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Managing PWSCC in Butt Welds by Mitigation and Inspection

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ABSTRACT

Operating experience has shown that Alloy 82/182/600 materials exposed to primary coolant water (or steam) under the normal operating conditions of pressurized water reactors (PWRs) are susceptible to primary water stress corrosion cracking (PWSCC). These materials were widely used in the original construction of domestic PWR reactor coolant systems (RCS). Cracking typically initiates at the inside surface of these materials when exposed to reactor coolant and in the presence of high tensile residual stresses introduced by welding. The locations in which PWSCC has been identified include partial penetration nozzles, nozzle welds, and piping butt welds. PWSCC increases the probability of a loss-of-coolant accident. This NUREG/CR pertains to managing PWSCC in Alloy 82/182 butt welds.

In response to this degradation mechanism, the nuclear industry and the U.S. Nuclear Regulatory Commission (NRC) undertook a variety of actions. These actions included conducting crack growth rate studies for Alloy 82/182/600 materials, developing augmented inspection programs for varied component configurations, and establishing an improved regulatory environment for addressing PWSCC. In Alloy 82/182 butt welds, the nuclear industry began implementing mitigation strategies for the most susceptible of these welds.

This report provides a summary of the operating experience with PWSCC in Alloy 82/182 butt welds and an overview of industry and regulatory activities to address the safety concern. This report describes the strategies being used to manage potential PWSCC in butt welds, the basic design and regulatory requirements of each strategy/mitigation technique, and an assessment of the issues that may impact the effectiveness of each management strategy. This report also summarizes the NRC regulatory requirements, ASME Code Cases, and the regulatory status of ASME Code Cases related to management of PWSCC in Alloy 82/182 butt welds. A historical summary and timeline of the major events, activities, and decision processes is provided in an appendix.

The effectiveness of the mitigation and inspection strategies being used is evaluated and issues that could affect the reliability of inspections that are required to be performed are also discussed.

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FOREWORD

The U.S. Nuclear Regulatory Commission (NRC) started approving leak-before-break (LBB) analyses in 1984 by granting exemptions from General Design Criterion (GDC)-4, “Environmental and dynamics effects design bases.” In 1987, GDC-4 was revised to allow dynamic effects associated with postulated pipe ruptures to be excluded from the design basis when analyses reviewed and approved by the Commission demonstrate that the probability of fluid system piping rupture is extremely low (i.e., less than 10^{-6}/RY). The statement of considerations for the proposed revision to GDC-4 in 1986 said that “the leak-before-break approach should not be considered applicable to fluid system piping that operating experience has indicated is particularly susceptible to failure from the effects of corrosion.” Standard Review Plan (SRP) 3.6.3, “Leak-Before-Break Evaluation Procedures,” states that, “… evaluations must demonstrate that these [degradation] mechanisms are not potential sources of pipe rupture.” In practice, review criteria were implemented by excluding systems with potential corrosion degradation mechanisms. Satisfying SRP review criteria was considered a demonstration that the probability of fluid system piping rupture is extremely low.

SRP 3.6.3 also contains guidance on the application of LBB to boiling water reactor (BWR) piping which is susceptible to intergranular stress corrosion cracking (IGSCC). The SRP indicates that LBB could be considered for this piping provided at least two mitigation methods (e.g., resistant materials, stress improvement, enhanced water chemistry) were applied to the piping. In the regulatory actions taken to provide acceptable inspection intervals for managing IGSCC in BWR piping, credit has been given for the number of mitigation techniques employed. At the time these criteria were developed, they were based on engineering judgment. However, it has been observed through operating experience that two mitigation methods in BWR piping provide improved resistance to IGSCC as compared to one method, and that the use of two mitigation methods renders the piping highly resistant to cracking. Nevertheless, owners of BWRs have not requested NRC approval to apply LBB to this piping.

Beginning in 2001, operating experience in U.S. pressurized water reactors (PWR) occurred indicating that Alloy 82/182/600 materials in butt-welded configurations in the reactor coolant pressure boundary (RCPB) were susceptible to primary water stress corrosion cracking (PWSCC). The NRC determined that there was a low probability of near-term failure of welds, and that PWRs could continue to operate safely while the industry performed additional analyses and inspections (Sheron 2001). The Materials Reliability Program (MRP), an industry group formed to develop, in part, strategies for managing aging effects in nuclear plant systems and components, developed mandatory inspection and evaluation guidelines for dissimilar metal butt welds in the reactor coolant system of PWRs. These guidelines are contained in MRP-139, “Primary System Piping Butt Weld Inspection and Evaluation Guidelines,” and were implemented under Nuclear Energy Institute (NEI) 03-08, “Guidelines for the Management of Materials Initiatives.” The objective of MRP-139 was to manage PWSCC through a combination of inspection and mitigation, and the guidelines do not discriminate between welds approved by the NRC for LBB and other dissimilar metal butt welds.

The development of mitigation and inspection strategies, and the assessment of their effectiveness, to ensure that the probability of rupture remains extremely low has been complicated. Several projects and multiple experts have been required. The purpose of this report is to provide a historical summary and timeline of the major events, an overview of industry and regulatory activities to address the safety concern, and the strategies being used to manage potential PWSCC in butt welds. The basic design and regulatory requirements of each strategy/mitigation technique, and an assessment of the issues that may impact the effectiveness of each management strategy, are also provided. This report will be a useful resource in understanding the history of LBB and recent efforts to address a new degradation mechanism.

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EXECUTIVE SUMMARY

Operating experience has shown that Alloy 82/182/600 materials exposed to reactor coolant water (or steam) under the normal operating conditions of pressurized water reactors (PWRs) are susceptible to primary water stress corrosion cracking (PWSCC). PWSCC was observed in Alloy 600 mill annealed steam generator tubing by the early 1980s (Cullen and Mintz 2004). PWSCC has affected a number of other nickel alloy reactor coolant systems, such as upper and lower reactor vessel head penetrations and various vessel shell/nozzle and piping butt welds. This report provides an assessment of PWSCC in reactor pressure vessel (RPV) nozzle and piping butt welds.

Operating experiences beginning with the V.C. Summer through-wall axial cracking event in 2000 prompted the nuclear industry to issue inspection guidelines, as the safety consequences of inadequate inspections could have been significant. In 2005 the industry Materials Reliability Program (MRP) issued MRP-139, *Primary System Piping Butt Weld Inspection and Evaluation Guidelines* (MRP 2005). MRP-139 provided industry guidance for volumetric and visual inspections of unmitigated and mitigated butt welds in PWR primary coolant systems. Appendix B of this report provides a summary of operating experience with PWSCC in butt welds from the first incidence at Palisades in 1993 (Rogers 1993; NRC 2008a) through the present.

In 2005 the American Society of Mechanical Engineers (ASME) approved the development of a Code Case on appropriate inspection requirements to address PWSCC in Class 1 butt welds containing Alloy 82/182. This case was later numbered Code Case N-770 (ASME 2009b). Code Case N-770 was revised in 2009 to address NRC concerns and Code Case N-770-1 was issued later that year (ASME 2009a). Code Case N-770-1 contains requirements for inspection of unmitigated as well as Alloy 82/182 reactor coolant system (RCS) butt welds mitigated by certain techniques. The NRC incorporated ASME Code Case N-770-1 by reference into 10 CFR 50.55a(g)(6)(ii)(F) (76 FR 36232) in June 2011. This rule includes 10 conditions the NRC placed on the use of this Code Case to address safety concerns the NRC had with the implementation of Code Case N-770-1.

The predominant methods used by the nuclear industry to mitigate and repair PWSCC susceptible welds include weld overlays and the mechanical stress improvement process (MSIP). With weld overlays, Alloy 52/152 is applied by welding on the outside pipe wall over the susceptible weld and on some distance on either side of the weld. Weld overlays may have a thickness that exceeds one-third the thickness of the original pipe weld. Weld overlays may generate compressive residual stresses in the inner region of the pipe weld to minimize the likelihood of crack initiation or propagation of PWSCC through the weld. However, the main function of weld overlays is to provide structural reinforcement and an improved platform for performing inservice inspection. MSIP modifies the existing ID residual tensile stresses in the weld metal and heat-affected zone of butt welds in piping. A load is applied to the outside surface of the pipe with a large two-piece mechanical hydraulic clamping device connected by two pairs of tangentially positioned studs. MSIP results in compressive residual stresses in the interior region of the pipe weld to minimize the likelihood of initiation or propagation of PWSCC

into the weld. These two methods had been used successfully in boiling water reactors (BWRs) to repair and mitigate welds susceptible to intergranular stress corrosion cracking.

Another mitigation method that has been used by the nuclear industry, to a much less extent, involves the application of Alloy 52/152 material over the inside of a susceptible weld to provide a barrier between the susceptible material and reactor coolant. Alloy 52/152 material is more resistant to PWSCC than the underlying Alloy 82/182 weld material. This barrier is called either an inlay or onlay, depending upon the preparation of the weld to be mitigated.

This report provides an assessment of the effectiveness of nondestructive examination (NDE) performed on mitigated and unmitigated Alloy 82/182 welds, a summary of ASME Code Case N-770-1 inspection requirements and the NRC conditions in 50.55a, an assessment of weld inspection intervals, and conclusions on the effectiveness of Code Case N-770-1 requirements for mitigated and unmitigated welds.

Inspection limitations can alter the effectiveness of NDE. Geometry, surface conditions, or access may limit performing complete weld examinations. For monitoring of potential PWSCC, and to enable mitigated and unmitigated welds to perform as expected, the NDE applied has to be effective and reliable. Information on geometric limitations to performing inspections of typical Westinghouse and Combustion Engineering plant RCS Alloy 82/182 welds is contained in Appendices C and D. This information is applicable to unmitigated welds as well as pre- and post-MSIP, pre-weld overlay (WOL) examinations, and pre-inlay/onlay examinations.

The examination requirements of ASME Code Case N-770-1 appear to be complete and parallel existing Section IWB Class 1 requirements. For unmitigated welds the requirements reflect a philosophy of more frequent monitoring for an active degradation mechanism. An assessment for unmitigated welds showed times for crack growth of initiated flaws 10% to 25% through-wall to be shorter than Code Case N-770-1 inspection intervals. Baseline examinations have been completed and, although axial cracks have been found, some involving through-wall leakage, no instances of circumferential or axial PWSCC have been observed that exceeded ASME Code structural factors. It will be important to assess the results of second-round inspections against Code Case N-770-1 inspection intervals requirements.

An evaluation showed that WOLs provide effective mitigation against the initiation of PWSCC and against the growth of existing PWSCC that has been detected and allowed to remain in service. Based on a review of Code Case N-770-1, as implemented with NRC conditions, it is concluded that the inspection requirements for WOLs provide an acceptable approach for monitoring potential PWSCC.

Assuming that the performance criteria of Code Case N-770-1, Appendix I, are satisfied, an evaluation also showed MSIP provides effective mitigation against the initiation of PWSCC and against the growth of existing PWSCC that has been detected and allowed to remain in service. Based on a review of Code Case N-770-1, as implemented with NRC conditions, it is further concluded that the requirements for MSIP provide an acceptable approach for monitoring potential PWSCC.

There are a number of issues that need to be addressed for the application of inlays and onlays as described in Code Case N-766. Code Case N-766, which has not been accepted by the NRC, contains ASME Code rules for the design, installation, and fabrication inspections of inlays and onlays. NRC staff's issues with Code Case N-766 and the revision of this Code Case, N-766-1, are discussed in Section 6.5 of this report. Once the issues are resolved, Code Case N-766 and Code Case N-770-1 would be expected to provide an acceptable approach for designing, installing, and examining welds mitigated by inlays/onlays and for monitoring potential PWSCC in inlays and onlays. Resolution of the issues with Code Case N-766 and Code Case N-766-1 may necessitate some changes to Code Case N-770-1.

This report does not contain an assessment of chemical mitigation. As of the date of this report, the industry is studying this mitigation technique and has not sought regulatory credit for reduced examination frequencies of Alloy 82/182 butt welds based on chemical mitigation. Accordingly, NRC has limited its resources on chemical mitigation of Alloy 82/182 to keeping abreast of industry activities and progress on this topic. An Electric Power Research Institute (EPRI) report on the status of industry activities in this area is contained in MRP-263 NP (EPRI 2012b), which is available for download at www.epri.com.

Likewise, this report does not contain an assessment of mitigation by peening, although a brief description of mitigation by peening is provided in Section 2.3.4.1. The industry refers to this mitigation method by the term surface stress improvement. PWSCC is caused by a combination of three factors—tensile surface stress, susceptible material, and the elevated temperature environment of PWR coolant. The mitigation methods implemented by industry have the objective of removing one or more of those three factors. The industry has focused on the surface stress improvement techniques of laser peening and water jet peening. These methods operate by imparting a pressure shock wave to the surface of an Alloy 82/182 weld, which introduces a compressive residual stress on the treated surface. Industry prepared MRP-335 (EPRI 2012d) to document its basis for the effectiveness of peening as a mitigation technique for PWSCC and to support a potential reduction in examination frequencies as currently specified in ASME Code Case N-770-1. MRP discussed its request for NRC staff review of this report in a letter from EPRI dated May 1, 2013 (Crooker 2013). MRP-335 was under NRC staff review at the time of the issuance of this report.

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ACRONYMS AND ABBREVIATIONS

AFEA	advanced finite element analyses
ASME Code	ASME Boiler and Pressure Vessel Code
ASME	American Society of Mechanical Engineers
B&W	Babcock & Wilcox
BCL	Battelle Columbus Laboratory
BWR	boiling water reactor
BWROG	BWR Owners' Group
BWRVIP	Boiling Water Reactors Vessels and Internals Project
CAL	Confirmatory Action Letter
CASS	cast austenitic stainless steel
CE	Combustion Engineering
CFR	Code of Federal Regulations
CGR	crack growth rate
CRV	Code-required volume
DHR	decay heat removal
DM	dissimilar metal
DMW	dissimilar metal weld
EPRI	Electric Power Research Institute
ET	eddy current testing
FSWOL	full structural weld overlay
GDC	General Design Criteria
HAZ	heat-affected zone
ID	inner/inside diameter
IGSCC	intergranular stress corrosion cracking
IN	Information Notice
INPP	Ignalina Nuclear Power Plant
ISI	inservice inspection
LBB	leak before break
MRP	Materials Reliability Program
MSIP	mechanical stress improvement process
MWe	megawatt electric
NAPS-1	North Anna Power Station, Unit 1
NDE	nondestructive examination
NEI	Nuclear Energy Institute
NIFG	NDE Improvement Focus Group
NPS	nominal pipe size

NRC	U.S. Nuclear Regulatory Commission
OD	outer/outside diameter
OWOL	optimized weld overlay
PA	phased array
PAUT	phased array ultrasonic testing
PDI	Performance Demonstration Initiative
PEWR	partial excavation and weld repair
PNNL	Pacific Northwest National Laboratory
POD	probability of detection
PORV	power operated relief valve
PT	liquid penetrant testing
PWR	pressurized water reactor
PWROG	PWR Owners' Group
PWSCC	primary water stress corrosion cracking
PZR	pressurizer
RCP	reactor coolant pump
RCPB	reactor coolant pressure boundary
RCS	reactor coolant system
RES	NRC Office of Nuclear Regulatory Research
RIL	Research Information Letter
RMSE	root-mean-square error
RPV	reactor pressure vessel
RT	radiographic testing
SCC	stress corrosion cracking
SG	steam generator
SNR	signal-to-noise ratio
SRP	Standard Review Plan
SS	stainless steel
SSI	surface stress improvement
TFC	thermal fatigue crack
TI	Temporary Instruction
TMI-1	Three Mile Island, Unit 1
TRL	transmit-receive longitudinal
TRS	transmit-receive dual shear-wave
UT	ultrasonic testing
VE	visual examination
WOL	weld overlay
WRS	weld residual stress

1 INTRODUCTION

Operating experience has shown that Alloy 82/182/600 materials exposed to primary coolant water (or steam) under the normal operating conditions of pressurized water reactors (PWRs) are susceptible to primary water stress corrosion cracking (PWSCC). These materials were widely used in the original construction of domestic PWR reactor coolant systems (RCS). Cracking typically initiates at the inside surface of these materials when exposed to reactor coolant and in the presence of high tensile residual stresses introduced by welding. The first incidence of PWSCC that was observed in a butt weld occurred at Palisades in 1993 in the heat-affected zone of a power operated relief valve (PORV) Alloy 600 safe end pipe segment. PWSCC had been identified earlier than 1993 in components such as Alloy 600 steam generator tubes and Alloy 82/182 pressurizer control rod drive partial penetration welds. PWSCC in butt welds was also observed in 2000 at V.C. Summer in a field-welded Alloy 82/182 reactor vessel nozzle-to-RCS piping weld. Since the V.C. Summer event, there have been well over a dozen indications recorded in butt welds in domestic PWRs that have been attributed to PWSCC (Rogers 1993; NRC 2008a).

Operating experiences beginning with the V.C. Summer through-wall axial cracking event in 2000 prompted the nuclear industry to issue inspection guidelines, as the safety consequences of inadequate inspections could have been significant. The absence of an effective inspection regime could, over time, result in unacceptable circumferential or axial cracking or the degradation of RCS components by corrosion from leaks through these welds. These degradation mechanisms increase the probability of a loss-of-coolant accident. The American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code)-required inspections of Alloy 82/182 butt welds were not sufficiently frequent to ensure that ASME Code-allowable safety margins would continue to be met in the event that PWSCC initiates. The growth rate of PWSCC in these welds is rapid; thus, PWSCC could lead to leakage or rupture before the degradation would be detected by the inspections required by the ASME Code in Section XI, which is incorporated into the U.S. Nuclear Regulatory Commission (NRC) regulations in Title 10, Section 50.55a, Codes and Standards, of the *Code of Federal Regulations* (10 CFR 50.55a).

Prior to regulatory actions being initiated by the NRC, the commercial nuclear power industry began to implement strategies to manage potential or existing PWSCC at Alloy 82/182 butt welds in PWRs. One general strategy consists of management by a combination of mitigation plus inspection, where three or four mitigation techniques have been used by industry. The other general strategy was to manage potential PWSCC by inspection alone. Materials Reliability Program (MRP)-139 provided industry guidance for the volumetric and visual inspections of unmitigated and mitigated butt welds in PWR primary systems (EPRI 2005, 2008a). MRP-139 augmented the inspections of these locations that were already required by Section XI of the ASME Code.

In December 2005, the NRC sent a letter to ASME (Dyer 2005) requesting that the Section XI standards body address inspection requirements for Class 1 PWR piping butt welds fabricated with Alloy 82/182 weld materials. ASME approved the development of an ASME Code Case on appropriate inspection requirements to address PWSCC in Class 1 butt welds containing

Alloy 82/182. This case was later numbered Code Case N-770 (ASME 2009b). Code Case N-770 was revised in 2009 to address NRC concerns and Code Case N-770-1 was issued later that year (ASME 2009a). The NRC incorporated ASME Code Case N-770-1 by reference with conditions into 10 CFR 50.55a (76 FR 36232) in June 2011. Code Case N-770-1 contains requirements for inspection of unmitigated as well as mitigated Alloy 82/182 RCS butt welds.

The purpose of this NUREG is to provide (a) a description of the strategies being used to manage potential PWSCC in butt welds, the basic design and regulatory requirements of each strategy/mitigation technique, and an assessment of the issues that may impact the effectiveness of each management strategy; (b) a summary of operating experience with PWSCC in dissimilar metal welds (DMWs); (c) a summary of regulatory requirements, ASME Code Cases, and the regulatory status of ASME Code Cases related to management of PWSCC in DMWs; and (d) a historical summary and timeline of the major events, activities, and decision processes.

Section 2 provides a high-level discussion of PWSCC events affecting Alloy 82/182 butt welds; industry, ASME Code, and NRC actions taken to maintain the structural integrity; each of the mitigation techniques that have been used; and the status of emergent mitigation techniques. Section 3 provides an assessment of the effectiveness of nondestructive examination (NDE) performed on unmitigated Alloy 82/182 welds, a summary of ASME Code Case N-770-1 inspection requirements for unmitigated welds and NRC conditions in 50.55a on unmitigated welds, an assessment of unmitigated weld inspection intervals, and conclusions on the effectiveness of Code Case N-770-1 requirements for unmitigated welds.

For welds mitigated by the mechanical stress improvement process, weld overlays, and inlays and onlays, Sections 4–6, respectively, provide discussions of operating experience, design requirements, NDE reliability, ASME Code Case N-770-1 inspection requirements and related NRC conditions in 50.55a(g)(6)(ii)(F). These sections also provide an assessment of weld inspection frequencies and conclusions on the effectiveness of Code Case N-770-1 requirements for mitigated welds. Section 7 contains overall conclusions based on information provided in Sections 2 through 6. Section 8 contains a summary of NRC requirements that apply to Alloy 82/182 butt welds.

Appendix A contains a summary of major events, industry and regulatory activities, and decision processes related to management of PWSCC in Alloy 82/182 butt welds. Appendix B provides a summary of U.S. and foreign operating experience with PWSCC in Alloy 82/182 butt welds. Appendices C and D provide information on Alloy 82/182 butt weld ultrasonic testing inspection limitations for a typical Westinghouse and a typical Combustion Engineering plant. These appendices provide drawings of scan plots showing assessments of axial and circumferential weld inspection coverage and photographs of the welds. Lastly, Appendix E contains a summary of the results of four crack growth studies that were assessed for insights they provide regarding the inspection intervals for unmitigated Alloy 82/182 welds specified in ASME Code Case N-770-1.

2 BACKGROUND

2.1 Major PWSCC Events

In 2000, a large accumulation of boric acid deposits observed during a refueling outage at V.C. Summer led to the discovery of cracking in the 'A' reactor pressure vessel (RPV)-to-hot leg nozzle Alloy 82/182 weld (Casto 2001; Cotton 2001; Byrne 2002; NRC 2008a). The weld had a through-wall axial flaw with a small circumferential component and other small part-through-wall axial flaws. The axial crack growth of the flaw stopped or arrested when the crack reached the low-alloy (ferritic) steel nozzle on the one side of the weld and the stainless steel (SS) pipe on the other side of the weld.

The circumferential flaw grew a short distance through a portion of the nickel-based alloy butter on the inside of an undercut portion of the low-alloy steel nozzle. The outward radial growth of the circumferential flaw was arrested when it ran into the low-alloy steel nozzle. Because the sizes of the axial and circumferential cracks were bounded, it would not have been possible for these cracks to lead to a piping rupture. The safety significance of this occurrence was limited to leakage of primary coolant. If a circumferential flaw had initiated closer to the center of the weld, it could have caused a more safety-significant situation.

Ultrasonic testing (UT) examination of the remaining nozzle-to-pipe welds in all the loops found no flaws. Eddy current testing (ET) identified a number of small indications on the inside diameter (ID) of the 'A' hot leg nozzle weld, which were not identified by UT. ET also identified similar small indications on the ID of four of the other five nozzle-to-pipe welds. The 'A' hot leg weld was cut out and replaced with a nickel-alloy weld more resistant to primary water stress corrosion cracking (PWSCC). Metallurgical analysis of the weld confirmed the through-wall leak was from an axial crack 64-mm (2.5-in.) in length at the ID surface with a 5-mm (3/16-in.) opening length on the outside diameter (OD) surface of the nozzle-to-pipe weld. The analysis also showed a number of the small ET indications to be shallow cracks. The cracking was determined to be PWSCC. An integrity evaluation was performed to justify continued plant operations without removal of the indications in the other four welds. The destructively determined flaw sizes of the ET indications in the loop 'A' hot leg nozzle-to-pipe weld were used to support the crack growth calculations of the ET indications found in the other nozzle-to-pipe welds. On February 20, 2001, the U.S. Nuclear Regulatory Commission (NRC) issued a safety evaluation documenting its review of the integrity evaluation. The safety evaluation concluded that V.C. Summer nuclear plant could be safely operated for one fuel cycle (1.5 years) with the cracks discovered via ET indications in the other nozzle-to-pipe welds allowed to remain in service (Cotton 2001). During the subsequent outage, a mechanical stress improvement process (MSIP) was applied to the 'B' and 'C' hot leg nozzle welds.

