nozzle	12		1.3	2

1. Figures only show locations in pipes greater than 1" NPS and operating at temperatures greater than about 550°F.
2. Some plants with original reactor vessel closure heads have CEDM/ICI nozzles with Alloy 82/182 nozzle-to-flange butt welds.
3. One plant does not have Alloy 82/182 welds at reactor coolant pump.
4. One plant has 8 cold leg letdown/drain nozzles.

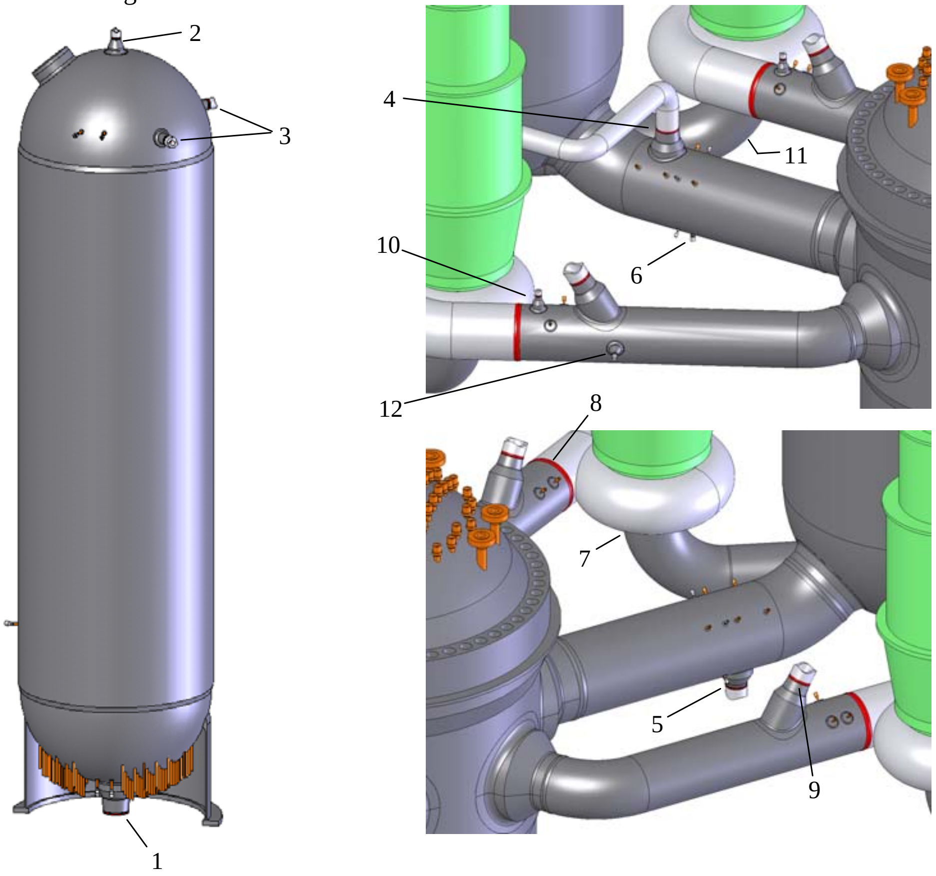

Figure 2-2
Typical Locations of Alloy 82/182 Butt Welds in Combustion Engineering Design Plants

Application	Reference Number in Figure Below	Typical Temperature (°F)	Typical ID (inches)	Typical Number
Pressurizer				
- Surge Line Nozzle	1	650	10	1
- Spray Nozzle	2		4	1
- PORV Nozzle	3		2.5	1
- Safety Relief Nozzles	4		2.5-3	2
Reactor Vessel[2]				
- Core Flood Nozzle	5	577	14	2
RCS Hot Leg Pipe				
- Surge Line Nozzle	6	601-605	10	1
- Decay Heat Nozzle	7		12	1
RCS Cold Leg Pipe				
- RCP Inlet Nozzles	8	557	28	4
- RCP Outlet Nozzles	9		28	4
- High Pressure Injection Nozzles	10		2.5	4
- Letdown/Drain Nozzles	11		1.5-2.5	4
Core Flood Tanks				
- Outlet Nozzle	12	RT	14	2
- Pressure Relief	13		2	2

1. Figures only show locations in pipes greater than 1" NPS and operating at temperatures greater than about 550°F.
2. As of July 2004, there are two remaining B&W plants that have reactor vessel closure heads with Alloy 600 CRDM nozzles and Alloy 82 nozzle-to-flange butt welds (69 4" welds at temperature < 605°F).