The first incidence of PWSCC in butt welds that was observed in a foreign plant occurred at Ringhals Unit 3 in 1999 in a reactor vessel hot leg nozzle-to-safe–end weld. Two axial flaws were found in 1999 and were left in service to be reexamined during the next outage. These flaws were measured by UT to be 9 mm (0.35 in.) deep in 2000 and 13 mm (0.51 in.) and 16 mm (0.63 in.) deep in 2001. A new flaw was found in 2001 and measured at 8 mm (0.31 in.) deep. All three flaws were removed by excavation (boat samples were obtained for metallurgical analysis) and repaired by Alloy 52 filler material in 2001. At Ringhals Unit 4 in 2000, four axial flaws were found by UT. All four flaws were also removed by excavation and repaired by Alloy 52M. All four flaws were confirmed to be surface-breaking and the two deepest flaws were determined to be 22 mm (0.87 in.) deep by destructive examination (Skanberg 2001; EPRI 2004a; Gérard and Daoust 2004b; Miteva and Taylor 2006; NRC 2008a).

Between 2001 and 2006, axial and circumferential indications attributed to PWSCC were found in reactor coolant system (RCS) welds at six other plants. None of these indications resulted in through-wall leakage. Where sizing information was available, none of the indications were believed to be deeper than 50% through-wall. On October 13, 2006, the Wolf Creek Nuclear Operating Corporation performed pre-weld overlay inspections using UT techniques on the pressurizer surge, spray, relief, and safety nozzle-to-safe end Alloy 82/182 and safe end-to-pipe SS butt welds (Garrett 2006; NRC 2008a). The inspection identified three circumferential indications in the surge nozzle-to-safe–end Alloy 82/182 butt weld, one in the relief nozzle-to-safe–end Alloy 82/182 butt welds, and one in the safety nozzle-to-safe–end Alloy 82/182 butt weld. The licensee attributed the indications to PWSCC. The UT sizing techniques used were not qualified; however, based on the sizes estimated by the examiners, some of the flaws were significantly longer circumferentially than flaws previously seen in the industry. All five flaws were estimated to be less than approximately one-third of the wall thickness in depth. The licensee applied full structural weld overlays (FSWOLs) to these welds.

Initial flaw evaluation studies based on the estimated flaw sizes at Wolf Creek indicated that flaws of similar size in uninspected pressurizer nozzle welds could result in leakage or rupture. The NRC concluded that licensees needed to complete inspections or mitigations of the pressurizer nozzle Alloy 82/182 welds by the end of 2007 and implement interim enhanced leakage monitoring (Evans 2007c). Subsequently, industry and the NRC staff independently performed advanced finite element analyses (AFEA) that indicated the plants with uninspected pressurizer nozzle welds could continue to operate until their next scheduled inspections (EPRI 2007a; Rudland et al. 2007b). Innovative analytical techniques were developed to perform the AFEA and large resources were required to develop these techniques and perform the analyses. The Wolf Creek inspection results had major implications for the operation of about ten pressurized water reactors (PWRs) that had yet to inspect the Alloy 82/182 pressurizer nozzle welds by the end of 2007. If the AFEA techniques had not been developed or if the results of the AFEA had not been successful, the PWRs with uninspected pressurizer nozzle welds would have faced mid-cycle inspections to maintain safety. Additional events related to PWSCC in nickel-alloy butt welds are discussed in the paragraphs that follow.

On January 4, 2008, while Davis-Besse was in cold shutdown with the reactor head in place and fuel in the reactor vessel, the licensee began to install a weld overlay on the decay heat removal drop line-to-RCS nozzle weld (NRC 2008a). This weld is located inside containment and the RCS was in a partially drained condition. During the first weld pass on the drop line weld, the welding operator noticed water seeping from the weld. Visual inspection confirmed a small leak, yet surface examinations before welding showed no abnormal conditions or leakage. The licensee subsequently determined that the leak was from an axial through-wall flaw and attributed the flaw to PWSCC. The licensee was able to complete a FSWOL to this weld.

The licensee for Salem Unit 1 performed examinations on all eight reactor vessel nozzle hot and cold leg Alloy 82/182 welds during a fall 2008 refueling outage (Braun 2009). During the examinations, a circumferential inside surface-connected flaw was reported on one of the hot leg Alloy 82/182 welds. The flaw was measured to be 24% through-wall (16.1 mm [0.634 in.]) and 52.3-mm (2.06-in.) long on the ID surface. All eight reactor vessel nozzle welds were mitigated by MSIP during this outage.

During the October 2009 refueling outage inservice inspection (ISI) examinations at Seabrook Station, an axial 21% through-wall flaw was reported in a reactor vessel hot leg nozzle-to-safe–end weld (O'Keefe 2010; Freeman 2011). The flaw was attributed to PWSCC and the licensee performed MSIP on this weld.

On March 24, 2012, axial indications at North Anna Power Station, Unit 1, were found as a result of leakage in the ‘B’ reactor coolant loop hot leg-to-steam generator nozzle weld. The leakage was found during the performance of work activities to support weld overlay work. After preparatory OD surface machining, workers noted a small amount of water seeping from two flaws in the nozzle weld area. Approximately 2.54 cm (1 in.) of weld material thickness 360 degrees around the circumference had been removed prior to identification of the seepage. A UT examination of this weld had been conducted prior to the excavation, and none of the five flaws was detected. It has been determined that two of the cracks were greater than 80% through-wall and three were greater than 40% through-wall (Anderson et al. 2012). A FSWOL was applied to this weld. Questions were raised regarding why the flaws were missed during the UT examination performed prior to the pre-weld overlay machining. This topic is further discussed in Appendix A on major events and activities associated with PWSCC.

Alloy 82/182 welds are found in PWR Class 1 systems. Graphics showing locations of Alloy 82/182 welds in these systems may be found in Chapter 2 of MRP-139, Revision 1 (EPRI 2008a).

2.2 Industry, ASME Code, and NRC Actions

Because of the incidence of cracking and leakage in Alloy 82/182 butt welds in pressure boundary components, the Electric Power Research Institute (EPRI) Materials Reliability Program (MRP) prepared both proprietary and non-proprietary versions of the report, "PWR Materials Reliability Project Interim Alloy 600 Safety Assessment for U.S. PWR Plants (MRP-44), Part 1: Alloy 82/182 Pipe Butt Welds." These reports were submitted to the NRC staff for information in April 2001 (EPRI 2001). The NRC staff subsequently reviewed these reports to evaluate MRP’s assessment of the generic implications of cracking in Alloy 82/182 pipe butt welds. The NRC concluded that results of this interim safety assessment were sufficient to justify the continued operation of PWRs while the industry completes the development of the final version of the safety assessment. The NRC stated that, “the presently required in-service inspection (ISI) examinations need to be augmented in the near term” and “should the industry not be timely in resolving inspection capabilities to identify PWSCC in Alloy 600 welds, regulatory action may result” (Sheron 2001).

Soon after the V.C. Summer event, the U.S. commercial nuclear power industry began implementing strategies to manage potential or existing PWSCC at Alloy 82/182 dissimilar metal welds (DMWs) in PWRs. One general strategy consisted of management by a combination of mitigation plus inspection, with industry applying different mitigation techniques to Alloy 82/182 piping butt welds. The other general strategy was to manage potential PWSCC by more frequent inspections alone. In July 2005, the industry issued inspection guidelines, MRP-139, for Alloy 82/182 piping welds. This report and its revision in 2008 provided industry guidance for the volumetric and visual inspections of unmitigated and mitigated butt welds in PWR primary systems (EPRI 2005, 2008a). MRP-139 augmented the inspections of welded locations that were already required by Section XI of the ASME Code, which is incorporated into the NRC regulations by Title 10, Part 50, Section 50.55a, Codes and Standards, of the *Code of Federal Regulations* (10 CFR 50.55a 2011).

After the events at V.C. Summer and Ringhals in 2000, the NRC began to evaluate the adequacy of existing inspection requirements for Alloy 82/182 butt welds in the ASME Code, Section XI. In December 2005, the NRC sent a letter to ASME (Dyer 2005) requesting the standards body to address inadequate inspection requirements for Class 1 PWR piping butt welds fabricated with Alloy 82/182 weld materials. ASME approved the development of an ASME Code Case on appropriate inspection requirements to address PWSCC in Class 1 butt welds containing Alloy 82/182. This case was later numbered Code Case N-770 (ASME 2009b). Code Case N-770 was revised in 2009 to address NRC concerns and Code Case N-770-1 was issued later that year (ASME 2009a). The NRC incorporated ASME Code Case N-770-1 by reference into 10 CFR 50.55a(g)(6)(ii)(F) (76 FR 36232) in June 2011. Code Case N-770-1 contains requirements for inspection of unmitigated as well as Alloy 82/182 RCS butt welds mitigated by certain techniques. Paragraph 10 CFR 50.55a(g)(6)(ii)(F) required PWR licensees to implement the requirements of ASME Code Case N-770-1, subject to the conditions specified in paragraphs (g)(6)(ii)(F)(*2*) through (g)(6)(ii)(F)(*10*), by the first refueling outage after August 22, 2011. Paragraph 10 CFR 50.55a(g)(6)(ii)(F) also required PWR licensees to complete baseline examinations for unmitigated welds by the end of the next refueling outage after January 20, 2012. ASME has continued to develop revisions to Code Case N-770-1. Code Case N-770-2, approved by ASME on June 9, 2011, was developed to provide separate inspection items (categories) for welds mitigated by stress improvement. Specifically, the revision of the Code Case contains inspection items for welds mitigated by optimized weld overlays and welds mitigated by stress improvement without welding. Code Case N-770-3, approved by ASME on April 7, 2013, was developed to change the inspection interval for cold leg temperature welds from every second period not to exceed 7 years to once per interval with the time between examination not to exceed 13 years. At the time this report was issued, Code Case N-770-4 was being developed to include inspection intervals for welds mitigated by peening and 10 CFR 50.55a had incorporated only ASME Code Case N-770-1.

ASME has been working on Code Cases to provide requirements for applying mitigation techniques to welds susceptible to PWSCC. Code Case N-740-2 provides requirements for design, installation, and examination of full structural weld overlays for Class 1, 2, and 3 items in PWRs and boiling water reactors (BWRs). Code Case N-740-2 provides requirements for both repair and pre-emptive mitigation. Code Case N-754 provides requirements for design, installation, and examination of optimized weld overlays for Class 1 items in PWRs. The Case is limited to mitigation repair of as-found flaws that measure not more than 50% in depth from the inside surface. Code Case N-766 provides alternative rules for the design, installation, and examination of a weld inlay or onlay onto full penetration, nickel alloy, DMWs associated with Class 1 component nozzles and piping in PWRs. Inlays and onlays are installed to isolate the Alloy 82/182 weld material from the reactor coolant. Code Case N-766 contains requirements for both repair and pre-emptive mitigation. At the time this report was issued, the NRC had not approved Code Cases N-740-2, N-754, or N-766 in U.S. NRC Regulatory Guide 1.147 or in Draft Regulatory Guide DG-1231 (NRC 2013).

2.3 Mitigation Techniques

Decisions to mitigate welds susceptible to PWSCC have been driven by several factors. Because the majority of PWR butt weld mitigations implemented to date have been pressurizer (PZR) nozzle welds, and because those welds have the highest operating temperature and tend to present considerable inspection challenges because of tapers, contours, and materials issues, weld overlays have been applied extensively. Weld overlays create a new surface from which to inspect and result in a new examination volume that can, typically, be fully inspected. Mitigation by MSIP was generally not a viable option for these welds because of their design geometries and accessibility. These issues caused volumetric inspection limitations for the majority of PZR nozzle-to-head welds; thus, the required pre-MSIP examinations could not be performed, although MSIP was used to mitigate the PZR spray, safety/relief and surge nozzle welds at Calvert Cliffs 1 and 2, and the pressurizer surge outlet nozzle Alloy 600 safe end-to-stainless steel surge line upper elbow at Palisades (EPRI 2006).

Weld inlays and onlays are designed to be applied to the inside surface of DMWs to isolate the susceptible Alloy 82/182 material from the reactor coolant environment. Weld inlays and onlays are designed to be about 3-mm (1/8-in.) thick and made of Alloy 52, a material believed to be much less susceptible to PWSCC.

As noted previously, the industry began performing baseline examinations under MRP-139 and 10 CFR 50.55a(g)(6)(ii)(F), with these examinations of unmitigated welds to be completed by the end of the next refueling outage after January 20, 2012. The baseline examination results for primary system hot leg and cold leg temperature weld locations have been generally favorable, which has decreased the urgency to mitigate these welds in the short term.

2.3.1 Weld Overlays

Weld overlay (WOL) repairs were first applied on austenitic SS piping welds in BWRs in 1982 (EPRI 1991). WOLs were initially applied as interim measures to welds affected by intergranular stress corrosion cracking (IGSCC) to allow the plants to return to power while long-term repairs or piping replacements were planned. NUREG/CR-4877 (Scott 1987) provides an assessment of the load-carrying capacity design basis for weld-overlay repairs which concludes, in part, that a WOL based on a design basis flaw of 100% through the original thickness of the pipe/weld wall overlay would be suitable for long-term plant operation. WOLs were recognized by the NRC in NUREG-0313 (Hazelton and Koo 1988) as a mitigation and repair technique, which could be credited for reducing the frequency of inspection for welds susceptible to IGSCC. The Electric Power Research Institute (EPRI 1991) provides a compilation of the results of experimental, analytical, and operational WOL programs conducted by nuclear utilities, the NRC, and EPRI.

ASME Code Case N-504 was developed to address design and preservice examination aspects of full structural weld overlays for BWRs. Regulatory Guide 1.147, Revision 16, issued in October 2010 (NRC 2010a), conditionally accepted Code Case N-504-4 (ASME 2006). FSWOLs and optimized weld overlays (OWOLs) were evaluated by Fredette and Scott in 2010 as a mitigation or repair strategy for PWSCC in Alloy 82/182 welds in PWRs (Fredette and Scott 2010). The results of this study showed that for the geometries considered, weld overlays are an effective method to reduce weld residual stresses at the pipe weld inside surface which can lead to PWSCC in DMWs in PWR piping systems.

There are two types of weld overlays for PWR Alloy 82/182 welds susceptible to PWSCC—FSWOLs, which have a minimum thickness of one-third the pipe wall thickness, and OWOLs, which have much less weld metal, in some cases having as few as three layers of applied weldment. Weld overlays extend in both axial directions some distance beyond the weld. Weld overlays extend 360 degrees circumferentially around the pipe. For FSWOLs, no structural credit is taken for the original pipe thickness. For OWOLs, structural credit is taken for the outer 25% wall thickness of the DMW. These weld overlays are constructed of Alloy 52/152-type weld materials, which during testing at Pacific Northwest National Laboratory (PNNL) did not show any significant stress corrosion cracking (SCC) in PWR primary water (Toloczko and Bruemmer 2009).

The owner for Davis-Besse elected to apply Alloy 52 FSWOLs to the core flood nozzle-to-safe end welds, Alloy 52 OWOLs to the reactor coolant pump (RCP) discharge nozzle welds, and FSWOLs to the RCP inlet nozzle welds (White 2010).

In February 2011, the owner of Calvert Cliffs, Units 1 and 2, received NRC approval to apply Alloy 52 FSWOLs on a contingency basis in case any unacceptable indications of cracking are found during the fourth ISI interval in the reactor coolant pump inlet and outlet nozzles, PZR surge hot leg nozzles, safety injection cold leg nozzles, PZR spray cold leg nozzles, PZR relief nozzles, cold leg letdown drain nozzles, cold leg charging inlet nozzles, and cold leg loop drain nozzles (Salgado 2011). Since 2006, no indications of unacceptable cracking attributed to PWSCC have been found at Calvert Cliffs 1 or 2. Accordingly, no FSWOLs have been applied in these locations at these units under the licensee's alternative approved by the NRC in 2011.

The owner of North Anna Power Station, Unit 1 (NAPS-1) requested NRC authorization in March 2011 to mitigate PWSCC susceptibility of steam generator (SG) hot leg nozzle DMWs by installing an Alloy 52M FSWOL on each of these welds during the NAPS-1 spring 2012 refueling outage (Price 2011). The NRC authorization for this licensee proposal was issued on January 27, 2012 (Salgado 2012). Axial flaws in a NAPS-1 hot leg SG nozzle were not detected during a manual pre-WOL inspection performed in March 2012. However, leaks through two flaws were found when the nozzle weld OD region was machined in preparation to install weld overlays (Anderson et al. 2012).

These mitigation approaches provide an alternative to relying on inspection alone as a means to manage potential PWSCC at these locations. In PWRs, the weld overlay process consists of applying an annulus of Alloy 52-type weld material on the outside of a pipe over the susceptible Alloy 82/182 DMW and the materials on either side of the DMW. Weld overlays are expected to continue to be relied upon in the mitigation of Alloy 82/182 welds in PWRs. Details on design and evaluation of WOLs are provided in Chapter 5 of this report.

2.3.2 Mechanical Stress Improvement Process

MSIP was first used in 1986. The NRC Office of Nuclear Regulatory Research issued Research Information Letter (RIL) Number 149, “Evaluation of the Mechanical Stress Improvement Process,” on February 12, 1987 (NRC 1987). RIL No. 149 was based on a review by Argonne National Laboratory (ANL) of information on MSIP submitted to the staff by O’Donnell & Associates, Inc. and Westinghouse Electric Corporation, the developers of the process. Also, ANL performed analyses and tests to determine the changes in weld residual stress using two large-diameter pipe sections supplied by Vermont Yankee that were modified by MSIP. The RIL states that, “Based on the results of our research work and the data and analyses provided by O’Donnell & Associates, MSIP is judged to be an effective means of improving the residual stress state of piping system weldments. It is as effective for large diameter piping as small diameter piping.” MSIP was approved by the NRC for BWR applications in 1988 with the issuance of USNRC Generic Letter 88-01 (NRC 1988) and the guidelines contained in NUREG-0313, Revision 2 (Hazelton and Koo 1988).

Mitigation provides an alternative to relying on inspection alone as a means to manage potential PWSCC at these locations. MSIP modifies the existing ID residual tensile stresses in the weld metal and heat-affected zone of butt welds in piping. A load is applied to the outside surface of the pipe with a large two-piece mechanical hydraulic clamping device connected by two pairs of tangentially positioned studs. The clamping device is placed a short distance away from the weld being mitigated. Stainless steel, “waffled” contact plates are placed between the tool and the pipe outer surface to aid in uniformly distributing the load. The studs are tightened with hydraulic tensioners. Displacement is controlled to pre-assigned limits by using shims, providing safety from over-straining the pipe. Loading plastically strains the pipe causing the pipe diameter to decrease in the region under the clamps. In the nearby weld and counterbore region, the plastic strain caused by the clamps generates compressive residual stress around the weld ID and counterbore region. Weld residual stresses (WRS) after application of MSIP are most compressive in the weld on the pipe inside surface and the WRSs increase and become tensile toward the outside surface. Likewise, WRSs at the inside surface increase at increasing distances away from the weld fusion line (Smith et al. 1987).

The generation of residual compressive stresses has been verified and confirmed by independent tests and analyses. These tests include residual stress measurements on BWR mockups and welds taken from discontinued plants. Weld residual stress analyses and crack growth analyses have been performed as well as sensitivity studies on process parameters, such as the location and axial length of the clamping device and the amount of plastic strain imparted. The following references discuss the results of these studies: Smith et al. (1987), Phillips et al. (1993), Findlan et al. (2004), and Fredette and Scott (2009).

The current holders on the patent for MSIP, NuVision Engineering, have indicated that MSIP has over 25 years of successful operating experience in the United States with more than 1000 welds treated (NuVision 2011).

The largest diameter Alloy 82/182 welds in the primary loop of the RCS are the reactor vessel nozzle-to-pipe welds in Westinghouse plants and the RCP nozzle-to-pipe welds in Combustion Engineering and Babcock and Wilcox plants. MSIP has been implemented on reactor vessel nozzle DMWs at V.C. Summer, Salem Unit 1, and Seabrook. MSIP was used at these plants to stabilize the reactor vessel nozzle welds with indications of cracking. Except at Seabrook, MSIP was used to preemptively mitigate other reactor vessel nozzle welds that did not have indications of cracking (Dodson 2008; Burritt 2009; O'Keefe 2010).

In 2010, the owners for D.C. Cook, Unit 1, elected to perform UT and ET of the RPV hot leg nozzle welds pre-MSIP, and the cold leg nozzle welds post-MSIP (Cameron 2010). For the hot leg nozzle welds, the licensee performed pre- and post-MSIP Section XI, Appendix VIII, qualified UT examinations, as modified by an NRC-approved ASME Code relief request (Kobetz 2006). For the cold leg nozzle welds, the licensee performed only a post-MSIP Section XI, Appendix VIII, qualified UT, as modified by an NRC-approved ASME Code relief request, and an ET examination from the inside surface of these piping welds. The licensee noted that ASME Code Case N-770 has provisions to accept post-MSIP UT examinations for these particular nozzles, if supplemented by ET. No indications were found as a result of the inspections of these welds.

MSIP has been applied at Watts Bar, Unit 2, to the six pressurizer nozzles, the four reactor vessel hot leg nozzles, and the four reactor vessel cold leg nozzles. This plant is undergoing licensing review (Watts Bar, Unit 2, Final Safety Evaluation Report, Section 5.5.3.3.1).

MSIP has been reported to stabilize existing cracks, or even close them sufficiently, such that they are no longer detected with ultrasonic NDE techniques (Findlan et al. 2004; Crawford et al. 2011). Details on design and evaluation of MSIP are provided in Section 4 of this report.

2.3.3 Inlays/Onlays

Weld inlays and weld onlays are methods to mitigate potential PWSCC by applying Alloy 52/152 material to the inside pipe wall over an existing Alloy 82/182 weld. Alloy 52/152 material is considered more resistant to PWSCC than Alloy 82/182. Weld inlays and onlays are applied to isolate the existing Alloy 82/182 material from the reactor coolant.

In larger bore piping (e.g., RPV hot leg outlet nozzle), mitigation by a method such as FSWOL is very costly because of the amount of weld metal that must be deposited and outage time required to perform this welding. Additionally, OD access space may limit the ability to use MSIP in certain plants. To provide an alternative mitigation approach, industry developed inlay and onlay methods. The inlay process consists of excavating a small portion of the susceptible material on the ID surface of the pipe weld and applying Alloy 52/152 material in its place to form a more corrosion-resistant barrier between the Alloy 82/182 weld and butter materials, and reactor coolant. With the onlay process, no excavation of material is performed prior to applying the barrier of Alloy 52/152 material. During these methods, only a small layer of 2 to 3 weld beads would be deposited on the inside surface of the pipe. Industry proposed a weld inlay and onlay thickness of approximately 3 mm (1/8 in.). The ASME Code developed Code Case N-766, “Nickel Alloy Reactor Coolant Inlay and Onlay for Repair or Mitigation of PWR Full

Penetration Circumferential Nickel Alloy Welds in Class 1 Items," to document the process for applying weld inlays and onlays.

Based on industry presentations to NRC staff (Tsao 2008c, d), the first layer of weld metal would be a type 308L or 309L SS buffer on the existing SS safe end on one side of the susceptible weld and on the SS cladding on the nozzle adjacent to the butter. These buffer layers are to prevent hot cracking, which is possible if Alloy 52/152 material is deposited directly onto the existing SS. These SS buffer layers would stop short of application to the existing Alloy 82/182. A buffer layer of Alloy 82 may be applied directly to the existing Alloy 82/182 in between the SS buffer layers. The Alloy 82 and SS buffer layers would be blended to form a smooth first layer. Two weld metal layers of Alloy 52/152 material would be applied continuously over the SS and Alloy 82 first layer. Subsequent layer(s) of 52/152 material may be applied to provide material for machining and adequate thickness after surfacing, if needed. After welding, the surface of the weld would be machined to a relatively smooth condition. The ends of the welds would be blended into the surrounding areas.

Industry also indicated that the addition of Alloy 52/152 weld material to the inside surface of each nozzle/safe end junction would have no adverse effect on the flow through these nozzles. The inside diameter of the completed onlay would be larger than the supply pipe inside diameter; therefore, the onlay should not be a limiting feature of the flow path. Industry indicated that the structural qualification of the joint would not be adversely affected. No credit is taken for the strength of the onlay, which is considered as added cladding (Tsao 2008c).

The design of inlays is expected to be similar to onlays except that the existing weld and portions of the safe-end and nozzle cladding are excavated to accommodate the thickness of the weld inlay (Tsao 2008c). As part of a confirmatory analysis, the NRC staff and its contractor, Engineering Mechanics Corporation of Columbus, conducted both welding residual stress and flaw evaluation analyses to determine the effectiveness of inlay welds as a mitigative technique (Rudland et al. 2010).