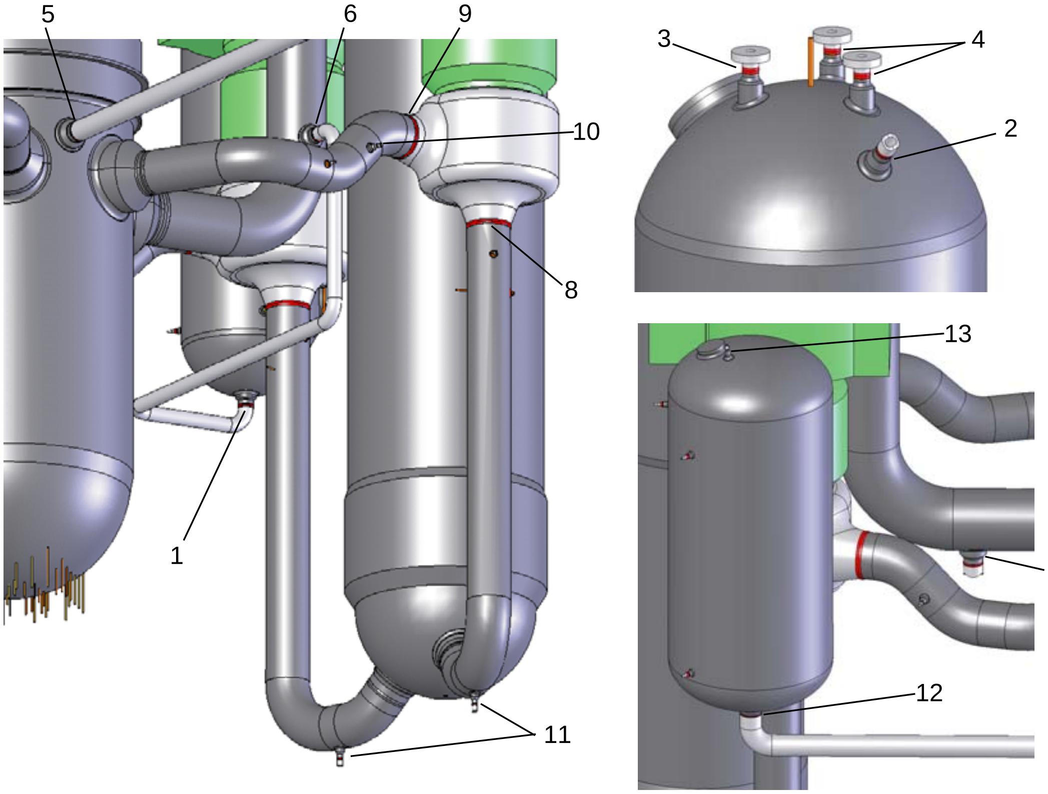

Figure 2-3
Typical Locations of Alloy 82/182 Butt Welds in Babcock & Wilcox Design Plants

3

SUMMARY OF PWSCC MITIGATION PROCESSES

This section discusses various approaches for mitigating PWSCC. While section 2.0 discussed factors that contribute to susceptibility of weldments to PWSCC, this section discusses specific methods to modify the material, environment, or stress condition of susceptible locations. To date, there have been several approaches to mitigate SCC, especially in BWRs. These include stress improvement (SI) processes such as the induction heating stress improvement (IHSI) process and Mechanical Stress Improvement process (MSIP™); environment changes or controls such as hydrogen water chemistry (HWC) and noble metal chemical (NMC) addition in BWRs; and material changes such as replacement of susceptible piping with more resistant piping or with resistant weld metal.

The intent of this section is not to provide all details regarding mitigation, but to identify what a mitigation measure must accomplish to be considered fully effective. As will be presented later in section 5, the frequency of examination of primary system welds is a function of whether the weldment has been subjected to a mitigative process. Significant credit is provided for those locations that have been treated with some type of mitigation.

3.1 Mitigation by Modification of Materials

PWSCC-resistant material is considered to include austenitic stainless steels, cast stainless steels, and high nickel alloy materials with nominally 30% Cr. Resistant welding materials include Alloy 52 and Alloy 152. To change a PWSCC-susceptible weldment to a PWSCC-resistant weldment, the non-resistant material must be replaced or totally isolated from the primary water/steam environment. For example, weld inlay (cladding on inside pipe surface) made from Alloy 52 that covers all Alloy 182 exposed to the primary coolant would be considered an effective PWSCC-mitigative measure.

Application of a full structural weld overlay also introduces a resistant material if it is made from PWSCC-resistant material such as Alloy 52. Although the susceptible material remains exposed to the primary coolant (since the weld overlay is applied to the outside surface of the weld) and may contain a crack, the thickness of the overlay is sufficient to meet required ASME Code safety factors without taking credit for the original pipe wall. If the crack were through the original wall, the inside diameter of the weld overlay would be exposed to the environment. However, since Alloy 52 is resistant to PWSCC, cracking would be considered mitigated. Note also that full structural weld overlays also act as an SI process, subjecting the inner portion of the pipe to compressive stress.

Replacement of PWSCC-susceptible material with PWSCC-resistant material, including the weld metal, also would be considered an acceptable mitigation for the particular weld location.

3.2 Mitigation by Stress Improvement

Various SI processes have been used, especially in BWRs, and are currently available. Those mitigation techniques mentioned in this report are not intended to be the only acceptable methods. Other methods may be used if they are demonstrated to meet the requirements listed in the discussion below.

3.2.1 SI of Uncracked Weldments

To be considered an effective PWSCC mitigation process, the SI process must significantly modify the residual stress field at the weld location. For the uncracked weld condition, this is accomplished by producing sufficient compressive stress on the ID wetted surface such that, when sustained operating loads are added, the stress on the inside pipe surface remains compressive. The presence of the compressive stress inhibits initiation and propagation of PWSCC.

Historically, SI is considered effective if it is followed by qualified volumetric or surface examination(s) [33]. If cracks are found, they must be sized both in depth and length by procedures and personnel qualified to perform sizing evaluations. If cracks are found, they would be reevaluated according to the following discussion (section 3.2.2) regarding cracked piping subjected to SI.

Examples of qualified SI that have been applied in light water reactors (LWRs) include

- MSIP™;
- WOL – weld overlay; stress improvement only (design weld overlays);
- WOL – weld overlay; full structural overlay;
- IHSI; and
- heat sink welding (HSW) (for small diameter piping).

Other SI processes such as surface conditioning (burnishing, laser peening) can be used as they become available and qualified (if they can be shown to develop sufficient compressive residual stress such that compressive stress exists on the inside surface during normal operation).

3.2.2 SI of Cracked Weldments

SI of cracked components also can be considered an effective mitigation process when applied to weldments with short or shallow cracks. Specifically, welds with cracks that are no longer than 10% of the circumference and no deeper than 30% of the wall thickness can be considered to be mitigated by an effective SI [22, 30]. The requirement for the SI process to be effective on a cracked component is that the stress intensity factor must be negative at the crack tip. The stress intensity factor must include residual stress and all sustained operating loads (primary and secondary). SI effectiveness also must be shown on a weld repaired as-welded condition unless it can be definitively shown that no weld repairs exist. Additional margins (for flaws larger than 10% of circumference or 30% of the wall thickness) may be demonstrated by performing component-specific analytical or experimental evaluations.

As mentioned in section 3.2.1 for uncracked weldments, historically the SI process is only considered to be effective if it is followed by a qualified UT examination [33]. If cracks are found by this examination, they must be sized both in depth and length by procedures and personnel qualified to perform sizing evaluations.

The full structural weld overlay is a special case of an SI process. Due to the fact that it replaces fully the underlying cracked component, this mitigation measure can be used under conditions where deep, long cracking exists in the component being overlay repaired. Additional details regarding application of these full structural weld overlays are presented in section 6.0.

Other SI processes may be considered as they become available. These SI processes must be able to produce a negative stress intensity factor at the crack tip during normal operating conditions to be considered effective.