In 2010, the ASME Code, Section XI, approved Code Case N-766, "Nickel Alloy Reactor Coolant Inlay and Onlay for Mitigation of PWR Full Penetration Circumferential Nickel Alloy Dissimilar Metal Welds of Class 1 Items" (ASME 2010). The ASME prepared Code Case N-766-1 in response to NRC staff comments on Code Case N-766. ASME approved Code Case N-766-1 on April 7, 2013. At the time this report was issued, the NRC had not approved Code Case N-766 or Code Case N-766-1 in U.S. NRC Regulatory Guide 1.147 or in DG-1231 (NRC 2013). NRC staff issues with these code cases are discussed in Section 6.5.

Weld onlays were applied to the core flood nozzles to reactor vessel DMWs at Arkansas Nuclear One Unit 1 during the fall 2008 outage (Clark 2009) and the 'A' core flood nozzle weld at Three Mile Island Nuclear Station, Unit 1 (TMI-1) in 2009 (Bellamy 2010). V.C. Summer has SG inlet and outlet DMWs with Alloy 152/152 inlays from its SG replacement (Gatlin 2012a, b, c). A discussion on the V.C. Summer SG inlays is contained in Section 6.1 of this report.

Details on design and evaluation of inlays and onlays are provided in Section 6 of this report.

2.3.4 Emergent Mitigation Techniques

2.3.4.1 Peening

In the United States, the techniques used to mitigate butt welds against the initiation or propagation of PWSCC have been weld overlays, MSIP and, to a lesser extent, inlays and onlays. Due to obstructions and limited space, weld overlays and MSIP may not be practical for some locations. Surface stress improvement (SSI) (i.e., peening) is another mitigation method that has been extensively used in Japanese PWRs and BWRs and is being considered as an additional or alternative PWSCC mitigation technique in the United States for Alloy 82/182 butt welds and other Alloy 82/182 locations. The SSI treatment is applied to the entire area of the wetted surface that is susceptible to PWSCC. This technique is reported to mitigate PWSCC by reversing the tensile stress at the surface exposed to reactor coolant to compressive residual stress.

Peening is considered by EPRI to be cost-effective and lower in dose than mitigations involving welding. EPRI has been working in recent years to establish the technical basis for applying SSI treatments as an alternative PWSCC mitigation method to protect key PWR plant assets. The program underway is intended to establish the effectiveness of SSI treatments and to identify Alloy 600/82/182 locations for which relaxation of inspection requirements is appropriate after applying SSI mitigation treatments. EPRI is investigating laser peening and water jet peening (WJP). Japanese vendors are working with EPRI on this effort, including Toshiba on laser peening and Mitsubishi and Hitachi-GE on water jet peening. EPRI reported that in mockups of reactor vessel bottom-mounted nozzles (BMN) constructed of Alloy 600/82/182 where the BMN ID, OD, and J-groove weld were peened with laser peening or WJP, the residual stress was compressive to a depth of at least 1.0–1.5 mm in most cases and for WJP of the inner surface of BMNs, the residual stress was compressive to a depth of about 0.5 mm.

Representatives of Toshiba, Mitsubishi, and Hitachi-GE made presentations to the ASME Task Group on High Strength Nickel Alloy Issues at several meetings in 2011 and 2012. These presentations can be found by ASME volunteers on the ASME Codes and Standards website but are not publicly available. Similar but less detailed information on peening is available in Crooker and Sims (2011) and White et al. (2012e). The ASME Code, Section XI, is developing proposed inspection requirements for peened welds, which would be a relaxation compared to current inspection requirements for unmitigated welds in Code Case N-770-1. EPRI prepared two reports on peening of DMW butt welds: Materials Reliability Program: Technical Basis for Primary Water Stress Corrosion Cracking Mitigation by Surface Stress Improvement (MRP-267, Revision 1) (EPRI 2012c) and Materials Reliability Program: Topical Report for Primary Water stress Corrosion Cracking Mitigation by Surface Stress Improvement (MRP-335) (EPRI 2012d). EPRI made these reports available to download from its website at www.epri.com. These reports were developed, in part, to support regulatory review of peening techniques and to support development of ASME Code rules on peening. MRP discussed its request for NRC staff review of this report in a letter from EPRI dated May 1, 2013 (Crooker 2013). MRP-335 was under NRC staff review at the time of the issuance of this report.

2.3.4.2 Partial Excavation and Weld Repair

An alternative mitigation and emergent repair strategy is being developed called partial excavation and weld repair (PEWR). The industry has discussed this strategy with the NRC staff, including during a meeting held on April 29, 2010 (EPRI 2010). The PEWR repair technique involves removal of a significant portion (approximately 50%) of the wall thickness of a DMW from the OD, and replacing the removed material with Alloy 52, which is less susceptible to PWSCC than Alloy 82/182. PEWR has been proposed as a technique that can be performed preemptively as a PWSCC mitigation technique or as a repair technique upon discovery of a PWSCC flaw. In addition, it has been proposed that PEWR can be applied to a partial arc of the weld or to the full weld circumference.

The PEWR concept was proposed as being similar to FSWOLs in that all design loads would be carried by the newly applied Alloy 52M weld material for full circumferential 360-degree repair, but without the compressive residual stress benefit at the weld ID.

The three options that have been proposed are preemptive mitigation with a full 360-degree PEWR, full 360-degree PEWR repair in the presence of PWSCC, and partial arc repair only in the area of an axial or limited circumferential flaw. The partial arc repair has been characterized as possibly being used as a temporary repair.

ASME Code Section XI is working to establish rules for partial excavation and weld repair in the form of an ASME Code Case. This work is being coordinated by the ASME Section XI, Task Group on Partial Excavation and Weld Repair of Dissimilar Welds. The Code Case will address fatigue and PWSCC crack growth from flaws detected in the weld, or flaws assumed for analysis purposes if no flaws are actually detected prior to installation of PEWR. The Code Case will also address welding considerations. The examination requirements and acceptance criteria for PEWRs are planned to be incorporated in a future revision of Code Case N-770-1. There are potential regulatory issues with PEWR because NRC approval would be necessary and approval for repairs requested on short notice, that is, during a refueling outage, may involve certain risks for the licensee.

3 MANAGEMENT OF PWSCC IN UNMITIGATED WELDS BY INSPECTION

3.1 NDE Reliability Issues in Unmitigated Welds

Nondestructive examination (NDE) reliability can be expressed in terms of the degree to which an examination system consistently achieves its purpose of detecting and characterizing targeted flaws. For this section on NDE reliability, the volumetric examination method being assessed is ultrasonic testing (UT), notwithstanding that there are a number of different qualified UT techniques, such as:

- Conventional UT – utilizes probes that insonify the material at a single angle to examine the intended examination volume for each direction scanned.
- Phased Array UT – utilizes search units that insonify the intended examination volume with multiple examination angles.
- Both conventional UT and Phased Array UT
  - May have data acquired and reviewed by the analyst in real time, or
  - May have data acquired and encoded for subsequent review.
    - Encoded data may be gathered with automated or manually manipulated systems.

In assessing reliability, Pacific Northwest National Laboratory (PNNL) considered various factors that may influence UT performance. This section provides a discussion on UT issues related to detection and characterization of stress corrosion cracking (SCC) in unmitigated welds. Section 3.2 summarizes information on limitations to performing inspections to ASME Code, Section XI requirements. Section 3.3 provides an assessment of uncertainty for Appendix VIII piping examinations conducted from the inside surface. Section 3.4 provides an assessment of NDE required by ASME Code Case N-770-1. The conclusions reached on NDE reliability are presented in Section 3.5. Probability of detection (POD) is an accepted analytical method for quantifying NDE reliability and is often represented as a relationship between detection probability as a function of flaw size, for a given flaw type and examination technique. POD curves may also provide information about the threshold of detection of flaws and can often be used to assess false call probabilities. However, this NUREG/CR does not include an assessment on POD of flaws in nickel alloy butt welds. In 2009, the Materials Reliability Program (MRP) issued MRP-262, *Development of Probability of Detection Curves for Ultrasonic Examination of Dissimilar Metal Welds*. The MRP report discusses the development of POD curves based on testing of UT examination candidates under the Performance Demonstration Initiative (PDI) managed by the Electric Power Research Institute (EPRI) and presents results based on these demonstration tests. Based on a review of the MRP report, PNNL identified a number of issues with the resulting POD curves. These concerns were provided to EPRI; however, as of the date of this report EPRI has not responded to these concerns. Additional work will need to be performed on POD by the nuclear industry, and possibly also by the U.S. Nuclear Regulatory Commission (NRC), to be able to include POD in an assessment of NDE reliability for nickel alloy welds.

3.1.1 Introduction

On May 8 and 9, 2012, PNNL held a workshop in Richland, Washington, with Lambert, MacGill, Thomas, Inc. (LMT), an NDE vendor for the commercial nuclear power industry. LMT uses UT examination methods qualified under ASME Code, Section XI, Appendix VIII. Both phased array (PA) and conventional UT techniques in encoded and non-encoded delivery modes are employed, as specified by the utility. LMT performs examinations of piping welds from the outer-diameter (OD) surface and has been involved with the inspection of a number of welds in pressurized water reactors (PWRs) and boiling water reactors (BWRs) in which indications were attributed to SCC.

The topics that were discussed during this workshop included:

- Characterization of flaws attributed to SCC,
- Encoded versus non-encoded examinations, and
- Characterization of embedded flaws in field welds.

3.1.2 Discussion

Encoded phased-array UT (PAUT) techniques were used to detect and characterize SCC found in a BWR control rod drive (N9) nozzle dissimilar metal weld (DMW) during a spring 2008 refueling outage and in a PWR pressurizer (PZR) surge line DMW during a spring 2007 refueling outage. In both cases, the stress corrosion cracking was subsequently mitigated with NRC-approved full structural weld overlays (FSWOLs). Additionally, encoded UT examinations were performed in 2008 on safety and relief nozzle welds on a PZR removed from St. Lucie, Unit 1, to assess results obtained previously from manual non-encoded PA examinations.

In the case of the BWR N9 weld, the full ASME Code-required inspection volume was not achieved with encoded PAUT techniques because of an interfering weld crown, geometry limitations from the nozzle contour, and the presence of an end cap. Only axial scanning for circumferentially-oriented flaws was conducted using PA, as the component was being prepared for a FSWOL procedure and full ASME Code UT volume coverage was not needed or required.

With minor geometric reflections in this weld, a circumferential flaw was readily detected and was localized at the weld-to-butter interface, determined to be inner-diameter (ID)-connected, and was attributed to intergranular stress corrosion cracking (IGSCC). The overall thickness of the weld was approximately 19 mm (0.75 in.) and the crack was depth-sized at approximately 60% through-wall. A general observation made by LMT analysts during the workshop was that this circumferential flaw was relatively easy to detect and characterize on this somewhat thin-walled component. They noted that inspection of heavier-walled components can present additional challenges.

Regarding the surge line flaw, full volumetric inspection of the flawed region was precluded by the specimen’s taper and by the presence of lugs near the nozzle weld. During the initial conventional manual (non-encoded) examination, an axial flaw was detected. A decision was made to remove the lugs and use encoded PAUT to fully characterize the axial flaw as well as to conduct a more complete inspection of the Code-required inspection volume. Using encoded

PAUT, an ID-connected circumferential flaw was observed that was not initially detected by the manual conventional UT examination. The weld thickness is approximately 38 mm (1.50 in.) at the flaw location, and the flaw was depth-sized at 34% through-wall. It is unclear whether interference by the lugs prevented detection of the circumferential flaw during the initial manual examination. However, general observations made by the LMT analysts were that use of the encoded PAUT technique facilitated detection and characterization of this flaw, which would not have been straightforward in this weld using manual non-encoded techniques, even with the lugs removed. This observation is based on the presence of spurious reflections caused by a short safe end, numerous geometrical reflections, and various mode-conversion signals. The use of encoded techniques provides a more comprehensive assessment of the examination volume and enables analysts to use imaging techniques to sufficiently distinguish circumferential flaws from other spurious reflections and characterize them properly.

In the case of the St. Lucie, Unit 1, PZR safety and relief nozzle welds, the conclusions of the initial manual (non-encoded) PA examinations were that these welds contained deep non-uniform 360-degree ID-connected circumferential flaws indicative of SCC. This result raised questions about the applicability of the advanced finite element analyses (AFEA) safety assessment performed after circumferential flaws were detected in 2006 in Wolf Creek PZR nozzles (EPRI 2007a). The Wolf Creek flaws were attributed to primary waster stress corrosion cracking (PWSCC). A number of operating PWRs had deferred the PZR nozzle weld inspections to their next refueling outage based on the AFEA assessment. Because of the significance of the initial St. Lucie, Unit 1, inspection result to these operating PWRs, initial manual PA examinations were reevaluated and the welds were reexamined shortly thereafter with encoded techniques. A PNNL NDE expert closely observed the reexamination activity. Further scanning and data analysis indicated that the welds were not cracked, but rather contained embedded fabrication flaws, attributed to slag, porosity, and/or lack of fusion, and machining geometry. The 360-degree indications at the ID were signals from fabrication-related flaws. There was also an indication from a machining flaw due to a fabrication boring operation performed from both the vessel ID and the safe end. The boring operations were not aligned properly and resulted in an eccentric step. The indication from the eccentric step could be confused with a root signal, but it was about an inch away from the actual weld root. This eccentric step was confirmed by eddy current testing (ET) during the reexamination process. The presence of this geometrical discontinuity was demonstrated to the PNNL NDE expert who observed the reexamination activity.

Despite the abundance of fabrication-related flaws, a reevaluation of the fabrication flaws in accordance with ASME Code Section III criteria confirmed that the welds were acceptable. During the reevaluation, numerous problems were found with the initial examinations. These problems included use of probes that were inappropriately focused for the welds being examined, improper execution of PDI-qualified procedures, and the inability of the examiners to distinguish the signals from the fabrication flaws from potential PWSCC flaws with the manual techniques applied.

The workshop participants noted the disadvantage of using manual PA techniques in this situation because of the inability to review the UT data and carefully determine the origin of the signals present; this problem is inherent in all non-encoded UT, including both conventional and PA techniques. It was also noted that opportunities in the PDI qualification process for candidates to be required to interpret reflections from false call signals such as those weld roots, counterbores, and welding fabrication flaws, may not be sufficiently realistic. Thus, examiners may pass the PDI qualification process with manual (both conventional and PA) non-encoded techniques without adequately demonstrating an ability to distinguish ID-connected flaws from other signals that are expected to be present in a weld inspection volume, especially in DMWs.

Workshop participants indicated that there are numerous factors that affect the reliability of UT to detect and characterize flaws. These factors include the ability of the techniques used to obtain full ASME Code-required coverage of the inspection volume, access limitations posed by component geometry or surface conditions, the presence of interfering signals from geometric or metallurgical reflectors, the use of manual versus encoded techniques, the quality of the UT data, the reflectivity of the flaw, the impedance(1) of the materials being examined, the signal attenuation and dispersion(2) through those materials, and the experience and skill of the examiner. Other related factors may include the use of proper modeling methods to design the examination and the representativeness of the mockups used for performance demonstration to qualify UT examiners. The St. Lucie, Unit 1 experience and the recent North Anna Power Station, Unit 1 (NAPS-1) experience in 2012 (discussed in Section 2.1 above), reinforce the importance of carefully considering these factors before conducting an examination.

In this NUREG/CR, statements are made regarding the significance of *effective and reliable* ultrasonic examinations, which in the authors' opinions, involve techniques having optimized sound field intensities, with a sufficient number of beam angles to produce adequate volumetric coverage within the areas of interest (especially in coarse-grained austenitic materials) and applying proper contouring of wedges for full coupling across the entire transmitting surfaces of the probes. In addition, the applied sound fields should cover the optimum range of impingement angles for flaw detection using appropriate interrogation frequencies for the materials within the examination volume. Finally, for a general population of nondestructive examiners, the most effective and reliable UT methods are those using independent review of encoded data, thus limiting the use of manual non-encoded techniques to low risk examinations.

3.2 Inspection Limitations

Information on limitations to performing inspections of a typical Westinghouse and a typical Combustion Engineering (CE) plant reactor coolant system (RCS) Alloy 82/182 welds was also obtained from LMT during the workshop PNNL held in May 2012. Appendices C and D contain weld coverage assessment diagrams for these plants showing the probe angles used and percent coverage obtained with Section XI, Appendix VIII, qualified techniques. These appendices also indicate the materials of construction for the welds depicted. Qualified UT

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(1) Impedance of a material is inversely related to the amount of acoustic energy that is transmitted through it and reflected at the boundary with another material having a different acoustic impedance value.

(2) Dispersion is the phenomenon of a sound wave separating into its component frequencies as it passes through a material. In the presence of dispersion, sound velocity is no longer uniquely defined, resulting in a decrease in signal amplitude.

examinations are required prior to mitigation by the mechanical stress improvement process (MSIP) and optimized weld overlay (OWOL), as noted in Sections 4 and 5, respectively.

For the plant-specific designs used to prepare Appendices C and D, Tables 3.1 and 3.2 provide the Code-required volume coverage achievable for Alloy 82/182 RCS butt welds in the typical Westinghouse and CE plants used for this assessment. The Westinghouse reactor pressure vessel (RPV) nozzle welds in this study were examined from the OD, although the RPV nozzle welds in many Westinghouse plants are examined from the inside surface, where inspection limitations differ and greater Code-required inspection coverage is generally understood to be obtained for axial scans at hot leg locations.

Table 3.1 RCS Alloy 82/182 Butt Weld Code Required Volume Coverage Obtained for a Typical Westinghouse Plant

Description	Axial Scan, %	Circumferential Scan, %
PZR surge nozzle	80	100
PZR surge nozzle	40	34
PZR safety and relief nozzle	0	0
RPV hot leg nozzle	28.8	100
SG hot leg nozzle	95.4	100
SG cold leg nozzle	95.4	100
RPV cold leg nozzle	100	100

Table 3.2 RCS Alloy 82/182 Butt Weld Code Required Volume Coverage Obtained for a Typical Combustion Engineering Plant

Description	Axial Scan, %	Circumferential Scan, %
RPC suction to RC pipe	100	44.3
RCP discharge to RC pipe	77	34
RC[(a)] loop surge nozzle	82.4	31.3
Letdown and drain nozzle	100	100
Hot leg drain nozzle	100	100
Charging inlet nozzle	100	100
Safety injection nozzle	94.3	26.6
Shutdown cooling nozzle	98	100
Spray nozzle	100	100
PZR surge nozzle	100	100
PZR spray nozzle	100	68.9
PZR safety nozzle	100	100
(a) RC – reactor coolant		

In CE plants, the safe ends of medium- and large-bore piping are typically made of cast austenitic stainless steel (CASS). The Code-required volume (CRV) coverage presented in Table 3.2 takes credit for the scan coverage in the CASS safe ends using the Supplement 10 techniques used for the carbon steel and Alloy 82/182 volumes. This approach for reporting CRV coverage was used because Code Case N-770-1 requires the examination volume to be examined by Appendix VIII procedures to the maximum extent practical, including 100% of the susceptible material volume.

Inspection limitations exist for welds adjacent to CASS products. Currently, there are no performance demonstration qualification requirements for inspection of cast piping welds, as Appendix VIII, Supplement 9 has yet to be developed. Some NRC regulatory guidance on performing examinations of welds adjacent to CASS products is contained in a summary of the July 12, 2011, public meeting with industry (Collins 2011), held by the NRC to discuss implementation of Code Case N-770-1. Additional regulatory guidance may be found in a summary of the NRC public meeting with the PWR Owners' Group on January 10, 2012 (Rowley 2012). This meeting was held to discuss an industry template for a generic relief request from the requirements of Code Case N-770-1, as conditioned by the NRC. The NRC staff noted in Collins (2011) that under 50.55a(g)(6)(ii)(F)(*3*) a licensee may use an Appendix III procedure under the requirements of Appendix VIII to meet the ASME Code-required examination volume of essentially 100% to credit previous examinations as baseline inspections. However, all other required inspections under 10 CFR 50.55a(g)(6)(ii)(F) for inspection of DMWs joined to cast stainless steel items require the licensee to meet the inspection coverage requirements of -2500(b) of ASME Code Case N-770-1. Subparagraph −2500(b) states that, "For cast stainless steel items for which no supplement is available in Appendix VIII, the required examination volume shall be examined by Appendix VIII procedures to the maximum extent practical including 100% of the susceptible material volume (non-stainless steel volume)." This wording requires that Appendix VIII procedures, not Appendix III procedures, be used for the examination of the required examination weld volume, including 100% of the susceptible material volume.

There appears to be some uncertainty regarding the requirement to examine "100% of the susceptible material volume." Figure 1 in CC-770-1 shows the required examination volume for an unmitigated weld. This figure shows a typical weld with no "wrap around." The term "wrap around" refers to Alloy 82/182 cladding that may extend from the end of the stainless steel (SS) cladding on the inside wall of a ferritic nozzle to the nozzle weld butter. Because Figure 1 in CC-770-1 shows a typical weld with no wrap around, the inspection volume may have been interpreted to exclude this area per the figure, but the words in the Code Case say 100% of the susceptible material has to be examined.

ASME, Section XI, prepared Code Case N-824, entitled, "Alternate Requirements for Ultrasonic Examination of Cast Austenitic Piping Welds from the Outer Diameter Surface." The basis for Code Case N-824 is research performed by PNNL for the NRC Office of Nuclear Regulatory Research (RES). The requirements in this Code Case are deterministic rather than performance-based. However, this Code Case is considered to be a first step in the development of Appendix VIII, Supplement 9. NDE reliability would be expected to be substantially improved by applying this Code Case, with certain conditions based on NRC research, in situations where 100% of the susceptible material of the DMW cannot be examined from the ferritic side of a weld. The NRC staff supported the development of ASME Code Case N-824, however, at the time this report was issued, the NRC had not yet taken regulatory action to approve or impose ASME Code Case N-824.

Research conducted by RES on inspection of CASS demonstrated that current ASME Section XI, Appendix III, UT techniques are inadequate when applied to cast materials. This research has shown that through-wall cracks of 10 to 50 percent depth in PZR surge line CASS components 5.1 cm (2.0 in.) or less in wall thickness could be readily detected when using phased array techniques at examination frequencies up to 1.0 MHz. Much lower frequency ranges are needed for primary system CASS piping [greater than 5.1 cm (2.0 in.) in thickness]. In thick-walled CASS specimens, that is, specimens between 6.6 and 8.1 cm (2.6 and 3.2 in.), using phased array techniques at an inspection frequency of 500 kHz, examinations have been shown to reliably detect flaws in an approximately 30% and greater through-wall depth range. Additional information is contained in NUREG/CR-6933, *Assessment of Crack Detection in Heavy-Walled Cast Stainless Steel Piping Welds Using Low-Frequency Ultrasonic Methods* (Anderson et al. 2007). NUREG/CR-7122, *An Evaluation of Ultrasonic Phased Array Testing for Cast Austenitic Stainless Steel Pressurizer Surge Line Piping Welds* (Diaz et al. 2011), provides information on crack detection with UT in thinner-walled CASS. The information in these NUREGs should be helpful to industry in improving the reliability of inspections and to the NRC Office of Nuclear Regulatory Research in evaluating relief requests and inspection-related issues involving CASS.

3.3 Uncertainty for Appendix VIII Piping Examinations Conducted from the Inside Surface

The PDI specimens for large-bore Appendix VIII testing have representative geometries with challenging ID surfaces. These surfaces can provide poor contact for ultrasonic probes and the ID geometry can prevent a probe from impinging directly on certain crack features. Procedures for examination of DMWs from the ID surface have been demonstrated to satisfy the detection requirements of Appendix VIII, Supplement 10. However, currently no procedure for ID examination of these welds has been successfully demonstrated to satisfy ASME Supplement 10 through-wall depth sizing root mean square error (RMSE) requirements.

Dozens of NRC-approved relief requests, beginning in 2003, have allowed licensees to add the difference between a procedure-demonstrated RMSE and the ASME acceptance criterion of 3.18 mm (0.125 in.) to the size of any flaw found in the field. The 3.18-mm (0.125-in.) value is the Appendix VIII, Supplement 10, allowed RMSE for flaw depth measurements as compared to flaw true depth during performance demonstration. This allowance was expected in 2003 to be a short-term remedy; however, no alternative approach has been found and agreed upon between industry and the NRC to supersede this allowance.