3.3 Mitigation by Environment

Mitigation can be obtained by implementing changes to the operating environment that reduces the material’s susceptibility to PWSCC. The following represent some of the approaches that are being considered to mitigate this susceptibility. It should be noted that other methods may be used as they become available if they can be technically justified. The effectiveness of the processes described in this section for PWSCC mitigation will be evaluated on completion of the respective studies.

It also should be noted that the examination requirements in section 6.0 of this guideline do not currently consider credit for environment-based mitigation. Once environment-based mitigation processes become qualified for PWSCC, the examination recommendation should be revised.

3.3.1 Change in Electrochemical Potential (ECP)

The ECP of a material in an environment strongly affects its response to the corrosive effects of that environment. In particular, the PWR environment produces a corrosion potential for nickel base alloys that is very reducing (typically lower than -750mV standard hydrogen electrode, or SHE) [29]. Below these potentials, susceptibility to PWSCC has been observed in nickel alloys. Several investigators have demonstrated that elevating ECP (making it more anodic) by several hundred millivolts can decrease the susceptibility of nickel alloys in the PWR environment. To this end, MRP has initiated a study investigating anodic protection for these alloys in the PWR primary environment.

3.3.2 Zinc Addition

Zinc addition to BWRs has been demonstrated to be effective in reducing susceptibility to IGSCC of austenitic materials [26, 28]. A similar measure has been proposed to mitigate PWSCC in nickel base alloys by adding zinc to the primary coolant. Laboratory tests have demonstrated that zinc appears to extend the time to crack initiation and may retard crack propagation rates of active PWSCC. MRP is conducting studies to evaluate the effectiveness of zinc on PWSCC of these alloys and also will establish effectiveness parameters. The effectiveness of zinc as a PWSCC mitigation measure awaits the outcome of these studies.

3.3.3 Temperature

Temperature is one of the important factors affecting PWSCC of nickel alloys. Elevating temperature has a deleterious effect on PWSCC of nickel alloys. One consideration in the PWR industry for ranking relative susceptibility of a component or system to PWSCC has been the system’s operating temperature. Temperature effects on both initiation and growth appear to follow an Arrhenius relationship (exponential relationship) for these alloys.

While reducing the operating temperature may have a positive effect on PWSCC of these alloys, the economic impact on reduced power may argue against this potential mitigation approach.

4

CURRENT EXAMINATION REQUIREMENTS AND RESULTS

The following is a review of current butt weld examination requirements, examination results through the Fall 2004 refueling outages, the current status of butt weld inspection technology as it relates to the probability of detecting butt weld flaws, and conclusions regarding the condition of Alloy 82/182 butt welds based on inspections performed to date.

4.1 ASME Code Section XI Examination Requirements

To date, utilities have followed the required ASME Code Section XI examination requirements for the subject locations.

-	Welds	≥ 4 Inch NPS	Visual, Surface and Volumetric
-	Welds	> 1 Inch NPS and < 4 Inch NPS	Visual and Surface (Volumetric for HPI)
-	Welds	≤ 1 Inch NPS	Visual Only

Table IWB-2500-1 of Section XI requires that 100% of dissimilar metal vessel nozzle-to-safe end welds (Category B-F) and dissimilar metal piping welds (Category B-J) be included in the percentage requirements of Note 1 (Table IWB-2500-1, Category B-J) and be inspected at 10-year intervals. Essentially all of the key Alloy 82/182 pipe welds are dissimilar metal welds joining low-alloy or carbon steel nozzles to stainless steel pipe. Accordingly, most Alloy 82/182 butt welds have been inspected to the visual, surface, or volumetric examination requirements noted above, depending on the nominal pipe size.

4.1.1 ASME Weld Risk Informed Section XI Examination

In recent years, building on industry experience, many utilities have implemented risk-informed inspection approaches, consistent with EPRI TR-112657 or WCAP14572. Applying these methodologies reduces the number of welds to be inspected at 10-year intervals for both B-F and B-J welds. Applying Code Case N663 reduces the number of surface examinations to be conducted on B-F and B-J piping welds 4” NPS and larger. Some of these applications have resulted in eliminating examination of Alloy 82/182 locations. Regardless of the application through RI-ISI or CC N663, visual examination of this piping, with insulation, is conducted during the leakage test once per refueling outage. Risk-informed ISI programs are required to be living programs. As such, recent industry experience with Alloy 82/182 cracking will be incorporated as these programs are updated.