This short-term allowance has been used very rarely because of low numbers of flaw detections in DMWs and has not yet been used to demonstrate that PWSCC flaws are acceptable for continued service without mitigation or alternate examination. The issue of flaw sizing uncertainty is germane for unmitigated welds as well as welds intended for mitigation by MSIP or OWOL. Indications of flaws that are detected in DMWs (and other butt welds in primary system piping) must be dispositioned by repair, replacement, mitigation, or acceptance/evaluation for continued service. The replacement, and often the repair, option remove the indication, but the mitigation and acceptance/evaluation options require the licensee to consider the depth of the flaw indication determined by NDE.

As discussed in Section 2.3.2, MSIP mitigates SCC by introducing a permanent compressive residual stress field on the inside surface of the DMW by way of mechanical surface deformation. A standard provision for applying MSIP to a weld is that an examination must be performed to show that there are no crack indications on an ID surface deeper than 30% of the wall or having a total extent greater than 10% of circumference. This provision ensures that such flaws are effectively mitigated by the process, considering factors such as the uncertainty in the flaw depth, the uncertainty in the depth of the compressive residual stress zone, and the effect of operating load stresses.

For installation of OWOLs, the flaw depth limit per ASME Code Case N-754 is 50% of pre-OWOL wall thickness. For installation of FSWOLs, there is no pre-FSWOL flaw depth limit.

Industry met with the NRC staff on March 16, 2012, to discuss a permanent approach for addressing the depth-sizing uncertainty issue (Cumblidge 2012). The approach proposed by industry was not accepted by the NRC staff. However, another approach was developed that is contained in ASME Code Case N-696-1, "Qualification Requirements for Appendix VIII Piping Examinations Conducted from the Inside Surface, Section XI, Division 1." This Code Case would replace the 3.18-mm (0.125-in.) RMSE acceptance criterion for depth-sizing of dissimilar metal and austenitic piping welds 54 mm (2.1 in.) and greater in wall thickness with a maximum RMSE of 6.35 mm (0.250 in.). Code Case N-696-1 was approved by the ASME Code, Section XI Committee on Nuclear Inservice Inspection, on May 7, 2014. The NRC staff member of the Section XI Committee on Nuclear Inservice Inspection voted affirmatively on this Code Case. This Code Case approach appears to be promising but is yet to be accepted by NRC.

3.4 Assessment of Code Case N-770-1 Inspection Requirements

3.4.1 Overview of Code Case N-770-1

ASME Code Case N-770-1 specifies examination methods, volumes or areas, and frequencies for Alloy 82/182 butt welds that are unmitigated as well as for Alloy 82/182 butt welds that have been mitigated against PWSCC by one of several specified methods. The requirements of this Code Case pertain to inspections for potential PWSCC. The ASME Code, Section XI, IWB-2500, requirements continue to apply to Alloy 82/182 welds to monitor for other degradation mechanisms, such as fatigue. Code Case N-770-1 contains baseline and inservice inspection (ISI) requirements for unmitigated Alloy 82/182 butt welds and preservice and ISI requirements for mitigated Alloy 82/182 butt welds.

The structure of Code Case N-770-1 is patterned after the requirements of Section XI, Subsection IWB. The Code Case has requirements in Sections -1000, -2000, and -3000 that parallel the requirements in Subsection IWB-1000, -2000, and -3000. Section XI addresses repair/replacement activities that may be needed so there are no -4000 requirements in this Code Case. Similarly, pressure test requirements are unaffected so there are no -5000 requirements in the Code Case.

The examination requirements are contained in Table 1 of the Code Case in the -2000 section. Inspection Items in Table 1 are assigned for each "type and condition" of component. Inspection Items in the Code Case are similar to Examination Categories and Item Numbers used in the Section XI, Table IWB-2500-1. The "type and condition" of component refers to: (1) unmitigated welds at three different service temperatures addressed by Inspection Item A-1, A-2, and B; and (2) cracked and uncracked welds, mitigated by one of several specified methods addressed by Inspection Items C through K. The Code Case includes various figures needed to implement the examination requirements.

The examination methods specified in the Code Case are visual, volumetric, and surface examinations. The visual examination (VE) requirements are the same as the VE requirements of Code Case N-722-1. The requirements of Code Case N-722-1, with conditions, were imposed by 10 CFR 50.55a(g)(6)(ii)(E). Volumetric examinations are required to be performed by UT methods that meet the applicable requirements of Appendix VIII. Surface examinations by eddy current are required to satisfy IWA-2223 and by liquid penetrant testing are required to satisfy IWA-2222.

Welds in Inspection Items A-1, A-2, and B are required to be examined by VE and UT. Inspection Item A-1 welds, hot leg welds with an operating temperature greater than 625°F (325°C) (i.e., pressurizer nozzle DMWs), are required to be examined visually each refueling outage and volumetrically every second refueling outage. Inspection Item A-2 welds, hot leg welds with an operating temperature less than or equal to 625°F (325°C), are required to be examined visually each refueling outage and volumetrically every 5 years. Inspection Item B welds, cold leg welds with an operating temperature greater than or equal to 525°F (274°C) and less than or equal to 580°F (304°C), are required to be examined visually once per interval and volumetrically every second inspection period not to exceed 7 years. This information is presented in Table 3.3.

Table 3.3 Examinations for Inspection Items A-1, A-2, and B

Inspection Item	Parts Examined	Examination Method	Extent and Frequency of Examination
A-1	Unmitigated butt weld at Hot leg operating temperature > 625°F (329°C)	Visual	Each refueling outage
A-1		Volumetric	Every second refueling outage
A-2	Unmitigated butt weld at Hot Leg operating temperature ≤ 625°F (329°C)	Visual	Each refueling outage
A-2		Volumetric	Every 5 years.
B	Unmitigated butt weld at Cold Leg operating temperature ≥ 525°F (274°C) and < 580°F (304°C)	Visual	Once per interval
B		Volumetric	Every second inspection period not to exceed 7 years

Table 1 of Code Case N-770-1 contains the examination requirements and includes the parts examined, the examination volumes and surfaces shown in figures, examination methods, references to acceptance standards, extent and frequency of examination, and rules regarding deferral of the examination to the end of the interval. In Code Case N-770-1, Table 1 includes 18 explanatory notes that contain additional requirements. These notes are necessary because of the range of weld types and conditions covered by the case.

The examination requirements of Table 1 and the notes were developed to provide a set of comprehensive inspection requirements that parallel existing Section IWB Class 1 requirements.[3]

3.4.2 Code Case N-770-1, Table 1 Notes

The notes to Table 1, which are applicable to welds in Inspection Items A-1, A-2, and B, are (1), (2), (3), (4), and (5).

Note (1) states that, "Volumetric examination requirements, methods, acceptance standards and frequencies are applicable to Class 1 PWR piping and vessel nozzle butt welds nominal pipe size (NPS) 2 (DN 50) or greater." Paragraph-1100(a) indicates that Code Case N-770-1 contains visual examination requirements of greater than NPS 1 (DN 25) pressure-retaining Class 1 PWR piping and vessel nozzle butt welds fabricated with Alloy 82/182 materials. Volumetric examination requirements do not apply to butt welds less than NPS 2, while visual examination requirements apply to unmitigated butt welds larger than NPS 1.

Note (2) states that, "A visual examination (VE) shall consist of the following:

> "(a) A direct examination of the bare metal surface of the entire outer surface of the weld with the insulation removed or lifted to allow access for the VE.
>
> "(b) The direct VE shall be performed at a distance not greater than 4 ft (1.2 m) from the weld and with a demonstrated illumination level sufficient to allow resolution of lower case characters having a height of not greater than 0.105 in. (2.7 mm).
>
> "(c) Alternatively, the VE may be performed with insulation in place or removed using remote visual equipment that provides resolution of the weld metal surface equivalent to a bare metal direct VE as defined in (a) and (b), above.
>
> "(d) Personnel performing the VE shall be qualified as a VT-2 visual examiner and shall have completed at least four hours of additional training in detection of borated water leakage from Alloy 600/82/182 components and the resulting boric acid corrosion of adjacent ferritic steel components.
>
> "(e) Examination may be performed with the system depressurized."

The requirements of Note (2) are essentially the same as the VE requirements of Code Case N-722-1.

Note (3) states that, "A VE may be performed during an outage when a volumetric examination is performed from the weld outer surface. An ultrasonic examination performed from the component inside or outside surface in accordance with the requirements of Table 1 and Appendix VIII (1995 Edition with the 1996 Addenda or later) shall be acceptable in lieu of the VE requirement of this table."

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(3) This overview is general in nature and is not reiterated in Sections 4, 5, or 6.

This note is essentially the same as a note in Code Case N-722 that applied to visual examination of full penetration welds (i.e., butt welds). Requirements for visual examination of full penetration welds were removed in the development of Code Case N-722-1 because these requirements were relocated to Code Case N-770.

Note (4) states that, "Ultrasonic volumetric examination shall be used and shall meet the applicable requirements of Appendix VIII." The requirements of this note are consistent with ASME Code Section XI and are implemented by NRC requirements in 10 CFR 50.55a.

Note (5) states that with regard to subsequent inservice inspection of unmitigated welds with inside surface-connected planar flaws, "(a) If planar surface flaws are detected in the butt weld/base metal inside surface, this weld shall be reexamined at the shorter frequency of every refueling outage or the frequency determined by the crack growth analysis of Code Case N-770-1 paragraph -3132.3; and (b) This weld shall be subsequently examined at the frequency required by (a) unless mitigated." The requirements of this note are consistent with ASME Code, Section XI requirements.

3.4.3 NRC Conditions on Code Case N-770-1

The NRC conditions for unmitigated welds in the 10 CFR 50.55a(g)(6)(ii)(F), which imposed Code Case N-770-1, are discussed in detail below. The NRC imposed these conditions, which are in addition to the Code Case requirements, to ensure that, in combination with the Code Case, adequate protection is provided for monitoring Alloy 82/182 welds.

On May 4, 2010, the NRC issued a notice of proposed rulemaking to amend its regulations to incorporate by reference the 2005 Addenda through 2008 Addenda of Section XI, Division 1 of the ASME Code, as well as other recent Code updates (75 FR 24324). The NRC proposed to add a new Section 50.55a(g)(6)(ii)(F) [§50.55a(g)(6)(ii)(F)] to require licensees to implement ASME Code Case N-770, with 15 conditions. The NRC stated that the application of ASME Code Case N-770 is necessary because the inspections currently required by the ASME Code, Section XI, were not written to address degradation of Alloy 82/182 butt welds by PWSCC, and the safety consequences of inadequate inspections can be significant. The NRC stated that it was concerned that the absence of an effective inspection regime could, over time, result in unacceptable circumferential cracking or the degradation of reactor coolant system components by corrosion from leaks in these welds. If not addressed, degradation by PWSCC would increase the probability of a loss-of-coolant accident.

About half of the NRC proposed conditions were related to specific issues that the NRC raised after Code Case N-770 was finalized and approved by ASME. These issues were addressed by the ASME, Section XI, Task Group on Alloy 600/182/82 Issues in Code Case N-770-1, which was approved by the ASME in December 2009. Although Code Case N-770-1 was approved by ASME before the proposed rule was issued, the NRC decided not to revise the proposed rule package to include Code Case N-770-1, because it would have delayed the entire rulemaking process. The proposed NRC conditions that were addressed by Code Case N-770-1 were not considered controversial and were accepted by ASME. As a result of public comments, the final rule imposed Code Case N-770-1 instead of Code Case N-770. The rule was issued on June 21, 2011 (76 FR 36232).

The remainder of this section discusses the conditions in the final rule imposing Code Case N-770-1 (76 FR 36232) that pertain to unmitigated welds; specifically, conditions §50.55a(g)(6)(ii)(F)(*1*), (*2*), (*3*), and (*4*).

Condition §50.55a(g)(6)(ii)(F)(*1*) of the rule requires licensees of existing operating PWRs as of July 21, 2011, to implement the requirements of ASME Code Case N-770-1, subject to the conditions specified in paragraphs (g)(6)(ii)(F)(*2*) through (g)(6)(ii)(F)(*10*) by the first refueling outage after August 22, 2011. This is the basic implementing requirement imposing Code Case N-770-1 with conditions.

Condition §50.55a(g)(6)(ii)(F)(*2*) states that, "Full structural weld overlays authorized by the NRC staff may be categorized as Inspection Items C or F, as appropriate; welds that have been mitigated by stress improvement without welding may be categorized as Inspection Items D or E, as appropriate, provided the criteria in Appendix I of the code case have been met; for ISI frequencies, all other butt welds that rely on Alloy 82/182 for structural integrity shall be categorized as Inspection Items A–1, A–2, or B (Inspection Items for unmitigated welds) until the NRC staff has reviewed the mitigation and authorized an alternative code case Inspection Item for the mitigated weld, or until an alternative code case Inspection Item is used based on conformance with an ASME mitigation code case endorsed in Regulatory Guide 1.147 with conditions, if applicable, and incorporated in this section." This condition applies to Alloy 82/182 butt welds with inlays or onlays or optimized weld overlays which have not been authorized by NRC, either on a weld-specific basis or through Regulatory Guide 1.147, to be categorized as Inspection Items D, E, or G–K. This condition is consistent with NRC philosophy to review and approve mitigation techniques prior to implementation and prior to a licensee taking credit for the reduced inspection frequencies for mitigated welds. The NRC evaluates mitigation methods to verify continued compliance with applicable General Design Criteria (GDC). An exception to the previous statement applies to MSIP welds, and this exception is discussed in some detail in Sullivan and Anderson (2013).

Condition §50.55a(g)(6)(ii)(F)(*3*) of the rule requires that, "Baseline examinations for welds in Table 1, Inspection Items A–1, A–2, and B, shall be completed by the end of the next refueling outage after January 20, 2012. Previous examinations of these welds can be credited for baseline examinations if they were performed within the re-inspection period for the weld item in Table 1 using Section XI, Appendix VIII requirements and met the Code-required examination volume of essentially 100 percent. Other previous examinations that do not meet these requirements can be used to meet the baseline examination requirement, provided NRC approval of alternative inspection requirements in accordance with paragraphs (a)(3)(i) or (a)(3)(ii) of this section is granted prior to the end of the next refueling outage after January 20, 2012."

This condition was imposed by the NRC, because the NRC did not agree with -2200 of Code Case N-770-1, which would allow two refueling outages from adoption of the Code Case to complete baseline examinations. Welds in Inspection Items A-1, A-2, and B are the welds most likely to experience PWSCC and some of these welds may not have received a baseline examination or received a complete examination, even under the industry initiative, MRP-139 (EPRI 2005; NRC 2010a). The NRC clarified in a public meeting (Collins 2011) on the rule that previously approved alternatives to ASME Code requirements regarding inspection frequency or coverage remain applicable during the duration authorized by the NRC. Further, licensees may, if the examination was previously performed within the inspection frequency of Table 1 of ASME Code Case N-770-1, count these inspections as meeting the baseline inspection requirement of 10 CFR 50.55a(g)(6)(ii)(F)(*3*). If a licensee's previous inspection did not meet ASME Code, Section XI, Appendix VIII requirements and the Code-required examination volume of essentially 100%, then relief in accordance with 10 CFR 50.55a(a)(3) remains an option to count these examinations as meeting the baseline examination requirement.

Code Case N-770-1, paragraph -2500(c) states that, "For axial and circumferential flaws, examination shall be performed to the maximum extent practical using qualified personnel and procedures. If essentially 100% coverage for circumferential flaws (100% of the susceptible material volume) can be achieved, the examination for axial flaws shall be completed to achieve the maximum coverage practical." The NRC disagreed with this provision. In the proposed rule, the NRC noted that the -2500(c) requirement on inspection limitations is inconsistent with comparable inspection requirements of the ASME Code, Section XI. Axial flaws can lead to through-wall cracks and leakage of reactor coolant, which is a safety concern. Condition §50.55a(g)(6)(ii)(F)(*4*) requires that the axial and circumferential (flaw) examination coverage requirements of -2500(c) may not be considered to be satisfied unless essentially 100% coverage is achieved. The industry guidelines of MRP-139 (EPRI 2005) allow less than essentially 100% coverage in some cases; therefore, a number of previously conducted baseline examinations may not satisfy the rule. This condition was added for the NRC to ensure that, through NRC review of an authorization of alternative inspection coverage, appropriate actions are being taken to address potential inspection limitations for axial flaws.

3.4.4 Assessment of Unmitigated Weld Inspection Intervals

The results of four deterministic flaw evaluations are presented in Appendix E. In these evaluations, an initial flaw size or sizes are assumed and flaw growth analyses were performed to determine the time for a crack to progress to either a Code maximum allowed flaw depth or to progress through-wall. In some of the studies, a number of parameters, such as loads or initial flaw sizes, were varied to conduct a sensitivity study. The results of these evaluations were used to assess the Code Case N-770-1 inspection interval requirements. Three of the evaluations pertain to circumferential cracking in pressurizer, hot leg temperature, and cold leg temperature welds. The fourth evaluation was performed to assess axial cracking. A deterministic assessment of inspection intervals has limitations, compared to a probabilistic assessment, in that it cannot account for a full range of variables and associated uncertainties. Nevertheless, the results from these evaluations are considered to provide useful insights.

In the first study, which is discussed in Appendix E.1, results from mitigation studies performed by Battelle Columbus Laboratory were provided for an RPV hot leg nozzle weld without a safe end weld, a surge nozzle weld, and a pressurizer safety nozzle weld. The welds were analyzed for normal operating pressure and temperature without bending-moment loading. In all three cases, it was concluded that either a postulated circumferential flaw would not propagate or would arrest before reaching one-third through the wall. This result is similar to Stress Case "C" analyzed with a safe end closure weld in the NRC staff's Hot Leg and Cold Leg Flaw Evaluation and Sensitivity Analyses summarized in Appendix E.3.

In the second study, which is discussed in Appendix E.2, results from pressurizer nozzle advanced finite element analyses of circumferential flaws were provided for a sensitivity study of a surge nozzle weld under various loading conditions and with various postulated initial flaws as shallow as 10% through-wall. A sensitivity case with high loads and long shallow flaws simulating multiple crack initiation sites and omitting the beneficial effect of a secondary SS weld showed little if any time between first leakage and rupture. For this bounding case, monitoring pressurizer nozzle Alloy 82/182 welds with ISI would not appear to be an adequate strategy. However, from information on the NRC website along with Stall (2007), Wadley (2008) and King (2006), all pressurizer surge nozzle DMW welds have been mitigated except at Palisades. As of mid-2014, there were unmitigated pressurizer nozzle butt welds at three plants. These welds have all been inspected at least once and no flaws were detected. The plants have committed to re-inspect these unmitigated welds at least once every 4 years, consistent with the requirements of Code Case N-770-1.

In the third study in Appendix E.3, results were provided for circumferential flaw evaluation sensitivity studies of hot leg and cold leg reactor vessel nozzle welds under various loadings for an initial flaw size of 24% through-wall. This initial flaw depth was selected based on the depth of a flaw found in a PWR hot leg reactor vessel nozzle weld. The flaw was attributed to PWSCC and the study was performed to assess the significance of the flaw. The results for the hot leg analyses showed that there is sufficient time between leakage and rupture to shut down the plant should through-wall leakage occur. Analyses with safe end welds showed times to initial leakage that bound the ASME Code Case N-770-1 inspection intervals for Inspection Item A-2 (hot leg temperature) welds. Addressing uncertainties by including analysis cases of welds without attached safe ends, the times to initial leakage for Load Cases A, B, and D do not bound the inspection intervals in Code Case N-770-1 for Inspection Item A-2 welds.

In the cold leg cases the times to initial leakage, with one exception, bound the maximum inspection interval of 7 years in Code Case N-770-1 for Inspection Item B, unmitigated butt welds at cold leg operating temperature ≥ 525°F (274°C) and < 580°F (304°C). The exception is a high load case with a partial arc repair and no safe end closure weld. For this case, the time to leakage was 6.71 years, just short of the maximum interval of 7 years. The times between leakage and rupture for the cold leg cases are equal to or longer than 7.4 years. The results of the cold leg analysis appear to support an inspection interval of at least 7 years.

In the fourth study in Appendix E.4, results were provided for an axial flaw evaluation of a steam generator nozzle to hot leg pipe DMW. The analysis showed for this example that an assumed 10% through-wall flaw would grow to 75% through-wall in approximately 3-1/3 years or 40 months. This interval of 3-1/3 years is considerably shorter than the required UT inspection interval of once every 5 years for Code Case N-770-1 Inspection Item A-2 welds.

Except for the results of the Battelle study, the analyses showed the time from an initial flaw size to through-wall leakage or to 75% through-wall cracking (in Appendix E.4) to be shorter than the inspection intervals for the Code Case N-770-1 Inspection Item A-1 and A-2 welds analyzed. Initial flaw sizes were assumed to be either 10% or approximately 25% through-wall depending on the study. Various flaw lengths were also assumed, again depending on the study, to model different sensitivity cases. Ten percent through-wall is frequently assumed to be a threshold of detection for UT. Initial circumferential flaw depths of approximately 25% were assumed to model flaws detected during actual inspections of DMWs. Flaws approximately 25% through-wall were found at a number of plants. In the fourth study involving an axial flaw, an analysis was performed to estimate the time it could have taken for the deepest flaw to grow to the depth measured when discovered at NAPS-1. By contrast, in the cold leg cases the times to initial leakage, with one exception, bound the maximum inspection interval of 7 years in Code Case N-770-1 for Inspection Item B, unmitigated butt welds at cold leg operating temperature.

Ideally, results from these studies for time to reach the ASME Section XI maximum depth of 75% through-wall or the Code stability limit would bound the ASME Code Case inspection intervals, because this is the regulatory basis for degradation as opposed to showing that there is sufficient time to shut down a plant after leakage is discovered. Nevertheless, there have not been any occurrences of circumferential cracking that have exceeded ASME Code limits. There has been one case of axial through-wall leakage during plant operation at V.C. Summer in 2000 and two cases of axial through-wall leakage that occurred during plant shutdown conditions at Davis Besse in 2008 and North Anna in 2012. With only a few exceptions, pressurizer (high-temperature) DMWs have been mitigated. Some hot leg temperature DMWs and a smaller number of cold leg temperature DMWs have been mitigated by a variety of techniques. Baseline visual and volumetric inspections of pressurizer, hot leg, and cold leg temperature Alloy 82/182 butt welds have been performed.

These deterministic analyses generally indicate that Code Case N-770-1 inspection intervals may be too long for use as a monitoring strategy to prevent PWSCC from exceeding the ASME Code limit of 75% maximum through-wall depth. The analyses also showed that there is sufficient time between leakage and rupture to shut down the plant should through-wall leakage occur. The Code Case N-770-1 inspection intervals were developed by industry and received NRC staff agreement during the Code Case development process and by virtue of its adoption in 10 CFR 50.55a. The welds to which this Code Case apply have received baseline examinations but few if any second-round examinations. Although axial cracking and axial through-wall leakage were found, no circumferential or axial PWSCC has exceeded ASME Code structural factors. While deterministic analyses indicate that Code Case N-770-1 inspection intervals may be too long, additional bases would be needed to support a modification to Code Case N-770-1 inspection intervals. Such support would have to be the result of unfavorable results of realistic probabilistic analyses and/or operating experience, including results of second and later sets of examinations.

3.5 Conclusions

In assessing the overall reliability of UT examinations to detect and accurately characterize service-induced SCC, there are a number of factors that must be considered. These include:

- ability of the applied NDE to obtain full coverage of the susceptible inspection volume,
- presence of interfering signals such as from geometric or welding fabrication reflectors,
- the use of non-encoded versus encoded techniques,
- general reflectivity of the service-induced flaw,

- acoustic impedance of the materials being examined and the signal attenuation and dispersion through those materials,
- relative experience and skill of the examiner (and/or data analyst),
- use of modeling to design and optimize examination parameters, and
- representativeness of mockups used for performance demonstration qualifications.

The use of encoded UT techniques offers a distinct and significant advantage over non-encoded techniques in detection and characterization of flaws, because of the ability to review the UT data off-line and carefully determine the origin of signals (both relevant and non-relevant) present in the images produced.

Current mockups and protocols used by industry during the PDI qualification process may not provide sufficient opportunities such that candidates may demonstrate adequate skills for interpreting realistic false call signals from non-crack reflection sources that may be encountered in the field; for example, fabrication flaws, weld root response variations, or other geometrical/metallurgical responses. Thus, examiners may pass the PDI qualification process without sufficiently demonstrating the ability to distinguish ID-connected flaws from other signals that may be expected to be present in a weld inspection volume, especially in DMWs.

Inspection limitations can affect the effectiveness of NDE requirements. Appendices C and D to this report contain weld coverage assessment diagrams for typical plants that show probe angles used and percent coverage obtained with Section XI, Appendix VIII, qualified techniques. ASME Code-required volumetric coverage appears achievable for many, although not all, Westinghouse and CE Alloy 82/182 RCS butt welds.

ASME Section XI prepared Code Case N-824, entitled "Alternate Requirements for Ultrasonic Examination of Cast Austenitic Piping Welds from the Outer Diameter Surface." NDE reliability would be expected to be substantially improved by applying this Code Case, with certain conditions based on NRC research, in situations where 100% of the susceptible material cannot be examined from the ferritic side of the weld. The examination requirements of ASME Code Case N-770-1 appear to be complete and parallel existing Section IWB Class 1 requirements. For unmitigated welds, the requirements reflect a philosophy of more frequent monitoring for an active degradation mechanism. The NRC imposed a number of additional conditions in combination with Code Case N-770-1 for monitoring Alloy 82/182 welds.

The results of the cold leg temperature deterministic flaw analyses support an inspection interval of at least 7 years. However, in general, the bounding cases from the hot leg temperature deterministic crack flaw growth sensitivity studies do not bound the inspection intervals in Code Case N-770-1 for unmitigated welds. All pressurizer welds, which would be the most likely to experience PWSCC, have been inspected and most have been mitigated or replaced with Alloy 52/152 welds. Baseline examinations of the welds addressed by MRP-139 and Code Case N-770-1 have been completed, and although axial cracking and axial through-wall leakage have been found, no instances of circumferential or axial PWSCC have been observed that exceeded ASME Code structural factors. While deterministic analyses indicate that Code Case N-770-1 hot leg temperature inspection intervals may be too long, additional bases would be needed to support a modification to Code Case N-770-1 inspection intervals. Such support could arise from unfavorable results of realistic probabilistic analyses and operating experience, including results of second and later rounds of examinations of these DMWs. It will be important to assess the results of the second and subsequent sets of Code Case N-770-1 DMW examinations against the Code Case N-770-1 inspection interval requirements.

4 MANAGEMENT OF PWSCC BY MSIP

4.1 Operating Experience with BWR Welds Mitigated by MSIP

Based on an information search performed by the authors as well as discussions with a number of industry experts familiar with decades of operating experience with boiling water reactors (BWRs), no instances were identified of leaks in welds mitigated by stress improvement (Findlan et al. 2004). However, there have been instances in which cracks, not identified when mitigating by the mechanical stress improvement process (MSIP), have been found during subsequent inspections.

During meetings held between U.S. Nuclear Regulatory Commission (NRC) staff and industry on May 25–26, 2010, representatives of the Boiling Water Reactors Vessels and Internals Project (BWRVIP) provided a summary of BWR operating experience in 2007 and 2008 for Category C and D welds containing Alloy 82/182 (Wirtz 2010). It was noted that NUREG-0313, Category C welds are those susceptible to intergranular stress corrosion cracking (IGSCC) that were treated by stress improvement after 2 years of operation while Category D contains welds susceptible to IGSCC with no stress improvement. Ten cases of these welds were found to have planar flaws; these were distributed among several BWRs. The presentation did not separate the cases by weld category. In 2008, after reviewing these ten cases of welds with planar flaws, the BWRVIP developed an accelerated inspection program for Category C and D welds containing Alloy 82/182 exposed to BWR environments that had not received an Appendix VIII, Supplement 10 examination.

Surface contour of the outside-diameter (OD) weld region appeared to be the major factor affecting accurate detection and sizing. The presence of weld crowns and radial shrinkage near the weld caused incomplete probe contact resulting in a loss of ultrasonic testing (UT) signal. As part of the accelerated inspection program, the BWRVIP provided guidelines to owners on surface conditioning to improve UT effectiveness.

During the meetings on May 25–26, 2010, the BWRVIP reported that five of the ten BWR Category C and D welds identified with flaws requiring IWB-3600 evaluations were subsequently overlaid. Some of the welds were determined to contain fabrication flaws and were found to be acceptable for continued service. During a meeting on July 20, 2012 (Wirtz 2012), it was reported that two flawed Category C welds were found by the accelerated inspection program since 2009. These welds were subsequently overlaid. It was also reported that four Category C welds remain to be examined and were scheduled to be inspected by June 2014. The owners of these BWRs believe that none of these flaws were the result of new or continuing IGSCC. Rather, they believe that the cracks were present at the time stress improvement was applied. It is reasonable to conclude that these cracks were not the result of new IGSCC. However, one has to consider that OD weld surface conditions may have had a negative effect on earlier examination results; therefore, the conclusion that none of the flaws were the result of new or continuing IGSCC cannot be proven.

This operating experience highlights the importance of weld OD surface conditioning, and in some cases, includes removing weld crowns, and the benefit of performing effective and reliable examinations by applying advanced technology such as Appendix VIII-qualified, encoded phased-array UT techniques, before and after application of MSIP.

4.2 MSIP Design Requirements

The ASME Code does not address the mechanical stress improvement process in Section XI requirements for repair and replacement as MSIP does not involve welding or replacement of components. Additionally, MSIP is essentially a proprietary process and, as such, the details of the design requirements are not publicly available.

During discussions between Pacific Northwest National Laboratory (PNNL) and the Chief Engineer of NuVision Engineering, the company that holds the patent for MSIP, it was indicated that the design process meets the criteria contained in ASME Code Case N-770-1, Appendix I, Performance Criteria and Measurement or Quantification Criteria for Mitigation by Stress Improvement. At a high level, this appendix requires that WRS calculations be performed to bench-mark the “squeezing” process. The applied radial load permanently reduces the OD and, to a lesser extent, the inside diameter (ID) in the region where the radial load is applied. A typical change in OD caused by MSIP is 1% of the as-built size, although the vendor may apply somewhat more or less than 1% to achieve the desired change in residual stresses in the pipe weld. This “squeeze” creates a beneficial compressive stress on the ID of the welded region of interest. Candidate welds have to be reviewed during the design process to ensure that the weld can be inspected before and after MSIP by a qualified technique. With one exception discussed later in this report, a pre-MSIP UT inspection is required to be performed. MSIP may be applied to uncracked welds and, depending on the severity of the crack, on cracked welds. Any flaws that are detected during the pre-MSIP UT have to be evaluated prior to mitigation using the rules of Section XI, IWB-3600, Analytical Evaluation of Planar Flaws. Westinghouse Electric Company works with NuVision Engineering to implement MSIP. Westinghouse indicates that the process is only applied to locations that have circumferential cracks where the lengths add to no longer than 10% of the circumference and the maximum through-wall depth of any crack does not exceed 30% of the piping wall thickness (Elder 2008). This follows the guidelines on application of MSIP that are provided in NUREG-0313, Rev. 2 (Hazelton and Koo 1988). A discussion of UT uncertainty for Appendix VIII piping examinations conducted from the inside surface is contained in Section 3.3.

MSIP causes a slight elongation of the region of the pipe being compressed. This elongation has to be analyzed to ensure that it does not adversely affect the piping system or cause ASME Code-allowable stresses to be exceeded. A more in-depth discussion of the Code Case N-770-1, Appendix I, criteria for MSIP is included in Section 5 of the report by Sullivan and Anderson (2013).

Fredette and Scott (2009), from Battelle Columbus Laboratory (BCL), performed finite element analyses on applying MSIP to pipe welds in multiple piping systems. They assessed initial WRS, including welds with and without an attached safe end weld. Weld residual stresses in both the dissimilar metal weld (DMW) and adjacent stainless steel (SS) weld (if present), after application of MSIP, were determined. Flaw growth calculations were also performed to understand the effect of applying MSIP to welds containing flaws. These analyses were reviewed by Sullivan and Anderson (2011) and confirm that compressive residual stresses at or near the inside surface are produced by MSIP. These analyses confirm the guidance in NUREG-0313, Rev. 2 (Hazelton and Koo 1988) on acceptable sizes of flaws that may be left in welds repaired by MSIP. The analyses by BCL also addressed the possibility of a deep flaw being missed or undersized during the pre-MSIP UT examination. The analyses showed that if MSIP is applied to a weld with a deep pre-existing flaw (> 60% through-wall), MSIP increases the stress intensity factor (K), such that the time required for the crack to grow through the remaining wall thickness of the treated weld (post-MSIP) is very short. From the perspective of applying MSIP to welds with flaws, Sullivan and Anderson (2011) also indicates that the Code-allowable flaw sizes under design basis seismic loading in some cases are small. These results highlight the importance of effective and reliable nondestructive examination (NDE) prior to the application of MSIP.

BCL considered a series of WRS sensitivity analyses and included the following effects: the effect of modeling fixed and free displacement boundary conditions at the ends of the modeled sections; the effect on WRS of having or not having a nearby secondary SS weld; and the effects of changes in MSIP clamp location, the level of plastic deformation introduced, and tool size. BCL also performed sensitivity studies on 3D versus 2D analyses. These sensitivity studies assessed factors that might affect the WRS state prior to and after application of MSIP, and showed that large changes in the analyzed variables could impact the effectiveness of MSIP, but that ranges of variations normally expected to be encountered would not have a significant impact on MSIP effectiveness.

4.3 NDE Reliability

To evaluate the reliability of ultrasonic inspections, PNNL considered flaws evaluated both before and after MSIP application. The data used to make UT comparisons came from multiple sources: UT data on unmitigated welds presented during a workshop held by PNNL in May 2012, a nuclear power plant in Lithuania, and a specimen built by PNNL. Section 3.1 summarizes the findings of the PNNL UT workshop on unmitigated welds, which is relevant to the reliability of pre-MSIP inspections. Section 4.3.1 summarizes the results of an investigation based on pre- and post-MSIP data acquired from cracked areas in 325-mm (12.8-in.) diameter piping at the Ignalina Nuclear Power Plant (INPP) in Lithuania. Section 4.3.2 summarizes the results of a follow-on exercise in which PNNL acquired and evaluated UT data from a PNNL DMW specimen containing implanted thermal fatigue cracks (TFCs). Section 4.3.3 contains a comparison of the UT data from Ignalina and the PNNL specimen (Crawford et al. 2011). Section 4.3.4 provides a discussion on potential limitations to conducting pre- and post-MSIP inspections.

4.3.1 Ignalina Nuclear Power Plant

4.3.1.1 Test Materials

Data was acquired from piping in the INPP (Crawford et al. 2011). The piping base material is 08X18H10T, 18% Cr, 10% Ni, C wrought SS with a nominal outside diameter of 325 mm

(12.8 in.) and a wall thickness of approximately 16 mm (0.63 in.). Two field welds and five shop-fabricated welds were included in this study.

Service-induced IGSCC was present in the heat-affected zone of many of the INPP piping welds because of high residual stresses imparted by autogenous root-welding procedures and the welds having been exposed to oxygen-rich water chemistry. Eight circumferentially-oriented flaws from the Ignalina plant were included in this study.

4.3.1.2 MSIP Application

During the MSIP process, plastic deformation of the pipe wall adjacent to the weld (under the mechanical clamp) results in contouring of the inner and outer surfaces of the weld. These surface conditions can potentially misalign subsequent ultrasonic transducer placement, causing examination volumes to be limited except at extremely high insonification angles, and may produce flaw reflections to be redirected at a higher angle than would occur on a flat surface. When scanning over this contour, this surface condition introduces a gap between transducers and the OD surface of the pipe, which decreases ultrasonic coupling, and causes lack of sufficient sound penetration and/or irrelevant signals in the data. Because the effects of possible ultrasonic beam redirection and loss of coupling in the ultrasonic data from the MSIP-applied side is a concern, only UT data from the non-MSIP side of the INPP welds is discussed.

4.3.1.3 Ultrasonic Methods

The pipes at INPP were scanned using a phased-array (PA) transmit-receive dual shear-wave (TRS) probe, which allowed examiners to scan the piping welds with good coverage in a short amount of time. A ZETEC Z-Scan phased-array system with a 32/128PR channel configuration was used to record rectified A-scan data in line scans. The shear-wave phased-array probe had 2×32 elements and was designed to operate at 4.0 MHz with refracted angles from 50° to 80°.

A 4.0-MHz shear-wave probe would likely be ineffective for penetrating austenitic welds in commercial U.S. reactors, as the dendritic grain structure of the weld metal absorbs and redirects sound beams, especially in this frequency regime. For this reason, most through-weld applications in austenitic piping at U.S. plants use refracted longitudinal waves in the 1.0- to 2.25-MHz frequency range. However, the titanium-stabilized SS used for INPP piping and welds produced a fine, equiaxed, and randomly oriented grain structure only slightly coarser than would be found in carbon steel. This grain structure allows higher frequency shear waves to penetrate the welds much more effectively, thus facilitating ultrasonic examination and producing higher-resolution images.

Line scans adjacent to the welds were acquired with a calibrated probe orientated perpendicular to the weld for detection of circumferential flaws; that is, flaws parallel to the weld. Data was acquired at 1-mm (0.04-in.) increments circumferentially while the sound beam was swept from 50° to 80° through the weld in 1° increments. The resolution of the mechanical scanning movement along the weld was 1.0 mm (0.04 in.).

4.3.1.4 Data Evaluation

Staff from INPP identified areas of the subject welds containing IGSCC found during previous inspections. Phased-array data were collected from the cracked pipe welds and on the crack-free pipe weld, typically for 360° around the pipe. Each of the areas containing indications was analyzed to determine the signal-to-noise ratio (SNR) and the depth and length of the indication. The SNR was calculated from the peak flaw response and the average noise level in a flawless zone at the same part path or depth. Flaw depth was estimated using tip-diffracted signals where present, and flaw length was measured to the loss-of-signal level.

One IGSCC indication in weld P27z1 was detected prior to MSIP but not during the post-MSIP inspection. The amplitude response for all but one of the indications decreased after MSIP, with the one indication exhibiting a very small increase in amplitude response. The measured length of all the indications decreased after MSIP.

4.3.2 PNNL Dissimilar Metal Weld Specimen

4.3.2.1 Test Materials

Data were acquired from a DMW specimen, 9C003, fabricated by PNNL to simulate a pressurizer surge nozzle (Crawford et al. 2011). The weld of interest is an A106B/A105 carbon steel nozzle welded to a 316 SS safe end. The safe end is welded to a 316 SS pipe, and a large carbon steel flange was added to the nozzle to provide rigidity during the MSIP. The nozzle butter and nozzle-to-safe end weld material are NiCrFe3 (Alloy 82/182) with the safe end-to-pipe weld material being 308 SS. The nozzle-to-safe end and safe end-to-pipe weld crowns were ground smooth and flush with the OD surface.

Six circumferential and one axial thermal fatigue cracks were implanted in the butter-to-weld region nearer the carbon steel nozzle side. The circumferential cracks were tilted between 8° and 15° and varied in depth from 16% to 90% through-wall. Flaws were implanted within the butter material to minimize the potential for disturbing the parent material, thus avoiding the introduction of implantation anomalies that could result in the reflection of coherent sound energy.

4.3.2.2 MSIP Application

MSIP on the 9C003 specimen was applied over the safe end-to-pipe weld adjacent to the targeted nozzle DMW containing the implanted flaws. A 0.94% reduction was achieved on the specimen as measured by NuVision during the MSIP application. Circumferential change measurements were taken at an axial mark on the safe end before and after MSIP.

4.3.2.3 UT Methods

The PNNL 9C003 specimen was examined with two phased-array probes with designed center frequencies of 1.5 and 2.0 MHz. Both probes were operated in a transmit-receive longitudinal mode.

Phased-array data was acquired with a ZETEC DYNARAY system in conjunction with a manual-encoded scanner mounted directly on the specimen. Two encoders provided positional information in the circumferential direction for line scans and in both circumferential and axial directions for raster scans. The probes were water-coupled and data were acquired over inspection angles of 30° to 70° in 1° increments. Line scan and raster scan data were acquired from both sides of the weld with the 1.5-MHz probe for the six circumferential flaws and the axial flaw. Line and raster data were also acquired from both sides of the axial flaw at 1.5 MHz. At 2.0 MHz, line scan data were acquired from both sides of the weld on the six circumferential flaws. Raster data was limited to three of the circumferential flaws from both sides of the weld and no data were acquired on the axial flaw.

4.3.2.4 Data Evaluation

All six of the implanted TFCs were detected with both probes before and after the MSIP application. Because the true dimensions of the implanted flaws are known, the error in measurements could be determined. The measurement error data show that the pre- and post-MSIP values overlap and do not indicate a reduction in flaw length after MSIP application. The smaller flaws are over length-sized in both the pre- and post-MSIP data. Root-mean-square errors (RMSEs) were within the ASME guidelines of 19.05 mm (0.75 in.) for acceptable length sizing.

The pre- and post-MSIP flaw depth values overlap, showing little difference between the two sets of measurements. The depth sizing was very good for all but the two deepest flaws. Neither PA probe focused well at the higher angles needed for detection of deep flaw tips. RMSEs were within the ASME guidelines of 3.18 mm (0.125 in.) in depth sizing for only half of the scans.

4.3.3 Comparison of Ignalina and PNNL 9C003 Specimen Data

A comparison of the changes in flaw characteristics between pre- and post-MSIP data for both types of flaws was made. One of the eight INPP flaws was no longer detected after MSIP; however, all six of the implanted flaws in the 9C003 specimen remained detectable after MSIP. On average, the Ignalina data show a length change of −18.4 mm (−0.72 in.) if all flaws are included. The change in length for the implanted flaws in the PNNL specimen does not show a negative or a positive trend. An increase in flaw length is unreasonable; therefore, any such observation of small growth is attributed to measurement error rather than an actual growth in the flaw length. This lack of a noticeable decrease in flaw length with the MSIP application in the PNNL specimen was not expected.

The Ignalina data show a loss in flaw response as measured by SNR at −6.4 dB if all eight flaws are included. The implanted flaw data on 9C003 for both probes, and line and raster images, trend toward a reduction in amplitude, but on average a small change of only −1.9 dB is observed.[1] On average, the six implanted flaws in the 9C003 specimen showed minimal change, if any, after MSIP. Because the flaw implantation process may have introduced a slight misalignment of the two crack faces on each flaw, it is hypothesized that during MSIP, this misalignment would have prevented the crack from closing, leading to similar ultrasonic responses for the pre- and post-MSIP data.

4.3.4 Inspection Limitations

Condition §50.55a(g)(6)(ii)(F)(*2*) of the rule that imposes Code Case N-770-1 allows welds mitigated by mechanical stress improvement to be categorized as Inspection Items D or E, as appropriate, provided the criteria of Appendix I of the Code Case have been met. Code Case N-770-1, Appendix I, Criterion 3 requires that mockup testing and NDE qualified to Appendix VIII performance demonstration requirements be performed to demonstrate that examination of the relevant volume of the mitigated component can be accomplished subsequent to mitigation including changes to the component geometry caused by MSIP. Code Case N-770-1, Appendix I, Criterion 5, requires that, "the mitigated weld shall be inspectable by a qualified process." Criterion 5 further requires that, "An evaluation shall be performed to confirm that the required examination volume of the mitigated configuration is within the scope of an Appendix VIII supplement or supplements and that the examination procedures to be used have been qualified in accordance with Appendix VIII. The evaluation shall confirm that the geometric limitations (e.g., weld crown, nozzle contour) of an Appendix VIII qualification are not exceeded for the mitigated weld." If examination of the required examination volume cannot be satisfied, a licensee would be expected to obtain NRC approval of an alternative examination prior to performing the mitigation.

Information on geometric limitations to performing inspections of typical Westinghouse and Combustion Engineering (CE) plant reactor coolant system (RCS) Alloy 82/182 welds was obtained from LMT, Inc., an NDE vendor for the commercial nuclear power industry, during a workshop PNNL held in May 2012. The information on inspection limitations acquired during this workshop is discussed in Section 3.2 of this report and in Appendices C and D. These appendices contain weld coverage assessment diagrams for a typical Westinghouse and a typical CE plant.

Another limitation to inspection of candidate welds for MSIP pertains to inspection of cast austenitic stainless steel (CASS). Research conducted by NRC Office of Nuclear Regulatory Research on inspection of CASS demonstrated that the Appendix III UT techniques are inadequate when applied to cast materials. This work is discussed in Section 3.2.

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(1) An earlier experiment that resulted in a loss of signal reflectivity was conducted at PNNL in the 1980 time frame. The experiment was performed by generating a compressive loading across a flaw face and measuring changes in UT flaw response. This work showed that a 12 ksi compressive load caused a −10 dB change in flaw response (Becker et al. 1981).

One additional potential examination limitation in the context of MSIP involves Westinghouse reactor vessel nozzle welds that are inspected from the nozzle ID surface. This limitation is discussed in Section 4.5 in connection with Code Case N-770-1, Note (12)(e).

4.4 Assessment of the Effectiveness of MSIP as a PWSCC Mitigation Strategy

Sullivan and Anderson (2013) performed an assessment of the effectiveness of MSIP as a PWSCC mitigation strategy based on the criteria in Appendix I to ASME Code Case N-770-1. Code Case N-770-1 requires that these criteria be satisfied and documented prior to being able to take credit for the reduced examination requirements for stress improved welds in Inspection Items D and E as compared the requirements for unmitigated welds in Inspection Items A-1, A-2, or B. These criteria are paraphrased as follows.

- The mitigation technique has to minimize the likelihood of crack initiation.
- The effect on the susceptible weld material produced by the mitigation process has to be permanent.
- The capability to perform UT of the required inspection volume of the component cannot be adversely affected by the mitigation.
- The mitigation process cannot have degraded the component or adversely affected other components in the system.
- The mitigated weld has to be inspectable by a qualified process.
- Existing flaws, if any, have to be addressed as part of the mitigation.
- The effect of the mitigation on any existing flaws has to be analyzed.

These performance criteria were developed for Code Case N-770-1 by ASME Section XI. They provide rules for the implementation of MSIP, because the rules of IWA-4000, Repair/ Replacement Activities, do not apply to MSIP. These criteria have been approved by ASME and adopted by the NRC as the set of factors needed to ensure effective mitigation by stress improvement. Therefore, they were used by the authors of this report to assess the effectiveness of MSIP.

The following conclusions were reached by Sullivan and Anderson (2013) in performing this assessment.

MSIP is effective in producing compressive WRS in the inner region of welds (Fredette and Scott 2009), thereby minimizing the likelihood of initiation and growth of PWSCC in Alloy 82/182 DMWs. Based on creep properties of the materials involved, the operating temperature of MSIP welds, and analyses to show that residual stresses do not relieve during subsequent loading cycles, the MSIP mitigation method is expected to be permanent. Analyses are required to be performed on the effect of MSIPs on other components in the system and ASME Code criteria are required to be satisfied, which makes it reasonable to conclude that the designs for mitigation by MSIP will satisfactorily preclude potential adverse effects it may have on other components in the system.

Mockup testing and NDE qualified to Section XI, Appendix VIII, performance demonstration requirements would be expected to show that the capability to perform UT of the weld has not been adversely affected by the mitigation, including possible geometric changes that may result from MSIP. Welds mitigated by MSIP are required to be inspectable by techniques and procedures qualified in accordance with Appendix VIII. An evaluation has to be performed to confirm whether the weld to be mitigated is within the scope of an Appendix VIII supplement and that the procedures to be used have been qualified. For these examinations to perform as intended, the NDE used has to be effective and reliable. Limitations involving incomplete coverage have to be reviewed by the NRC to ensure that alternative inspections satisfy regulatory criteria; for example, to ensure that an adequate level of quality and safety is provided.

Existing flaws must be shown using IWB-3600 to not become unacceptable over the life of the weld or before the next scheduled examination.

Assuming that these criteria are satisfied as discussed above, it is reasonable to conclude that MSIP provides effective mitigation against the initiation of PWSCC and against the growth of any existing PWSCC that has been detected and allowed to remain in service.

4.5 Assessment of Code Case N-770-1 Inspection Requirements

An overview of Code Case N-770-1 inspection requirements is contained in Section 3.4.1. An assessment of each note in Table 1 of the Code Case that applies to MSIP welds is contained in Appendix B of Sullivan and Anderson (2013).

Inspection Item D welds are uncracked butt welds mitigated with stress improvement. Inspection Item E welds are cracked butt welds mitigated with stress improvement.

Pre-MSIP examinations are required to be performed in the same outage as the MSIP is applied with one exception—for reactor vessel nozzle welds at cold leg temperatures that require the core internals to be removed to perform an examination, the volumetric examinations are not required prior to application of the MSIP. If the pre-MSIP volumetric examination is not performed, a post-MSIP preservice ID surface examination, in conjunction with the required post-MSIP volumetric examination, must be performed after removal of the core internals.