4.2 Flaw Detection Capability

The following is a summary of visual, surface and volumetric flaw detection capabilities.

4.2.1 Visual Examination

Bare metal visual inspections have proven to be a reliable method of finding small leaks from butt welds at V.C. Summer, Tsuruga 2, and other locations; CRDM nozzles; pressurizer heater sleeves; RPV bottom head nozzles; and small diameter instrument nozzles. The industry recommended in January, 2004, that all Alloy 600/82/182 pressure boundary locations be subjected to a bare metal visual examination or other equivalent examination within the next two refueling outages, with priority given to inspecting the highest temperature (pressurizer and hot leg) welds during the next outage to verify that there are no leaks [12]. This recommendation was made "needed" under the NEI 03-08 materials initiative in April 2004 [25]. Plants that have performed such an examination per MRP Letter 2004-05 during the last refueling need not repeat the examination. For plants that already have a comprehensive plan, the plan should be reviewed to ensure that the bases for the examination type and frequency remain valid and meet the intent of the industry recommendation [12, 25].

4.2.2 Surface Examination

Liquid penetrant examination of the external surface of a weld is capable of detecting through-wall flaws or outside-surface-initiated flaws. While surface examinations are capable of detecting through-wall cracks from the outside surface, visual inspections for boric acid leakage are expected to provide equally good detection of through-wall cracks. Visual eddy current testing (ECT) or liquid penetrant examinations from the outside surface cannot detect part-through-wall PWSCC cracks or subsurface cracks.

ECT examinations of the inside surface, where PWSCC cracks initiate, are only practical on the reactor vessel inlet and outlet nozzle butt welds since the inside surfaces of most butt welds are not accessible. Through 2004, reactor vessel inlet and outlet nozzles with dissimilar metal welds at VC Summer, Catawba Unit 2, Prairie Island Unit 1, Callaway 1, and Kewaunee have been inspected all or in part by surface examination techniques from the inside surface in domestic PWR plants. No crack-like indications were identified.

4.2.3 Volumetric Examination: Experience Prior to About 1990

All dissimilar metal welds, including those containing Alloy 182 in categories B-F and B-J, have been volumetrically examined every 10 years, following the requirements of ASME Section XI. Ultrasonic examination methods are used predominantly for this examination. Radiography also has been used, but not as extensively as UT. Dissimilar metal welds pose an examination challenge due to the microstructure of the weld combined with access constraints and weld geometry features.

The need for improving ultrasonic examination technology for austenitic piping, including DM weldments, multiple material types, and microstructures in the scan path, became evident during the early 1980s when extensive stress corrosion cracking was discovered in BWR stainless steel piping systems [13]. In many cases, piping welds that had passed examination leaked very soon afterward, showing that cracks could escape detection using ultrasonic methods in practice at that time. During this same period, several international round robin exercises were completed [14] that showed large scatter in the performance among examination teams. This experience created an impetus to improve ultrasonic examination technology. Also at this time, formal requirements for demonstrating the performance of examination procedures and personnel came into effect, but only for BWR piping inspections. The BWR piping examination [15] experience spurred improvements of UT instrumentation, procedures, and personnel training and performance was formally assessed and documented. Since no instances of similar cracking had been reported in PWR units, there was no corresponding effort to demonstrate performance for PWR piping examination at that time [16]. However, UT technology improvements that came from the BWR experience contributed to improving the technology applied to PWR units, although there were no regulatory requirements at the time to demonstrate capability for PWR applications [17].