Examination of Alloy 82/182 reactor pressure vessel (RPV) cold leg nozzle welds in Westinghouse plants requires core internals to be removed to access these welds when examined from the ID. The exception to performing pre-MSIP examinations of cold leg temperature RPV nozzle welds was developed because pre-MSIP examination that can only be performed from the ID (thus, requiring core internals removal) would negatively impact outage durations and cold leg weld locations are expected to be less susceptible to PWSCC than welds at hot leg temperatures. Per Code Case N-770-1, this exception can only be used for cold leg nozzles that require core internals to be removed to perform a full volumetric examination from the ID, which means that the cold leg exception can only be used when the examination requirements cannot be satisfied by accessing and examining these welds from the OD surface.

However, in order to perform MSIP on these welds, access to the OD surfaces must be made available. If these welds have enough access for MSIP, one would logically conclude that there should also be enough space to conduct an examination from the OD, especially if a technology such as encoded phased-array UT is applied. It is the authors' understanding that through proper OD surface conditioning (including weld crown smoothing or removal), volumetric examinations of many Westinghouse RPV cold leg nozzle welds could allow full axial and circumferential scan coverage. Scan coverage diagrams of the RPV cold leg nozzle welds for an example plant are shown in Appendix C, Figures C.20 and C.21. See also discussion in Section 3.2. On this basis, the RPV cold leg nozzle exception should not be used.

Post-MSIP examinations are required and are considered the preservice baseline examination. Per 10 CFR 50.55a(g)(6)(ii)(F)(*9*), Inspection Item D welds (uncracked butt welds mitigated by stress improvement) must all be examined no sooner than the third outage and no later than 10 years following MSIP. Examination volumes that show no indication of cracking shall be placed into a population to be examined once per interval on a 25% sample basis. Inspection Item E welds (cracked butt welds mitigated by stress improvement) must be examined once during the first or second refueling outage following MSIP. Weld examination volumes that show no indication of crack growth or new cracking shall be placed into a population to be examined once per interval on a 25% sample basis.

As noted above, Code Case N-770-1 requires both uncracked and cracked MSIP welds to be placed into 25% inspection samples. The once-per-interval inspection frequency reflects an implicit conclusion by the ASME and, in imposing the Code Case, by the NRC that the MSIP technique results in effective mitigation and that inspection of MSIP welds serves a defense-in-depth monitoring function rather than a degradation management function.

The rule imposing Code Case N-770-1 (76 FR 36232) imposed conditions (F)(*1*), (*2*), (*4*), (*6*), and (*9*) on welds mitigated by mechanical stress improvement. These conditions are in addition to the Code Case requirements and were imposed by the NRC to ensure that, in combination with the Code Case, adequate protection is provided for monitoring Alloy 82/182 welds.

Condition §50.55a(g)(6)(ii)(F)(*1*) of the rule requires licensees of existing operating pressurized water reactors (PWRs) as of July 21, 2011, to implement the requirements of ASME Code Case N-770-1, subject to the conditions specified in paragraphs (g)(6)(ii)(F)(*2*) through (g)(6)(ii)(F)(*10*) by the first refueling outage after August 22, 2011. This is the basic implementing requirement imposing Code Case N-770-1 with conditions.

Condition §50.55a(g)(6)(ii)(F)(*2*) of the rule allows welds mitigated by mechanical stress improvement to be categorized as Inspection Items D or E, as appropriate, provided the criteria of Appendix I of the Code Case have been met. As noted previously, the Code Case provides performance criteria in Appendix I for ensuring that the basic objectives of Section XI for maintaining structural integrity are met. Prior to this Code Case, MSIPs were performed following industry-qualified procedures and guidance in NUREG-0313 (Hazelton and Koo 1988). MSIP had not been subject to NRC review. Accordingly, under condition (F)(*2*) licensees are not required to obtain NRC approval to categorize MSIP welds as Inspection Items D or E but, per Code Case N-770-1, the criteria of Appendix I must be satisfied and an evaluation documented in accordance with Code Case N-770-1, Note (12)(d).

Code Case N-770-1, paragraph -2500(c) states that, "For axial and circumferential flaws, examination shall be performed to the maximum extent practical using qualified personnel and procedures. If essentially 100% coverage for circumferential flaws (100% of the susceptible material volume) can be achieved, the examination for axial flaws shall be completed to achieve the maximum coverage practical." The NRC disagreed with this provision. Axial flaws can lead to through-wall cracks and leakage of reactor coolant, which is a safety concern. Condition §50.55a(g)(6)(ii)(F)(*4*) requires that the axial (flaw) examination coverage requirements of -2500(c) may not be considered to be satisfied unless essentially 100% coverage is achieved. The industry guidelines of MRP-139 (EPRI 2005) allow less than essentially 100% coverage in some cases; therefore, a number of previously conducted baseline examinations may not satisfy the rule. This condition was added by the NRC to ensure that, through NRC review of an authorization of alternative inspection coverage, appropriate actions are being taken to address potential inspection limitations for axial flaws. This condition applies to pre- and post-MSIP examinations.

Condition §50.55a(g)(6)(ii)(F)(*6*) is an ISI reporting requirement for mitigated welds if growth of existing flaws is found that exceeds the previous IWB-3600 flaw evaluations or if new flaws are detected. In such cases, licensees are required to provide a report to the NRC prior to entering reactor re-start Mode 4 that summarizes the licensee's flaw evaluation with inputs, methodologies, assumptions, and the cause of new flaws or flaw growth. If volumetric examination detects new flaws or growth of existing flaws in the required examination volume, the mitigation will not be performing as designed and the NRC will need to evaluate the licensee's actions to address the problem. Therefore, this condition was added to verify the acceptability of the weld prior to being placed back in service.

Condition §50.55a(g)(6)(ii)(F)(*9*) pertains to scheduling and deferral of initial examinations. Condition (F)(*9*) clarifies that the first examination for Inspection Items D and E welds shall be performed as specified in Table 1 and not deferred.

These conditions were developed by the NRC to ensure that the level of quality and safety provided by the requirements for MSIP welds is consistent with that provided by existing ASME Code and NRC requirements for butt welds that are not susceptible to PWSCC.

Specific comments regarding ASME Code Case N-770-1, as implemented, are provided below. These comments are based on the assessment in Appendix B to Sullivan and Anderson (2013).

As noted above, it is the authors' understanding that if OD weld surfaces can be adequately conditioned to allow full volumetric examination from the OD to be performed, the reactor vessel cold leg nozzle weld exception should not be used. However, if using the cold leg nozzle weld exception can be justified, Note (12)(e) permits cold leg RPV nozzles mitigated by MSIP to forego a pre-MSIP examination provided that post-MSIP preservice UT and ID surface examinations are performed. The surface examination shall be performed on the butt weld inside surface and shall consist of an eddy current examination (ET) in accordance with Section XI, IWA-2223. IWA-2223 requires that ET be conducted in accordance with Appendix IV. Appendix IV contains demonstration requirements only and allows the demonstrations to be performed on notches. Because the MSIP may decrease or eliminate the UT response of cracks, the ability of the surface examination to detect cracks takes on greater significance.

Qualification of ET procedures and personnel by performance demonstration would increase the reliability of ET examination. Code Case N-773 contains ET performance demonstration requirements that may be used in lieu of Appendix IV, Supplement 2 when ET is used to complement UT performed on the inside surfaces of austenitic, DMW, and clad piping welds. The NRC proposed to unconditionally approve Code Case N-773 in DG-1231 and no public comments were received to the contrary, so it is expected that the final Regulatory Guide 1.147, Revision 17, scheduled to be published in fall 2014 will approve Code Case N-773. The ASME Code, Section XI, has initiated an action to incorporate the requirements of Code Case N-773 into Appendix IV. This proposed Code change incorporates ASME XI Code Case N-773 and provides rules for the qualification of procedures and personnel for automated ET examination of stainless steel and stainless clad piping and is intended as a complement to the ultrasonic examinations performed from the inside surface of piping. At the time this report was issued, this proposed Code change had not yet been approved by ASME.

Also, if using the cold leg nozzle weld exception can be justified, Code Case N-770-1 specifies that if no cracks are found during the post-MSIP preservice examinations of cold leg RPV nozzle welds, the welds will be considered uncracked and subject to the examination requirements of Inspection Item D. However, these provisions do not explicitly say what the user is required to do if, during the surface examination, the weld is determined to be cracked. There are currently no Appendix VIII, Supplement 10 procedures to examine welds from the ID surface qualified for depth sizing flaws in unmitigated welds. The compressive stresses in the mitigated weld may cause crack faces to close or partially close and change the UT response of the flaws. This phenomenon may increase the difficulty of qualifying procedures for detection as well as depth and length sizing. If a weld were determined by the surface examination to be cracked, the issue may have to be resolved outside of the rules of the Code Case, prior to restart, and involve the NRC staff review of a relief request.

Based on a review of the requirements of Code Case N-770-1, as implemented with NRC conditions, it is concluded that these requirements for MSIP, including the inspection intervals, provide an acceptable approach for monitoring potential PWSCC. It is appropriate to reiterate that for this monitoring to perform as expected, the NDE used has to be effective and reliable.

4.6 Conclusions

Based on information searches performed by the authors as well as discussions with a number of industry experts familiar with decades of operating experience with BWRs, no instances of leaks were identified in welds mitigated by stress improvement. However, there have been instances in which cracks, not identified when mitigating by MSIP, have been found during subsequent inspections.

Operating experience with MSIP in BWRs highlights the importance of removing weld crowns and the benefit of performing effective and reliable examinations including, for example, the use of Appendix VIII-qualified, encoded phased-array UT techniques, prior to and subsequent to application of MSIP.

A comparison was made of the changes in flaw characteristics between pre- and post-MSIP data for service-induced flaws and flaws implanted in a mockup. One of the eight service-induced flaws was no longer detected after MSIP; however, all six of the implanted flaws remained detectable after MSIP. On average, the service-induced flaw data show a decrease in length and SNR flaw response. The length of the implanted flaws remains basically unchanged and the SNR flaw response decreased only slightly. This difference in the observed responses was not expected.

Inspection limitations can affect the effectiveness of NDE requirements. Geometry or access may limit performing a complete pre-MSIP weld examination. Information on geometric limitations to performing inspections of typical Westinghouse and CE plant RCS Alloy 82/182 welds is contained in Appendices C and D.

It is the authors' understanding that if OD weld surfaces can be adequately conditioned to allow full volumetric examination to be performed from the OD, the exception in Code Case N-770-1 to performing a pre-MSIP reactor vessel cold leg nozzle weld examination should not be used.

Inspection limitations exist for welds adjacent to CASS products and qualification requirements do not yet exist in Appendix VIII for inspection of CASS piping welds. This limitation is discussed in Section 3.2 for unmitigated welds and is equally applicable to welds considered for mitigation by MSIP.

During the MSIP process, plastic deformation of the pipe wall adjacent to the weld (under the mechanical clamp) results in contouring of the inner and outer surfaces of the weld. These surface conditions can potentially misalign subsequent ultrasonic transducer placement causing examination volumes to be limited.

Assuming that the performance criteria of Code Case N-770-1, Appendix I, are satisfied and the NDE used is effective and reliable, it is reasonable to conclude that MSIP provides effective mitigation against the initiation of PWSCC and against the growth of any existing PWSCC that has been detected and allowed to remain in service.

Based on a review of the requirements of Code Case N-770-1, as implemented with NRC conditions, it is concluded that these requirements for MSIP provide an acceptable approach for monitoring potential PWSCC. For monitoring of potential PWSCC by MSIP to perform as expected, the NDE used has to be effective and reliable.

5 MANAGEMENT OF PWSCC BY WELD OVERLAY

5.1 Operating Experience with Welds Mitigated by Weld Overlays

A literature survey was performed to obtain information on operating experience with weld overlays (WOLs). The Electric Power Research Institute (EPRI) report (1999) contains summaries of the results of boiling water reactor (BWR) WOL inspections performed through about 1996. The inspections summarized in EPRI (1999) after about 1985 were performed using procedures qualified in accordance with the NDE Coordination Plan agreed upon by the U.S. Nuclear Regulatory Commission (NRC), EPRI, and the BWR Owners' Group (BWROG), generally referred to as the Tri-Party Agreement (DeYoung 1984). The conclusions of this report state that, "Volumetric examination of each weld overlay volume and a portion of the underlying piping material has been performed using ultrasonic techniques that have been qualified for detection of intergranular stress corrosion cracking (IGSCC). Each weld overlay has been examined multiple times, on an inspection frequency consistent with the requirements of NUREG-0313, Revision 2 for Category E welds. None of the examinations have revealed any indication of flaw propagation into the weld overlay repair or within the outer 25% of the component base metal. Some of the repairs [weld overlays] have been in service in excess of fifteen years, with no indication of weld overlay degradation." No other similar reports were located summarizing collective operating experience.

In an effort to acquire a different perspective on operating experience with weld overlays, the authors contacted industry representatives and laboratory staff who have spent careers working on piping weld degradation mechanisms, inservice inspection, and structural integrity issues since the early 1980s. The authors were informed that *there have been no instances of leaks in WOL welds or flaws propagating into overlays*. In summary, no service-related operating experience involving WOLs indicating crack growth or any other issues of concern was found.

Two experiences on difficulties with the installation of weld overlays in pressurized water reactors (PWRs(are discussed below.[a]

By letter to the NRC dated April 28, 2006 (Hoots 2006a), as supplemented by letters dated August 18, 2006 (Hoots 2006b) and September 14, 2006 (Jury 2006), Exelon submitted a request for relief from the ASME Code, Section XI, for Byron, Unit 1, for the third 10-year interval, which began June 30, 2006. The licensee requested relief from the repair/replacement requirements for structural weld overlays (FSWOLs) on pressurizer (PZR) spray, relief, safety, and surge nozzle safe ends. This relief request was motivated, in part, by the industry MRP-139 guidelines for PWR licensees to complete the inspections of PZR temperature Alloy 82/182 butt welds by December 31, 2007. This relief request was one of the early requests for NRC approval to apply FSWOLs to PWR butt welds. During a teleconference call between the NRC staff and the licensee on September 14, 2006, verbal relief was authorized for Byron, Unit No. 1, to install the WOLs. NRC's written authorization for the installation of these weld overlays was

(a) The experiences described are based, in part, upon the knowledge of E. Sullivan while at the NRC.

provided to the licensee in a letter dated January 29, 2007 (Marshall 2007). During the installation of many of the FSWOLs to the PZR butt welds at Byron, Unit 1, the licensee's examinations detected fabrication flaws in the weld overlays. These flaws exceeded the acceptance criteria proposed by the licensee in its relief request. These fabrication flaws were removed and the WOLs were subsequently successfully installed. This experience resulted in the NRC requesting that licensees seeking relief from ASME Code requirements to install WOLs include a commitment to provide the results of the ultrasonic examination of the structural weld overlays within 14 days after the completion of the last weld overlay preservice ultrasonic examination.

In 2009, problems with welding fabrication flaws occurred during the installation of FSWOLs on each of the reactor vessel hot leg nozzle welds at Catawba, Unit 2. Several attempts were made to resolve the welding issues, but prior to restart the WOLs were essentially removed by grinding (Bartley 2009). As of the writing of this report, the licensee had not attempted to reinstall WOLs on the Catawba, Unit 2, reactor vessel hot leg nozzles.

An experience with laminar flaws detected in WOLs at Diablo Canyon, Unit 2 is worth noting. During refueling outage 2R17 in early 2013 required inservice inspection (ISI) examinations detected laminar indications in the dissimilar metal weld (DMW) weld overlays on the pressurizer A, B, and C safety nozzle and the spray nozzle to piping DMWs. These laminar fabrication flaws were detected in the WOLs using a qualified phased-array ultrasonic testing (UT) technique. The licensee did not detect these indications after WOL installation in 2008 nor during the follow-on ISI examinations in October 2009 when using a qualified conventional UT technique. For the 2013 inspection results, the licensee reported that the indications in the WOL installed on safety nozzles A and B and spray nozzle exceeded the fabrication acceptance standards for examinations described in the original relief request for installing the weld overlays (Polickoski 2013).

In lieu of removing the laminar indications, the licensee performed flaw evaluations and stress analyses to demonstrate that the overlaid DMWs are acceptable for continued operation. The licensee performed the flaw evaluations of the laminar indications found in pressurizer safety nozzles A, B, and C, and the spray nozzle, using the requirements of ASME Code, Section XI, IWB-3600. The licensee also performed a stress analysis demonstrating that the interface length between the WOL and the nozzle/pipe base metal is sufficient in light of laminar indications using the rules of the ASME Code, Section III, NB-3227.2. The licensee committed to perform successive examinations over the next three ISI periods of safety nozzles A, B, and C and the spray nozzle to monitor the growth, if any, of the laminar indications in accordance with the ASME Code, Section XI, IWB-2420(b). The three successive examinations should verify the validity of the above crack growth and stress analyses and monitor the laminar indications. On March 8, 2013, the NRC provided verbal authorization to Diablo Canyon, Unit 2 for the fuel cycle following the 2013 refueling outage, to use their proposed alternative in lieu of removing the laminar indications (Polickoski 2013). Following the phased-array UT examination that detected the laminar flaws, the utility formed a team to investigate the causes that resulted in the flaws not being identified during previous examinations. Subsequently, the industry NDE Integration Committee (IC) formed a focus group to evaluate the utility's root cause report and determine appropriate industry actions.

The NDE IC issued NDE Alert 2014-02 dated February 10, 2014, to inform utilities and vendors of the inspection issue identified at Diablo Canyon, to convey industry actions, and to provide utilities with the NDE IC's recommendations. This NDE Alert is not publicly available. Nevertheless, during the annual NRC staff/Industry meeting held to discuss materials related issues, industry presented the following NDE IC's actions and recommendations during the NDE Program Update presentation (Hacker 2014).

The industry representative indicated that the following actions were taken based on the work of the NDE IC focus group.

- PDI-UT-8 was revised to provide enhancements for the areas identified in the Diablo Canyon root cause report. PDI-UT-8 is the generic Performance Demonstration Initiative (PDI) procedure for examining WOLs.
- New WOL demonstration samples were examined with both the non-encoded conventional and phased-array procedures to assure that no additional procedure changes are required to address these configurations.
- NDE IC approved a multi-year project to develop a training module that can be used to prepare examiners prior to qualification and examinations at the plant. This training will address the operating experience and contain specific guidance and recommendations highlighted by the utility root cause.
- PDI Program fabricated practice mockups representative of non-standard weld overlays. The NDE IC focus group recommended the use of these mockups prior to performing ultrasonic examinations of non-standard WOLs on site to allow the examiner to become familiar with the intricacies of performing examinations of these configurations.
- The NDE IC approved a project to modify the non-standard WOL practice mockups to implant fabrication flaws similar to those missed at Diablo Canyon for the purpose of providing indications representative of known field conditions to assist in preparing the examiners for the examinations.
- The NDE IC approved projects to perform additional research in 2014 to evaluate approaches to improve the surface contact for the zero-degree examinations of small diameter (< 8-in.-diameter) weld overlays.
- The NDE IC focus group evaluated the Diablo Canyon root cause evaluation to determine if this event was the direct cause of inadequate procedure, equipment, personnel qualifications, or the qualification process that requires an extent of condition evaluation at other sites. The focus group concluded that this event is related to implementation of the procedure guidance and does not require an industry extent of condition evaluation.

NDE IC made the following recommendations on this event to the Industry.

- Perform a detailed review of the Diablo Canyon root cause and corrective actions taken, specifically the enhancements made to the examination procedures, to address non-standard overlays, which include scan speed guidance and sensitivity adjustments.
- When applying non-encoded conventional UT examinations of WOL, implement the latest revision of the qualified examination procedure.

- Prior to performing examinations of non-standard overlays, utilize the practice mockups to prepare examiners.

This NDE event at Diablo Canyon is not discussed in Appendix B, Operating Experience with Butt Weld primary water stress corrosion cracking (PWSCC), because it did not involve PWSCC.

5.2 WOL Design Requirements

Depending on the weld geometry, fabrication practices, and the presence of a nearby safe end-to-pipe weld, Alloy 82/182 piping butt welds may have axial and hoop residual tensile stresses within a zone near the inside surface of the weld. This tensile zone contributes to the susceptibility of Alloy 82/182 to PWSCC. Weld overlays convert tensile residual stresses at and near the inside surface of piping in the weld to a zone of compressive residual stresses or substantially reduced tensile residual stresses. Weld overlays are beneficial from the standpoint of providing additional structural reinforcement. In addition, there is additional potential benefit that the WOLs may provide geometries more favorable for inspection.

There are two types of weld overlays—full structural weld overlays, which have a minimum thickness of one-third the pipe wall thickness, and optimized weld overlays (OWOLs), which have less weld metal applied—in some cases having as few as three layers of applied weldment. Weld overlays extend in both axial directions some distance beyond the weld. Weld overlays extend 360° circumferentially around the pipe. For FSWOLs, no structural credit is taken for the original pipe thickness.

Fredette and Scott (2010) performed finite element analyses on applying WOLs to pipe welds in multiple systems. Initial weld residual stresses (WRSs) were assessed, including welds with and without an attached safe end. Weld residual stresses after application of WOLs were determined and flaw stress intensity calculations were performed to understand the effect of applying WOLs to welds containing flaws. These analyses were reviewed by Sullivan and Anderson (2011). The analyses confirm that compressive residual stresses at or near the inside surface are produced by WOLs and, in contrast to the finding for the mechanical stress improvement process (MSIP), confirmed that FSWOLs should not increase the stress intensity factor of deep preexisting flaws potentially present in the weld.

The analyses by Fredette and Scott (2010) included sensitivity studies that were conducted to evaluate the effect of WOL weld sequencing on the resulting WRS in the field. Changing the welding sequence from left-to-right versus right-to-left weld deposition did not have a substantial effect on the resultant residual stresses in the weld. However, for the case where two weld heads start at different locations and move in the same direction, the resultant WRSs were larger (less favorable) than when a single head was used. This method might be used to complete the FSWOL in reduced time by doubling the amount of welding done in a given time. The analyses showed that some changes in weld sequencing can negate any claimed WRS benefit predicted for the WOL in the design process. In applying a FSWOL or an OWOL for a given geometry, it is crucial that the weld overlay fabricated in the field accurately reflects the design that was evaluated and approved.

Sensitivity studies on the effect of additional weld layers on the resulting WRS did not produce a consistent trend. The results for these sensitivity studies were presented for stresses at room temperature. Results for other analyses performed by Fredette and Scott (2009) show that for operating temperature the stresses change somewhat but follow similar trends to stresses at room temperature. For the surge nozzle geometry considered, the number of weld overlay passes had a minimal effect on the through-thickness axial stresses near the weld centerline. There was some effect of more layers on the inner diameter (ID) axial stresses at the butter/ferritic steel interface, but that effect tended to saturate after about three layers of overlay. However, the ID axial tension in the DMW area of the surge nozzle weld remains in tension in all cases and is only reduced to near zero with the application of the FSWOL thickness. For the hoop stress case, the effect was more pronounced with each successive layer further reducing the stresses. The safety nozzle and the reactor vessel cold leg nozzle results showed oscillation in the through-thickness axial stress with additional material. For the reactor coolant pump outlet nozzle, the axial stresses were also shown to oscillate. Application of layers one through three reduce the maximum stress, and layers five through eight raise the stress from the minimum achieved with layer three. OWOL actually produced better results than the FSWOL in the axial stresses, and the results were virtually the same for both OWOL and FSWOL in the hoop direction. Results for the geometries considered by Battelle Columbus Laboratory (BCL) indicate that the OWOL design can be an effective mitigation strategy for dealing with PWSCC in PWRs. However, these studies highlight the need for weld-specific analyses as part of the design process for defining the effect of weld sequencing and weld overlay thickness on the resulting WRS state.

The WOL thickness is designed based on a postulated flaw (the design-basis flaw) in the original pipe, DMW, or nozzle. The ASME Code, Section XI, establishes an allowable flaw size for the end-of-evaluation period based on the maximum flaw size that can be sustained in the component without exceeding the structural (safety) factors specified in the ASME Code. The end-of-evaluation period is the time period during which the flaw is calculated to be acceptable. The maximum allowable flaw size in accordance with the ASME Code, Section XI, IWB-3640, "Evaluation Procedures and Acceptance Criteria for Flaws in Austenitic and Ferritic Piping," is 75% of the component nominal wall thickness, which if applicable includes the thickness of the WOL. The weld overlay sizing requirements are described in MRP-169, Revision 1 (EPRI 2008b) and are also contained in ASME Code Cases N-740-2 for FSWOLs (ASME 2008) and Code Case N-754 for OWOLs (ASME 2011).

For the purpose of this discussion, pipe wall thickness and DMW wall thickness are the same. In addition, "pipe wall thickness" refers to the original pipe/weld thickness, not the thickness of the pipe wall plus the weld overlay thickness.

The FSWOL thickness is designed based on ASME Code, Section XI, IWB-3640 and Appendix C, "Evaluation of Flaws in Piping." The design-basis flaw is a circumferential flaw 100% through-wall and 360° around the weld circumference that is postulated to be present in the DMW. Once the FSWOL is applied, the design-basis flaw becomes the allowable flaw size for the end-of-evaluation period. The weld is not required to be inspected prior to application of a FSWOL. If a weld is not inspected prior to installation of a FSWOL, a post-FSWOL inspection must be performed to verify that the outer 25% of the original weld is free of planar flaws. If a pre-FSWOL inspection is not performed, then an initial flaw that is 75% through the original weld thickness is assumed in both the axial and circumferential directions in the design analysis for the service life of the weld. Any actual observed or postulated flaws in the DMW must be demonstrated, by a crack growth calculation, not to grow beyond the design basis flaw size before the next scheduled ISI.

If a pre-FSWOL inspection is conducted, an initial flaw size for the crack growth calculation is specified in ASME Code Case N-740-2. For example, if a qualified UT examination is performed prior to application of a FSWOL, and no inside surface-connected planar flaws are detected, initial flaws originated from the inside surface of the weldment equal to 10% of the original wall thickness are to be assumed in both the axial and circumferential directions in the design analysis for the service life of the weld.

The required ISI volume for a FSWOL includes the weld overlay thickness and the outer 25% of the original pipe wall as shown in Figure 2(a) in Code Case N-770-1 (ASME 2009a). Weld overlay sizing for FSWOLs is governed, in many cases, by the general requirements in the ASME Code, Section XI, IWB-3643, that no flaws of depth greater than 75% through-wall are acceptable. This maximum flaw depth dictates that the minimum FSWOL thickness, regardless of the applied loading, is one-third the thickness of the original pipe thickness, regardless of the applied loads. Thicknesses greater than this may be required depending upon the magnitude of the applied loadings and other factors, such as the resulting axial length of the overlay.

Code Cases N-754 (ASME 2011) and N-740-2 (ASME 2008) provide guidance for weld overlay length sizing, and these are the same for both FSWOLs and OWOLs. The underlying requirement is that sufficient weld overlay length be provided on either side of the observed crack to allow for adequate transfer of axial loads between the pipe and the weld overlay. For axisymmetric loading of a cylinder, local loading effects can be shown to attenuate to a small fraction of their peak value at an axial distance of $0.75\sqrt{Rt}$ from the point of loading (where R is the outer radius and t is the nominal wall thickness of the cylinder). Thus, if the weld overlay length is set equal to $0.75\sqrt{Rt}$ on either side of the crack, resulting in a total weld overlay length of $1.5\sqrt{Rt}$, the overlay will extend beyond any locally elevated stresses due to the crack. In application of weld overlays pre-emptively, however, no crack will have been detected, so the above criterion is conservatively applied such that the minimum weld overlay length must be $0.75\sqrt{Rt}$ beyond either side of the susceptible material. This will result in a total weld overlay length equal to $1.5\sqrt{Rt}$ plus the length of susceptible material (Alloy 82 or 182 weld metal and buttering) on the outer-diameter surface of the original DMW. The $0.75\sqrt{Rt}$ recommendation is only a rule of thumb, and shorter lengths may be used, if justified by stress analysis of the specific pre-emptive WOL configuration to demonstrate that adequate load transfer and stress attenuation are achieved. The length of the weld overlay can also be affected by the requirements to obtain full coverage of the required inspection volume.

The NRC notes in Blount (2010) that the structural integrity of the FSWOL does not take credit for the underlying DMW because the design-basis flaw is 100% through the original pipe wall and 360° around the circumference. Design requirements for FSWOLs applied over cast material, for which ASME Section XI, Appendix VIII, qualification requirements have not been written, are provided in Code Case N-740-2.

An OWOL may be used pre-emptively or for repair of DMWs with flaws of limited depth. The design-basis flaw for an OWOL is a circumferential flaw 75% through the original pipe wall and 360° around the DMW circumference. The OWOL design takes credit for the structural support of the outer 25% wall thickness of the DMW. The design-basis flaw depth assumption of 75% of original wall thickness already meets the general Section XI, IWB-3643 maximum through-wall flaw depth requirement of 75% without an overlay. Thus, the minimum OWOL thickness is not controlled by this limit, as with FSWOLs, but instead is based on the actual internal pressure and pipe loads at the location of the DMW being overlaid and the ASME Code, Section XI IWB-3641-allowable flaw size requirements. In addition, Code Case N-754 requires that the minimum thickness of the OWOL be sufficient to reduce residual stresses to less than 69 MPa (10 ksi) tensile at operating temperature and pressure on the internal wetted surface of all stress corrosion cracking-susceptible materials.

The OWOL design requires that the pipe weld be inspected immediately prior to the overlay application, using an inspection technique qualified in accordance with ASME Section XI, Appendix VIII and found to exhibit no evidence of circumferential or axial cracking greater than 50% of the wall thickness in the original weld. If a detected flaw has a depth greater than 50% through-wall, the OWOL design will not be applicable for the repair. A discussion of uncertainty for Appendix VIII piping examinations conducted from the inside surface is contained in Section 3.3.

The required inspection volume for OWOLs includes the OWOL thickness and the outer 50% of the original pipe wall as shown in Figure 5(a) in Code Case N-770-1 (ASME 2009a). Any actual observed flaws in the DMW must be demonstrated, by a crack growth calculation, not to grow beyond the allowable size before the next scheduled ISI. A qualified UT examination is performed prior to application of an OWOL. If no inside surface-connected planar flaws are detected, initial flaws originated from the inside surface of the weldment equal to 10% of the original wall thickness are to be assumed in both the axial and circumferential directions in the design analysis for the service life of the OWOL. In cases where no inside-connected planar flaws are detected, the OWOL is considered preemptive. Specific design and inspection requirements for OWOLs applied over cast material, for which ASME Section XI, Appendix VIII, qualification requirements have not been written, are provided in Code Case N-754 (ASME 2011). Post-overlay baseline UT and ISI examinations are required to verify the integrity of the applied OWOLs. Because OWOLs take credit for the underlying 25% wall thickness of the DMW material, the design may be required to account for the potentially lower toughness of the DMW material (particularly at the fusion line with the low-alloy or carbon steel nozzle) (EPRI 2008b).

Additional details on design and evaluation of WOLs are provided in MRP-169, Rev. 1 (EPRI 2008b) and the NRC's evaluation of MRP-169, Rev. 1 (Blount 2010).

5.3 NDE Reliability

To evaluate the reliability of ultrasonic inspections, Pacific Northwest National Laboratory (PNNL) considered flaws evaluated both before and after WOL application. The data used to make pre- and post-WOL UT comparisons came from multiple sources: UT data on unmitigated welds presented during a workshop held by PNNL in May 2012 and two specimens with implanted thermal fatigue cracks (TFCs). Section 3.1 summarizes the findings of the PNNL UT workshop on unmitigated welds, which is relevant to the reliability of pre-WOL inspections, required for OWOL but optional for FSWOL. Section 5.3.1 summarizes the results of an investigation based on pre- and post-WOL examination data acquired from two specimens containing TFCs. Section 5.3.2 provides a discussion on potential limitations to conducting pre- and post-WOL inspections.

5.3.1 Inspection of Dissimilar Metal Weld Overlay Specimens

Industry has been installing weld overlays with Alloy 52/152 as a means of corrective or pre-emptive action for PWSCC. The reliability of NDE of welds mitigated by overlays is important for determining whether any new flaws have initiated or existing flaws have propagated, and for assessing the effect of any potential flaws on the service life of the weld.

The reliability of NDE is relevant to welds mitigated by weld overlays for several reasons. Pipe welds to be mitigated by optimized weld overlays are required to be inspected immediately prior to the overlay application, using an inspection technique qualified in accordance with ASME Section XI, Appendix VIII, and found to exhibit no evidence of cracking greater than 50% of the wall thickness in the original weld. Undetected or mischaracterized flaws could compromise the structural factors required for OWOLs.

The reliability of NDE of post-WOL welds is also important for determining whether any new flaws have initiated or existing flaws have propagated, and for assessing the effect of any potential flaws on the service life of the weld. PNNL performed an ultrasonic NDE study to investigate the inspectability of weld overlay specimens. The Technical Evaluation Report that summarizes this work is *Ultrasonic Evaluation of Two Dissimilar Metal Weld Overlay Specimens,* PNNL-21502 (Crawford et al. 2012). To conduct this study, thermal fatigue cracks were implanted in two DMW specimens. The specimens were composed of a cast austenitic stainless steel (CASS) pipe welded to a carbon steel nozzle with Alloy 82/182 weld material. Each specimen was evaluated with phased-array ultrasonic testing to determine flaw detection and characterization capabilities. An Alloy 82/182 WOL was added to the specimens, and they were again evaluated ultrasonically for flaw detection and characterization. A WOL made of Alloy 52/152 was cost-prohibitive, so Alloy 82/182 was selected instead; this choice does not impact ultrasonic propagation as it is essentially equivalent in both alloys. Flaw characterization included length and depth measurements as well as a signal-to-noise determination. Objectives of this work included determining ultrasonic detection capabilities in DMW specimens with a WOL and assessing ultrasonic examinations through CASS material.

Specimen 10C-011 is a 516 Grade 70 nozzle and Alloy 82/182 butter section welded to a CASS pipe. Five circumferentially-oriented ID-connected TFCs were implanted in the center of the weld during the welding process to prevent implantation artifacts that could show in the ultrasonic data. The flaw depths range from 49.8% to 89.9% (49.8%, 59.7%, 69.5%, 79.7%, and 89.9%) through the original weld thickness, are tilted by 2 or 3 degrees, and are all circumferentially oriented. The flaw lengths vary from 3.8 to 6.4 cm (1.5 to 2.5 in.). This DMW mockup specimen is approximately 32.4 cm (12.8 in.) in diameter at the flaw position, and 68.4 cm (26.9 in.) in length, with a nominal 3.3 cm (1.3 in.) wall-thickness at the flaw location within the DMW. The weld overlay is approximately 2.0 cm (0.8 in.) thick at the weld location. The flaws were easily detected with ultrasonic techniques similar to those qualified to ASME Section XI, Appendix VIII.

PNNL next evaluated specimen 9C-034 which has shallower TFCs implanted in the weld-to-butter region. Specimen 9C-034 contains a DMW between a 516 Grade 70 carbon steel nozzle and a CASS pipe. The nozzle side butter and weld consisted of Alloy 82/182 material. Four TFCs were implanted in the weld-to-butter region with flaw depths ranging from 13% to 31% (13%, 19%, 26%, and 31%) deep through the original weld thickness. The flaws are ID surface-breaking with lengths at the ID in the range of 5.1 to 6.4 cm (2 to 2.5 in.). The flaws are vertical, have no tilt, and are circumferentially oriented. The individual section of CASS pipe was sent to FlawTech where it was welded to a carbon steel nozzle segment and the four TFCs were implanted into the butter region on the nozzle side of the welded specimen, reducing potential excavation and implantation artifacts. This DMW mockup specimen is approximately 32.5 cm (12.8 in.) in diameter at the flaw position and 58.4 cm (23 in.) in length, with a nominal 3.3 cm (1.3 in.) wall-thickness at the flaw location within the DMW. The four TFCs were inserted via a coupon-implant technique and were all circumferentially-oriented flaws. After the specimen was examined by UT, it was overlaid with Alloy 82/182. The weld overlay is approximately 2.0 cm (0.8 in.) thick at the weld location.

The thickness requirements for weld overlays are discussed in MRP-169 (EPRI 2008b). The minimum WOL thickness requirement for a FSWOL is one-third of the weld thickness. Based on the nominal weld thickness for Specimens 9C-034 and 10C-011, it is clear that the 2.0-cm (0.8-in.)-thick overlay represents a type of FSWOL. However, PNNL evaluated the length and depth sizing measurement errors of the flaws in Specimen 10C-011 as though it were an OWOL specimen. This approach is conservative because the sound path to the three flaws between approximately 50% (49.8%) and 75% through the original wall is longer than would be the case in an actual OWOL specimen.

A weld root signal was often ultrasonically detected and may have precluded a strong corner response from the flaw itself. The presence of a strong weld root signal that could not be separated from the flaw signal complicated flaw length sizing.

The specimens were examined using four phased-array (PA) probes: a 2.0-MHz transmit-receive longitudinal (TRL) probe arrangement, a 1.5-MHz TRL probe, a 1.0-MHz TRL probe, and a 0.8-MHz TRL probe. The 1.5-MHz transducer was chosen based on frequencies commonly used in reactor inspections of stainless steel (SS). The additional 0.8-, 1.0-, and 2.0-MHz probes were employed to more fully evaluate the entire frequency spectrum and provide data to better assess lower and higher frequency limits for inspecting the various DMW components. PA data were acquired on the nine flaws in the two specimens. In general, line scan and raster data were acquired from both sides of the flaw.

Supplement 11, Qualification Requirements for Full Structural Overlaid Wrought Austenitic Piping Welds, states that, “For flaws in base metal grading units (as opposed to overlay fabrication flaws), the candidate shall estimate the length of that part of the flaw that is in the outer 25% of the base metal thickness.” In Code Case N-653-1 (ASME 2012a) flaw length measurement is based on the part of the flaw that is in the examination volume. Extending the same approach to OWOLs, the examination volume includes the OWOL thickness plus the outer 50% of the base metal. At the time this report was issued, Code Case N-653-1 was not approved in U.S. NRC Regulatory Guide 1.147.

The four flaws in post-WOL Specimen 9C-034 with flaw depths ranging from 13% to 31% deep through the original weld thickness would not be included in the examination volume of either an OWOL or a FSWOL. Length-sizing measurements on the flaws in Specimens 9C-034 and 10C-011 were made for the ID flaw length rather than for the part of the flaw that is in the outer 25% or 50% of the base metal thickness. The reason for this approach is that the flaw profiles were not known, making it impossible to calculate root-mean-square error (RMSE) for length measurements at these depths. It is not clear why the Code requires length measurements of the part of the flaw that is in the outer 25% or 50% of the base metal thickness and comparison of these RMSE values with an acceptance standard because these length values appear to have no application to flaw evaluation rules.

Summarizing the results of the study, two DMW specimens, one with four shallow circumferential flaws (13% to 31% through-wall) and one with five deeper circumferential flaws (50% to 90% through-wall) were ultrasonically examined. The DMW specimens were examined from the nozzle and the CASS pipe side with both raster and line scans using four PA probes in the 0.8- to 2.0-MHz frequency range, although not every combination of scan, scan direction, and frequency was used to examine each flaw. An Alloy 82/182 WOL was added to each specimen and they were re-evaluated ultrasonically for flaw detection and characterization. All nine flaws were detected in the pre- and post-WOL condition.

For purposes of this report, sizing errors were only considered for the five flaws that were greater than or equal to about 50% (49.8%) of the original material, because these flaws are contained within the required inspection volume for OWOLs. Using data from a second analyst who emphasized time-of-flight tip-diffraction sizing when these tip signals could be observed, pre- and post-WOL depth sizing RMSE for both the raster and line scan data were found to be within the ASME depth-sizing allowable of 3.2 mm (0.125 in.). Length-sizing error for these same flaws was calculated based on their ID surface-breaking length. The pre- and post-WOL length-sizing RMSE values were found to be within the ASME qualification acceptance criterion of 19.1 mm (0.75 in.).

5.3.2 Inspection Limitations

Inspection limitations can affect the effectiveness of NDE requirements. A number of apparent inspection limitations are discussed in the following paragraphs.

Code Case N-770-1, Note (12) requires that stress improvement techniques meet the performance criteria in Appendix I of this Code Case, and requires that satisfaction of these criteria be demonstrated in an evaluation. In Code Case N-770-1, stress improvement techniques include OWOLs.

The criteria of Code Case N-770-1, Appendix I, paragraph 5 require that, “An evaluation … be performed to confirm that the required examination volume of the mitigated configuration is within the scope of an Appendix VIII supplement, or supplements, and that the examination procedures to be used have been qualified in accordance with the ASME Code, Section XI, Appendix VIII." Code Case N-770-1, Appendix I, paragraph 6, requires that, "An examination qualified to Section XI, Appendix VIII performance demonstration requirements shall have been performed … before the application of the mitigation process to identify and size any existing flaws." Any departure from these requirements of Code Case N-770-1, Appendix I, because of pre- or post-WOL inspection limitations beyond those permitted by Code Case N-770-1, as imposed by §50.55a(g)(6)(ii)(F), have to be evaluated and an alternative examination authorized by the NRC staff.

Geometry or access may limit performing a complete pre-WOL weld examination. Appendices C and D contain weld coverage assessment diagrams for typical Westinghouse and Combustion Engineering (CE) plant reactor coolant system (RCS) Alloy 82/182 welds that show the probe angles used and percent coverage obtained with Section XI, Appendix VIII-qualified techniques. These appendices also indicate the materials of construction for the welds depicted. As noted above, qualified UT examinations are required prior to installing optimized weld overlays.

For the plant-specific designs used to prepare Appendices C and D, Tables 3.1 and 3.2 provide the Code-required volume (CRV) coverage achievable for Alloy 82/182 RCS butt welds in the typical Westinghouse and Combustion Engineering plants used for this assessment. These tables indicate the welds for which Code-required inspection coverage would not be achieved based on the plant-specific designs. The Westinghouse reactor pressure vessel (RPV) nozzle welds in this study were examined from the OD, although the RPV nozzle welds in many Westinghouse plants are examined from the inside surface, where the inspection limitations differ and the CRV coverage obtained is generally understood to be higher.

In CE plants, the safe ends of medium- and large-bore piping are typically made of CASS. The CRV coverage presented in Table 3.2 takes credit for the scan coverage in the CASS safe ends using the Appendix VIII procedures applied for the carbon steel and Alloy 82/182 volumes. This approach for reporting CRV coverage was used by this vendor because Code Case N-770-1, Paragraph-2500(b) requires that Appendix VIII procedures be used to examine the Code-required volume, including 100% of the susceptible material volume, to the maximum extent practical. Inspection limitations exist for welds adjacent to CASS products. Because Appendix VIII, Supplement 9 requirements for examination of CASS piping welds have yet to be developed, there are no performance demonstration qualifications being performed for inspection of cast materials. Subparagraph-2500(b) states that, "For cast stainless steel items for which no supplement is available in Appendix VIII, the required examination volume shall be examined by Appendix VIII procedures to the maximum extent practical including 100% of the susceptible material volume (non-stainless steel volume)." Inspection limitations, such as an inability to examine 100% of the susceptible material volume, would be reviewed as part of the NRC process for authorizing the installation of WOLs.

ASME Section XI prepared Code Case N-824, entitled, "Alternate Requirements for Ultrasonic Examination of Cast Austenitic Piping Welds from the Outer Diameter Surface" (ASME 2012b). The requirements in this Code Case are deterministic rather than performance-based. However, this Code Case is considered to be a first step in the development of Supplement 9. Substantial improvement in NDE reliability would be expected by applying this Code Case, with certain conditions based on NRC research, in situations where 100% of the susceptible material cannot be examined from the ferritic side of the weld.

Research conducted by the NRC Office of Nuclear Regulatory Research on inspection of CASS demonstrated that current Appendix III UT techniques are inadequate when applied to cast materials. However, some of the techniques used during Appendix VIII qualifications may perform well on CASS, especially for thinner-walled CASS. NRC research has shown that, for piping less than approximately 4 to 5.1 cm (1.6 to 2.0 in.) in thickness, refracted longitudinal waves (transmit-receive L-waves) operating at frequencies between 0.8 and 2.0 MHz, work fairly well. Much lower frequency ranges, on the order of 0.4 to 1.0 MHz, are needed for primary system CASS piping (greater than 5.1 cm [2.0 in.] in thickness). To date using these frequencies, inspections can reliably detect flaws in the 25%–30% through-wall range. Additional information is contained in NUREG/CR-6933, *Assessment of Crack Detection in Heavy-Walled Cast Stainless Steel Piping Welds Using Low-Frequency Ultrasonic Methods* (Anderson et al. 2007). NUREG/CR-7122, *An Evaluation of Ultrasonic Phased Array Testing for Cast Austenitic Stainless Steel Pressurizer Surge Line Piping Welds* (Diaz et al. 2011), provides information on crack detection with UT in thinner-walled CASS. The information in these NUREGs should be helpful to industry in improving the reliability of inspections and to the NRC Office of Nuclear Regulatory Research in evaluating relief requests and inspection-related issues involving CASS.

5.4 Assessment of the Effectiveness of Weld Overlays as a PWSCC Mitigation Strategy

Sullivan and Anderson (2012) performed an assessment of the effectiveness of WOLs as a PWSCC mitigation strategy based on the criteria in Appendix I to ASME Code Case N-770-1. These performance criteria were developed for Code Case N-770-1 by ASME Section XI. They provide rules for the implementation of stress improvement. These criteria were originally written for MSIP, because the rules of IWA-4000, Repair/Replacement Activities, do not apply to MSIP. However, Note (12)(d) of Code Case N-770-1 requires that these criteria be satisfied and documented for stress improved welds in Inspection Items D and E, which includes welds mitigated by OWOLs. These criteria have been approved by ASME and adopted by the NRC as the set of factors needed to ensure effective mitigation by stress improvement. Therefore, they were used by the authors of this report to assess the effectiveness of OWOLs and FSWOLs.

These criteria are paraphrased as follows.

- The mitigation technique has to minimize the likelihood of crack initiation.
- The effect on the susceptible weld material produced by the mitigation process has to be permanent.
- The capability to perform UT of the required inspection volume of the component cannot be adversely affected by the mitigation.
- The mitigation process cannot have degraded the component or adversely affected other components in the system.

- The mitigated weld has to be inspectable by a qualified process.
- Existing flaws, if any, have to be addressed as part of the mitigation.
- The effect of the mitigation on any existing flaws has to be analyzed.

The following conclusions were reached by Sullivan and Anderson (2012) in performing this assessment.

It is clear that WOLs can produce significant compression in the inner regions of the pipe wall and result in weld residual stresses at the ID that have compressive or substantially reduced tensile stresses. However, as discussed in Section 5.2, analyses performed by BCL showed that some changes in weld sequencing can negate any claimed weld residual stress benefit predicted for the weld overlay in the design process. In applying a full structural weld overlay or an optimized weld overlay for a given geometry, it is crucial that the WOL fabricated in the field accurately reflects the design that was evaluated and approved.

Compressive or substantially reduced tensile stresses minimize the possibility that flaws would initiate in an overlaid weld. Based on creep properties of the materials involved, the operating temperature of WOLs, and analyses BCL performed showing that re-yielding does not occur on subsequent loading, the WOL mitigation method is expected to be permanent. Code Cases N-740 (FSWOLs) and N-754 (OWOLs) require analyses to be performed on the effect of WOLs on other components in the system and ASME Code criteria are required to be satisfied. Although these Cases are not approved by Regulatory Guide 1.147, Revision 16 (NRC 2010a), many of the provisions of these Cases, such as the one just discussed, are relied upon in requests for NRC authorization to install WOLs. Weld overlays are required by Code Case N-770-1 to be examined by qualified Appendix VIII procedures and WOLs tend to provide an improved platform for performing examinations. Any flaw detected must satisfy the structural factors required by the ASME Code, Section XI, under all postulated loading conditions. Limitations that prevent achieving the inspection coverage required by Code Case N-770-1, as incorporated by reference in 10 CFR 50.55a, have to be reviewed by the NRC to ensure that alternative inspections satisfy regulatory criteria. Nevertheless, even if flaws were not detected and propagate completely through the original weld thickness, WOLs provide reinforcement sufficient to maintain structural integrity under design-basis loading. Under these conditions, OWOLs satisfy safety factors required by Standard Review Plan 3.6.3 for leak before break, although not necessarily the factors required by the ASME Code. On this basis, it is reasonable to conclude that WOLs provide effective mitigation against the initiation of PWSCC and against the growth of any existing PWSCC that has been detected and allowed to remain in service.