4.2.4 Volumetric Examination: Improvements After 1990

General performance demonstration requirements first appeared as Appendix VIII to the 1989 Addenda of Section XI of the ASME Boiler and Pressure Vessel Code [14]. Appendix VIII requires demonstration of the capability to detect, discriminate, and size defects by examining realistic mockups containing intentional defects with well-known size and location. Essential variables used in the performance demonstrations were recorded and have become part of the qualification record. Supplements in Appendix VIII address specific components such as piping welds, vessel welds, vessel nozzles, and bolting. Supplement 10 of Appendix VIII addresses UT of dissimilar metal welds and was incorporated into 10 CFR50.55a, requiring implementation by November 22, 2002. All dissimilar metal weld examinations after that date have been required to be performed with Appendix VIII qualified procedures and personnel. Thus, incorporation of Supplement 10 into the rule introduced formal performance demonstration requirements for PWR and BWR piping DM weld inspections.

Discovery of a leak from the VC Summer hot leg weld in 2000, and the associated UT and ECT experience, showed that the geometry of the weld can dramatically affect the reliability of UT for examinations conducted from the inside surface of the pipe. Other experience, including Supplement 10 qualification results, confirmed the importance of knowing the weld configuration to enable adequate preparation for the examination. For examinations performed from the outside surface, the weld and nozzle geometry, and the roughness or waviness of the surface, have a particularly strong influence on examination effectiveness.

The industry responded to these events with further improvements of UT technology coupled with intense efforts to qualify procedures and personnel to Supplement 10 for PWR applications. The qualification to Supplement 10 was modified to include challenging weld configurations such as were encountered at VC Summer to ensure that procedures and tooling address the range of inside surface contours. These experiences have identified the most effective techniques and practices, and these practices have been incorporated into production examination procedures [18]. In many situations, procedures and equipment in place prior to Supplement 10 implementation had to be modified to improve performance to meet the new requirements. Another practical outcome of implementing Appendix VIII, in addition to documenting performance relative to standards, is formal documentation of procedure limitations. That is, the qualification record specifically documents the range of conditions, such as surface roughness or waviness, for which the procedure is qualified. This enables owners to identify where the procedures would not be effective and allows assessment and application of alternatives to address the limitations. This kind of formal documentation was not available prior to implementation of Appendix VIII. The most significant limitations pertain to surface conditions and weld configurations that preclude effective scanning. Owners can assess the applicability of qualified procedures only if the site-specific surface conditions and as-built weld configurations are known.

4.2.5 Volumetric Examination: Summary Status

PWR DM weld examinations conducted prior to implementing Appendix VIII were performed with a variety of techniques and with a range of effectiveness that is not possible to accurately quantify [13,18]. A review of industry experience [18] shows several instances where cracking, including circumferential cracking, escaped detection. The lack of detailed documentation of NDE capability prior to Supplement 10, coupled with the lack of detailed information on as-built weld configurations and access, makes it impossible to definitively characterize the capability of procedures applied in past examinations. Examination capability has been continually improving in response to service experience and the availability of technology innovations. Appendix VIII is the latest major improvement in a history of continuous capability improvement. Implementing Supplement 10 to Appendix VIII has resulted in development and application of improved procedures for UT detection and characterization of PWSCC in pipe butt welds. Structural integrity assessments can be made with confidence for those situations in which a qualified UT procedure can be applied.

In summary, while volumetric inspections prior to about 2002 may not have had the same detection capability or pedigree as inspections performed subsequent to implementation of Appendix VIII, Supplement 10, they have provided some assurance, in combination with the results of visual and surface examinations, that significant PWSCC is not widespread in dissimilar metal welds.

4.3 Examination Results Through Spring 2004 Refueling Outages

Alloy 82/182 butt welds in domestic PWR plants have been inspected as specified by Section XI of the ASME Code and by visual inspections for borated water leakage. As noted above, these inspections have involved visual inspections, surface examinations, and volumetric examinations. Similar inspections have been performed at PWR plants worldwide. As of the end of 2003 there have only been a small number of cases of part-through-wall axial flaws limited to the widths of the welds, two cases of leaks occurring from axial flaws, and one case involving a short, shallow circumferential flaw. The two leaks from axial flaws were detected by visual inspections for borated water leaks or in preparation for UT from the OD. None of the indications posed a safety concern at the time of detection.

4.4 Conclusions Regarding Butt Weld Condition

The following conclusions can be drawn from the above experience:

- There is potential for PWSCC of Alloy 82/182 butt welds.
- A significant number of butt welds have been inspected during plant ISI programs.
- Inspection capability over the past two years has improved significantly.
- There is no evidence of widespread PWSCC of Alloy 82/182 butt welds at present.
- All butt weld PWSCC detected to date has been generally associated with significant weld repairs.
- No safety concern has resulted from butt weld PWSCC to date.
- The few locations involving Alloy 600 safe ends or nozzles will require additional attention for two reasons. First, field experience has shown the potential for through-wall circumferential flaws in the base-metal-heat-affected zone. Second, axial cracks that initiate in Alloy 82/182 weld metal may continue to propagate into the Alloy 600 safe end. However, Alloy 600 safe ends in applications greater than 1” NPS and operating temperatures greater than 550°F are limited to pressurizer spray nozzles in B&W design plants and several nozzles in Palisades. In the case of the B&W pressurizer spray nozzle safe end or nozzle, the critical length for axial flaws is greater than the combined length of the Alloy 82/182 butt welds and the Alloy 600 safe ends.

5 EXAMINATION REQUIREMENTS

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6 EXAMINATION SCHEDULES

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7

EVALUATION METHODOLOGIES

This section summarizes evaluation methodologies that are considered applicable for the primary system piping butt weld locations. These methods can be applied to Alloy 600, 82, and 182 material at the subject welds since they are not considered PWSCC-resistant. For these materials, limit load analysis methods are applicable. This methodology can be used for various purposes including

- disposition of indications found during inspections (surface-connected or embedded flaws),
- determination of effectiveness of stress improvement processes, and
- determination of weld overlay (full structural or stress improvement) design.

ASME Code Section XI contains the methodology for performing disposition of flaws using limit load methods in IWB-3600 and Appendix C. Limit load is applicable to these locations due to the significant ductility of the materials and the fluence at the locations of interest is not sufficient to cause reduction in ductility. Other technically justifiable procedures such as elastic-plastic fracture mechanics (EPFM) or pipe burst theory also may be used.

Any indications that are found during inspections must be evaluated per ASME Code Section XI requirements. Indications that do not satisfy acceptance criteria of IWB-3500 must be dispositioned by analysis, repaired, or replaced. Per IWB-3500 of the ASME Code, indications must be evaluated to determine if they must be analyzed as surface-connected or can be considered embedded. Embedded flaws are considered isolated from the PWSCC environment and only subject to fatigue crack growth. Embedded flaws also must be evaluated to assure that cyclic loading does not result in the indication breaking the remaining ligament and, as a result, be subjected to the primary water environment. Surface-connected flaws would be subject to potential PWSCC. Any flaw attributed to PWSCC, regardless of depth, will be evaluated even if it meets IWB-3500 requirements.

7.1 Indication Disposition

In cases where indications cannot be dispositioned by ASME Code Section XI IWB-3500 acceptance standards, flaw evaluations similar to ASME Code Section XI IWB-3600 procedures can be performed. The disposition of indications requires the following steps be performed:

- Determination of allowable flaw size

    - Axial or circumferential

- Crack growth calculation
    - PWSCC and fatigue
- Comparison of predicted flaw size with allowable end-of-period flaw size

7.1.1 Allowable Flaw Size

To determine the allowable flaw size at a weld location, appropriate applied loads must be used in evaluating the stress condition at the butt weld location of interest. Using ASME Code Section XI methodology for the allowable flaw size evaluation, the limiting load conditions must be considered consistent with the plant design basis. For non-flux welds (for example, GTAW and GMAW), these loads typically include those due to pressure, deadweight, seismic, and other primary loads. For flux welds—for example, submerged arc welds (SAW), shielded-metal arc welds (SMAW]), and flux-cored arc welding (FCAW)—the applied loads must include secondary thermal loads.

The allowable flaw sizes evaluation must include all loading conditions—normal or upset, or emergency or faulted—since these load conditions require different safety factors.

Allowable flaw size evaluations can be performed for both axial and circumferential flaws. Note that the ASME Code in Section XI, Appendix C, does not permit any flaw to be deeper than 75% of the actual local pipe thickness.

7.1.2 Crack Growth Calculation

Crack growth calculations must be performed for the operating period of interest. Applicable loads are those present during sustained normal operation. These loads typically include those due to thermal stress, pressure, deadweight, and weld residual stress. Appropriate weld residual stress, for example, consideration of pipe thickness and diameter, must be considered in the crack growth calculation. The appropriate loads must be considered for the particular flaw orientation, axial or circumferential.

It is important to note that unless owners can definitively show that no repairs are present, a weld repair must be assumed at the location of interest. To date, cracking in non-resistant PWSCC material has been located in suspected repair areas. Thus, the residual stress distribution used in the crack growth calculation must be for a repaired configuration. If it can be demonstrated that there has been no weld repair at the location of interest, weld residual stress applicable for the as-welded fabrication weld may be used.

PWSCC crack growth rates (see section 2.6.2, Figure 2-4) must be used in crack growth rate calculations. These crack growth rates are a function of temperature as well as the applied stress.

It should be noted that these crack growth rates are significant and, in many cases, will limit the ability to demonstrate continued operation with the flaw left as is.

Cyclic loading also must be considered, and a fatigue crack growth calculation must be performed if thermal stresses are sufficient to cause crack growth. Fatigue crack growth must be added to PWSCC growth to obtain the end-of-operating period flaw size.

7.1.3 Determination of Flaw Acceptance

The end-of-operating period flaw size must be compared against the allowable flaw size to determine if the flaw is acceptable by demonstrating that the required safety factors are met through the entire operating period. If the safety factors are not met, the operating period may be reduced to accommodate an earlier examination to ensure that structural safety margins are maintained throughout the operating period. Alternatively, the weld will need to be repaired.

7.1.4 Stress Improvement Effectiveness

As mentioned in section 3.0, an SI is acceptable if it produces a significant change in the weld residual stress such that the stress is compressive when combined with other sustained operating loads for a preemptive SI. For an SI on a cracked weld, the SI is acceptable if the stress intensity factor at the crack tip is negative when all loads are considered. Stresses that must be included for determining SI effectiveness are stresses present during normal operation. Note that fatigue loading also must be considered, for example, fatigue loading due to thermal stratification. The appropriate SI residual stress must be included.

7.1.5 Weld Overlay Design

The design of the weld overlay depends on the type of overlay being considered. A full structural weld overlay is designed assuming no credit for the original pipe wall. ASME Code Case N-504-2 [21] can be used for guidance in the design of the weld overlay. Code Case N-504-2 provides guidance for the thickness and length of the full structural weld overlay.

As noted earlier, many weld overlays have been applied to BWR piping. U.S. Nuclear Regulatory Commission (USNRC) Generic Letter 88-01 [22] and NUREG 0313 Rev. 2 [23] provide the requirements/acceptance for weld overlays. NUREG 0313 Rev. 2 also provided guidance regarding designed weld overlays. Designed weld overlays are those that take credit for some of the remaining original pipe material. The design of these types of overlays must satisfy the safety factors of ASME Code Section XI.

Code Case N-638 also may need to be used if welding is required on nozzle material. Code Case N-638 allows for ambient temperature temper bead welding. Currently, Code Case N-638 limits the amount of temper bead welding on nozzle material to 100 in^2. If the limit of 100 in^2 is to be exceeded, a relief request must be submitted to USNRC. At this time, a Code Case is being developed to increase the 100 in^2 limit.

8
SUMMARY

This guideline has been prepared to meet the objectives and requirements of the NEI materials initiative [34]. It provides requirements classified as “mandatory” for inspecting Alloy 82/182 butt welds in PWR plants. Table 8-1 provides a summary of the required actions contained in this guideline.

Table 8-1 Required Actions Summary

Section	Requirements	Implementation Category
1.2	Each owner is required to implement this guideline and perform the first inspections consistent with the schedule outlined in this section.	Mandatory
5 (includes subsections)	This section provides the process for determining what NDE method should be used for each DM weld and if any additional analysis is necessary based on NDE method chosen.	Mandatory
6 (includes subsections)	This section provides the process for determining what re-examination frequency is required for each DM weld.	Mandatory

9
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DM WELD MEASUREMENT TEMPLATE

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B

DM WELD MOCKUP CRITERIA 5/28/04

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METHODOLOGY FOR FLAW EVALUATION

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