5.5 Status of ASME Code Cases N-740-X, "Full Structural Dissimilar Metal Weld Overlay for Repair or Mitigation of Class 1, 2, and 3 Items, Section XI, Division 1," and N-754, "Optimized Structural Dissimilar Metal Weld Overlay for Mitigation of PWR Class 1, Section XI, Division 1

Regulatory Guide 1.193, Rev. 3, *ASME Code Cases Not Approved for Use*, was issued in October 2010 (NRC 2010b). This guide includes ASME Code Case N-740-1, "Dissimilar Metal Weld Overlay for Repair of Class 1, 2, and 3 Items, Section XI, Division 1." The guide states that Code Case N-740-1 is unacceptable because of the total number of issues and the nature of some of the issues (e.g., lack of certain fundamental design details). The guide further states that the "staff believes that it would be inappropriate to attempt to conditionally approve either version 0 or 1 in Regulatory Guide 1.147. The staff will consider Revision 2 for approval when it is published by the ASME."

Code Case N-740-2 was approved in November 2008 and issued in Supplement 7 to the 2007 Edition of the ASME Boiler and Pressure Vessel Code. ASME stated that this revision was made to address previous NRC negatives as well as work done on MRP-169. This revision was also made to add requirements for fatigue crack growth and take out all preservice and inservice NDE for PWRs, because these requirements are contained in Code Case N-770-1. NRC listed Code Case N-740-2 in DG-1233 (Draft Regulatory Guide 1.193, Rev. 4), *ASME Code Cases Not Approved for Use*, which was issued in June 2013. The DG states that "(w)hile Revision 2 addresses some of the NRC staff concerns, significant issues remain. For example, the definition of nominal weld and base material appear to be inconsistent with the provisions of Section III. Also, additional detail is required on how to perform the flaw growth or design analysis. Finally, additional detail is required on how the overlays are designed."

Code Case N-754, "Optimized Structural Dissimilar Metal Weld Overlay for Mitigation of PWR Class I Items, Section XI, Division 1," was approved in June 2011 and issued in Supplement 6 to the 2010 Edition. Because of when the Code Case Regulatory Guides were published, at the time this report was issued, Code Case N-754 had not been addressed in either Regulatory Guide 1.147 or the draft Regulatory Guide on inservice inspection code case acceptability.

5.6 Assessment of ASME Code Case N-770-1 Inspection Requirements

The NRC incorporated ASME Code Case N-770-1 by reference into 10 CFR 50.55a(g)(6)(ii)(F) (76 FR 36232) in June 2011. Code Case N-770-1 contains requirements for inspection of unmitigated as well as Alloy 82/182 RCS butt welds mitigated by certain techniques.

An overview of Code Case N-770-1 inspection requirements is contained in Section 3.4.1. An assessment of each note in Table 1 of the Code Case that applies to WOL welds is contained in Appendix B of Sullivan and Anderson (2012).

Code Case N-770-1, Inspection Item D welds are uncracked butt welds mitigated with stress improvement, which includes stress improvement by welding of Alloy 52 OWOLs. Inspection Item E welds includes cracked butt welds mitigated by OWOL.

Pre-OWOL examinations are required to be performed in the same outage as the OWOL is applied with one exception—for reactor vessel nozzle welds at cold leg temperatures that require the core internals to be removed to perform an examination, the volumetric examinations are not required prior to application of the OWOL. If the pre-OWOL volumetric examination is not performed, a post-OWOL preservice ID surface examination, in conjunction with the required post-OWOL volumetric examination, must be performed after removal of the core internals. If these examinations do not detect cracks, the OWOL will be considered uncracked and be subject to the examination requirements of Inspection Item D. If these examinations detect cracks, the OWOL will be considered cracked and subject to the examination requirements of Inspection Item E. Additional flaw evaluation requirements apply if cracking is detected.

Examination of Alloy 82/182 RPV cold leg nozzle welds in Westinghouse plants requires core internals to be removed to access these welds when examined from the ID. The exception to performing pre-OWOL examinations of cold leg temperature RPV nozzle welds was developed because pre-OWOL examination that can only be performed from the ID (thus, requiring core internals removal) would negatively impact outage durations and cold leg weld locations are expected to be less susceptible to PWSCC than welds at hot leg temperatures. Per Code Case N-770-1, this exception can only be used for cold leg nozzles that require core internals to be removed to perform a full volumetric examination from the ID, which means that the cold leg exception can only be used when the examination requirements cannot be satisfied by accessing and examining these welds from the OD surface.

However, in order to perform OWOL on these welds, access to the OD surfaces must be made available. If these welds have enough access for OWOL, one would logically conclude that there should also be enough space to conduct an examination from the OD, especially if a technology such as encoded phased-array UT is applied. It is the authors' understanding that through proper OD surface conditioning (including weld crown smoothing or removal), volumetric examinations of many Westinghouse RPV cold leg nozzle welds could allow full axial and circumferential scan coverage. Scan coverage diagrams of the RPV cold leg nozzle welds for an example plant are shown in Appendix C, Figures C.20 and C.21. See also discussion in Section 3.2. On this basis, the RPV cold leg nozzle exception should not be used.

Post-OWOL examinations are required and are considered the preservice baseline examination. Per 10 CFR 50.55a(g)(6)(ii)(F)(*9*) Inspection Item D welds must all be examined no sooner than the third outage and no later than 10 years following application of the OWOL. Inspection Item E welds must be examined once during the first or second refueling outage following OWOL.

Per 10 CFR 50.55a(g)(6)(ii)(F)(*8*) OWOL welds are not permitted to be placed into a population to be examined on a sample basis and must be examined once each inspection interval.

Inspection Item C welds are uncracked welds reinforced by a FSWOL of Alloy 52/152 material. Welds inspected prior to application of a FSWOL and found to be uncracked may be placed in Inspection Item C. Inspection Item F welds are cracked butt welds reinforced by FSWOL of Alloy 52/152 material. If volumetric examination is not performed on the weld prior to FSWOL, the weld shall be assumed cracked and shall be classified Inspection Item F. If cracking is not observed during post-FSWOL preservice volumetric examination performed from the outside surface of the overlay, axial and circumferential cracks at least 75% through the original wall thickness are required to be assumed.

For reactor vessel nozzle welds at cold leg temperatures requiring the core internals to be removed to perform the examination, the volumetric examinations are not required prior to application of the FSWOL. If the pre-FSWOL volumetric examination is not performed, a post-weld overlay preservice examination consisting of a surface examination and a volumetric examination shall be performed after removal of the core internals. If these examinations do not detect cracks, the weld shall be considered uncracked and shall be subject to the examination requirements of Inspection Item C. Post-overlay examinations are required and are considered the preservice examination. If these examinations do detect cracks, the FSWOL will be considered cracked and subject to the examination requirements of Inspection Item F. Additional requirements related to evaluating the crack apply if cracking is detected.

Inspection Item C and F welds are required to be placed into a population to be examined on a 25% sample basis.

As noted, Code Case N-770-1 permits both uncracked and cracked FSWOLs to be placed into 25% inspection samples. The once-per-interval inspection frequency reflects an implicit conclusion by the ASME and, in imposing the Code Case, by the NRC that the FSWOL technique results in effective mitigation and that inspection of FSWOLs serves a defense-in-depth monitoring function rather than a degradation management function.

The rule imposing Code Case N-770-1 (76 FR 36232) imposed conditions (F)(*1*), (*2*), (*4*), (*6*), (*8*), (*9*), and (*10*) on welds mitigated by WOL. The NRC imposed these conditions, which are in addition to the Code Case requirements, to ensure that, in combination with the Code Case, adequate protection is provided for monitoring Alloy 82/182 welds.

Condition §50.55a(g)(6)(ii)(F)(*1*) of the rule requires licensees of existing operating PWRs as of July 21, 2011, to implement the requirements of ASME Code Case N-770-1, subject to the conditions specified in paragraphs (g)(6)(ii)(F)(*2*) through (g)(6)(ii)(F)(*10*) by the first refueling outage after August 22, 2011. This is the basic implementing requirement imposing Code Case N-770-1 with conditions.

Condition §50.55a(g)(6)(ii)(F)(*2*) of the rule allows existing FSWOLs authorized by the NRC staff to be categorized as Inspection Items C or F, as appropriate. At the time the rule was issued, only one plant had authorization to install OWOLs. The OWOLs at this plant could not be categorized as Code Case N-770-1 Inspection Item D or E without specific authorization by the NRC. Categorization of future FSWOLs as Code Case Inspection Items C or F and future OWOLs as Code Case N-770-1 Inspection Items D or E has to be specifically authorized by the NRC, generally, as part of NRC's authorization to install the WOLs. Plant-specific authorization from the NRC to install FSWOLs or OWOLs and categorize the WOLs as Inspection Items C, D, E, and F, as appropriate, will not be needed if ASME Code Cases N-740 and N-754, or a suitable revision of these Code Cases, are endorsed in a future revision of Regulatory Guide 1.147 with conditions, if applicable, and incorporated in §50.55a. This condition is intended to ensure that WOL mitigations are designed, installed, and examined in a manner that will ensure an acceptable level of quality and safety before credit can be taken for the inspection frequencies of Inspection Items C, D, E, and F, as appropriate.

Code Case N-770-1, paragraph -2500(c) states that, "For axial and circumferential flaws, examination shall be performed to the maximum extent practical using qualified personnel and procedures. If essentially 100% coverage for circumferential flaws (100% of the susceptible material volume) can be achieved, the examination for axial flaws shall be completed to achieve the maximum coverage practical." The NRC disagreed with this provision. Axial flaws can lead to through-wall cracks and leakage of reactor coolant, which is a safety concern. Condition §50.55a(g)(6)(ii)(F)(*4*) requires that the axial (flaw) examination coverage requirements of -2500(c) may not be considered to be satisfied unless essentially 100% coverage is achieved. This condition was added for the NRC to ensure that, through NRC review of an authorization of alternative inspection coverage, appropriate actions are being taken to address potential inspection limitations for axial flaws. The industry guidelines of MRP-139 (EPRI 2005) allow less than essentially 100% coverage in some cases. This condition of the rule applies to the examination of all inspection items, including C and F (for FSWOLs) and D and E (for OWOLs).

Condition §50.55a(g)(6)(ii)(F)(*6*) is an inservice inspection reporting requirement for mitigated welds if growth of existing flaws is found that exceeds the previous IWB-3600 flaw evaluations or if new flaws are detected. In such cases, licensees are required to provide a report to the NRC, prior to entering Mode 4, which summarizes the licensee's flaw evaluation with inputs, methodologies, assumptions, and cause of the new flaw or flaw growth. This condition applies to FSWOLs and OWOLs as well as welds mitigated by other techniques. If volumetric examination detects new flaws or growth of existing flaws in the required examination volume, the mitigation will not be performing as designed and the NRC will need to evaluate the licensee's actions to address the problem. Therefore, this condition was added to verify the acceptability of the weld prior to being placed back in service.

Condition §50.55a(g)(6)(ii)(F)(*8*) states that welds mitigated by OWOLs in Inspection Items D and E are not permitted to be placed into a population to be examined on a sample basis, as permitted by the Code Case, and must be examined once each inspection interval. It was the staff's view that if significant cracking were to occur in the Alloy 82/182 weld material, the more crack-resistant Alloy 52/152 optimized weld overlay material would substantially diminish or inhibit crack growth when the crack encounters the overlay. The postulation of a long flaw that is completely through the original weld is beyond the OWOL design basis, but it has been shown that OWOLs maintain structural integrity for such a flaw under design-basis loading, although the structural factors may be somewhat less than required by the ASME Code (Blount 2010). The NRC staff evaluated structural factors for this postulated flaw during its review of MRP-169. The NRC staff was concerned that an OWOL with a weld cracked to this degree could prevent the weld from leaking and could potentially rupture without prior evidence of leakage under design-basis conditions. The NRC considered Condition (F)(*8*) to be necessary to ensure that all optimized weld overlays are periodically inspected for potential degradation.

Condition §50.55a(g)(6)(ii)(F)(*9*) pertains to scheduling and deferral of initial examinations. The scheduling of initial examinations is discussed for Inspection Item D and E welds above. With respect to deferral of the initial examination, Condition (F)(*9*) clarifies that the first examination for Inspection Items D, E, and F welds shall be performed as specified.

Condition §50.55a(g)(6)(ii)(F)(*10*) pertains to the alternative examination volume for OWOLs discussed in Note (b) of Figure 5(a) of the Code Case. This condition states that this alternative examination volume may not be applied unless NRC approval is authorized under §50.55a(a)(3)(i) or (ii). This condition was applied because the alternative examination volume of Note (b) of Figure 5(a) was not provided for public comment in the proposed rule (75 FR 24324).

These conditions were developed by the NRC to ensure that the level of quality and safety provided by the requirements for WOLs is consistent with that provided by existing ASME Code and NRC requirements for butt welds that are not susceptible to PWSCC.

Based on a review of the requirements of Code Case N-770-1, as implemented with NRC conditions, it is concluded that these requirements for WOLs, including the inspection intervals, provide an acceptable approach for monitoring potential PWSCC. It is appropriate to reiterate that for monitoring to perform as expected, the NDE used has to be effective and reliable.

5.7 Conclusions

Based on a survey of operating experience with WOLs, the authors did not find any instances of leaks in WOL welds or flaws propagating into overlays. No service-related operating experience involving WOLs indicating crack growth was found.

The reliability of NDE is relevant to welds mitigated by weld overlays for several reasons. Pipe welds to be mitigated by optimized weld overlays are required to be inspected immediately prior to the overlay application, using an inspection technique qualified in accordance with ASME Section XI, Appendix VIII, and found to exhibit no evidence of cracking greater than 50% of the wall thickness in the original weld. Undetected or mischaracterized flaws could compromise the structural factors required for OWOLs. Reliable NDE is also of interest for pipe welds to be modified by FSWOLs. If a pre-FSWOL inspection is performed, the initial flaw size for the crack growth calculation is based on the results of the pre-FSWOL inspection. The calculated life of the FSWOL depends, in part, upon the reliability of the NDE performed.

The reliability of NDE of post-WOL welds is also important for determining whether any new flaws have initiated or existing flaws have propagated, and for assessing the effect of any potential flaws on the service life of the weld.

In WOL mockup testing performed by PNNL, all targeted flaws were detected in the pre- and post-WOL condition. Using carefully selected NDE parameters and encoded NDE techniques, pre- and post-WOL length and depth-sizing RMSE for flaws greater than 50% through the original wall thickness were found to be within the ASME depth-sizing qualification acceptance criterion.

Inspection limitations can affect the effectiveness of NDE requirements. Geometry or access may limit performing a complete pre-WOL weld examination. Information on geometric limitations to performing inspections of typical Westinghouse and CE plant RCS Alloy 82/182 welds is contained in Appendices C and D. Inspection limitations exist for welds adjacent to CASS products.

It is the authors' understanding that if OD weld surfaces can be adequately conditioned to allow full volumetric examination to be performed from the OD, the exception in Code Case N-770-1 to performing a pre-OWOL reactor vessel cold leg nozzle weld examination should not be used.

Based on an evaluation of WOLs using the criteria of Code Case N-770-1, Appendix I, it is reasonable to conclude that WOLs provide effective mitigation against the initiation of PWSCC and against the growth of any existing PWSCC that has been detected and allowed to remain in service. This statement is based, at least in part, on the proviso that the design that is evaluated and approved is the design that is actually created in the field.

Based on a review of the requirements of Code Case N-770-1, as implemented with NRC conditions, it is concluded that these requirements for WOLs provide an acceptable approach for monitoring potential PWSCC. For monitoring of potential PWSCC to perform as expected, the NDE used has to be effective and reliable.

6 MANAGEMENT OF PWSCC BY WELD INLAYS/ONLAYS

6.1 Operating Experience with Weld Inlays/Onlays

Weld inlays and onlays are methods to apply weld layers of Alloy 52/152 material on the inside pipe wall surface to mitigate potential primary waster stress corrosion cracking (PWSCC) in Alloy 82/182 dissimilar metal butt welds. Alloy 52 material has been shown to be more resistant to PWSCC than Alloy 82/182. Weld inlays and onlays provide a barrier to separate the Alloy 82/182 weld and butter from reactor coolant.

In pressurized water reactors (PWRs) in the United States, inlays and onlays have been used in two locations—Westinghouse plant replacement steam generator (SG) hot leg nozzle-to-safe end welds and Babcock & Wilcox (B&W) plant reactor vessel core flood nozzle to safe end welds.

In the 1990s, a number of plants replaced the SGs with Westinghouse-built SGs with Alloy 690 thermally treated tubing. Some of these SGs were installed with Alloy 52 or 152 inlays or cladding on the inside of the Alloy 82 hot leg nozzle-to-safe end welds (Karwoski 2003). These welds were made at the factory. The closure welds when the SG safe end welds were attached to the piping were made of stainless steel. Plants with these inlays included North Anna Power Station, Unit 2 (McCoy 2009), V.C. Summer (Gatlin 2012c), Point Beach, Unit 2 (Kunowski 2008b), and Kewaunee (Kunowski 2008a).

A description of the V.C. Summer SG nozzle-to-safe end weld inlays is provided in Gatlin (Gatlin 2012a, b, c). Although these letters were submitted to the U.S. Nuclear Regulatory Commission (NRC) in 2012, the V.C. Summer SG nozzle weld inlays have been in service since 1994. The letters were submitted, in part, to request NRC authorization to recategorize these welds as Code Case N-770-1, Inspection Item G, uncracked butt weld mitigated with an inlay, per 10 CFR 50.55a(g)(6)(ii)(F)(*2*). Gatlin (2012c) contains a summary description of the fabrication sequence as follows:

- The carbon steel channel head integral nozzle end is buttered with weld-deposited Alloy 82 and preliminarily machined per drawing.
- The channel head nozzle inside diameter (ID) is clad with weld-deposited stainless steel (SS) to within approximately 2 inches of the top of the buttered nozzle end per drawing. The first layer of cladding is 309L SS followed by 308L SS for the remaining layers.
- The nozzle ID region from the SS cladding to the end of the Alloy 82 buttered nozzle end is clad with weld-deposited Alloy 152.
- The nozzle end is machined with the safe end weld preparation.
- Post-weld heat treatment of the channel head nozzle end for 1.75 to 2.25 hours at 1125 ±25 degrees Fahrenheit is performed.
- The safe end forging is welded to the channel head nozzle with a double V-groove Alloy 82 weld.

- The final 0.27 inch of the nozzle inside diameter V-groove Alloy 152 weld (or inlay) is completed.
- The outside diameter (OD) and the ID of the nozzle with safe end are final machined.
- A shop hydrotest is performed and shipping covers are welded to the end of the nozzle safe end.
- The safe end is machined at site with the piping side weld preparation.

Gatlin (2012c) indicates that, "There is no issue regarding identification of the edges of the dissimilar metal welds, to ensure the coverage is complete, for the replacement steam generators. As shown in Attachment 1 (Figure 6.1, below), the inlay merges with the stainless cladding at a location over the carbon steel nozzles, so even if there was incomplete coverage, the susceptible materials would not be exposed. At the upper end of the configuration, the Alloy 52/152 extends to the edge of the weld preparation groove, thus ensuring that the coverage will be complete. Further verification that the coverage is complete comes from the NDE performed on the weld region before the replacement steam generators left the shop."

The configuration of the inlay at V.C. Summer, and possibly at the other replacement SG nozzles with Alloy 52 inlays from the 1990s time period, differs somewhat from the inlay designs proposed more recently. The newer inlay designs would extend the Alloy 52 inlay material into the safe end well past the safe end-to-Alloy 82/182 weld interface.

On September 18, 2008, the NRC staff met with Nuclear Energy Institute and other industry representatives in Rockville, Maryland, to discuss the regulatory approach to be used when applying weld inlays and onlays to mitigate potential PWSCC in Alloy 82/182 dissimilar metal butt welds (Tsao 2008a). The weld inlay and weld onlay configurations proposed during this meeting are shown in Figures 6.2 and 6.3.

At the September 18, 2008 meeting, industry presented technical papers that addressed ASME Code requirements relative to materials, applicable Code Cases, and Sections III and XI requirements. Per the requirements in draft Code Case N-766, the technical papers discuss chromium content, the implementation process, and nondestructive examination (NDE). Inlays and onlays are minimally 3-mm (1/8-in.) thick and installed using a minimum of two layers of weldment. These technical papers included the industry's bases for its conclusions that the use of inlays would require relief from ASME Code requirements, while onlays may not require relief depending upon welding issues, such as the ability to comply with ASME Code Case N-638-1 on the ambient temperature machine gas tungsten arc temper bead welding technique. At this meeting, industry representatives indicated that Entergy had plans to install weld onlays at Arkansas Nuclear One, Unit No. 1 in fall 2008. Code Case N-638-4 was conditionally accepted by the NRC in Regulatory Guide 1.147, Revision 16.

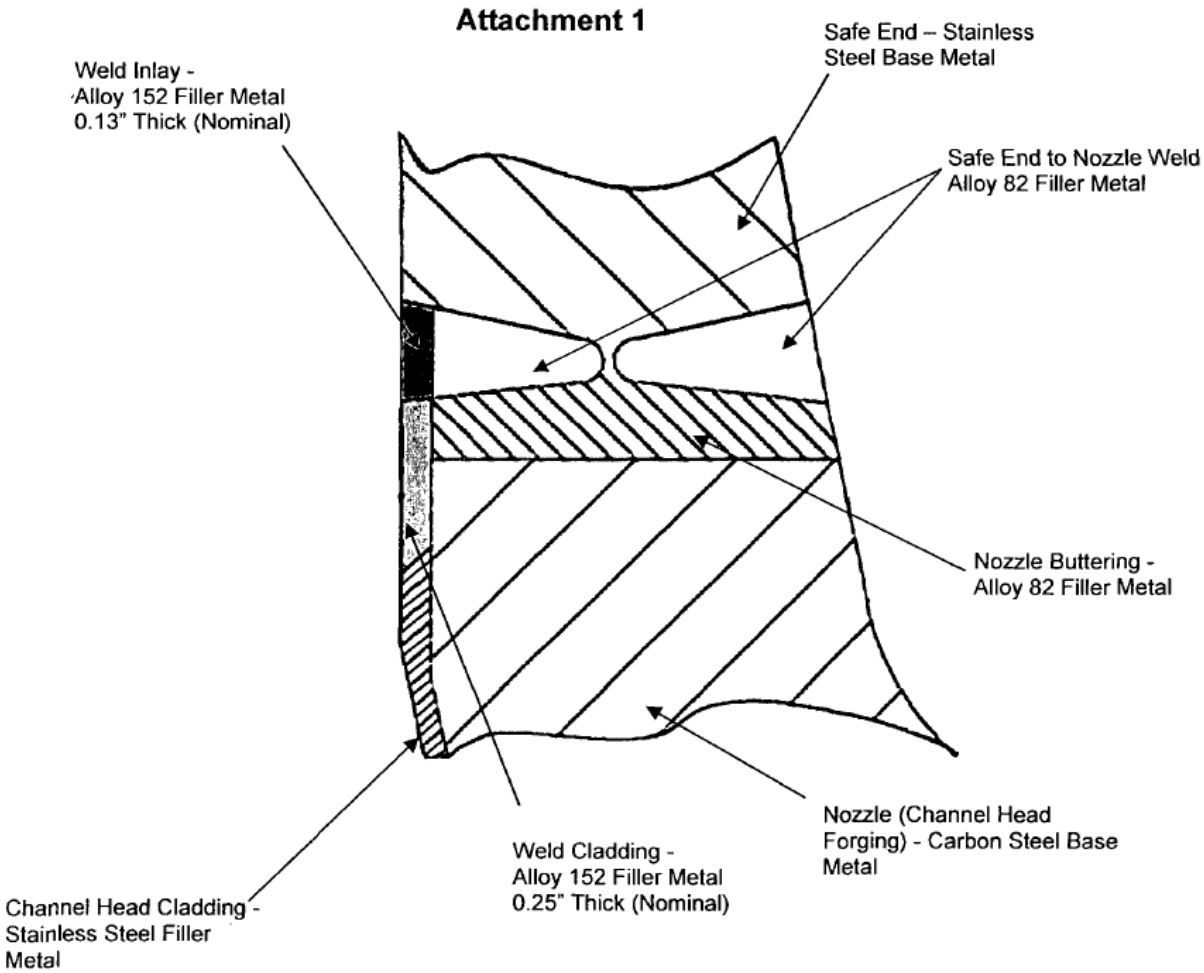


Figure 6.1 V.C. Summer, Unit 1 Replacement Steam Generator Primary Inlet/Outlet Nozzle to Safe End Weld Design

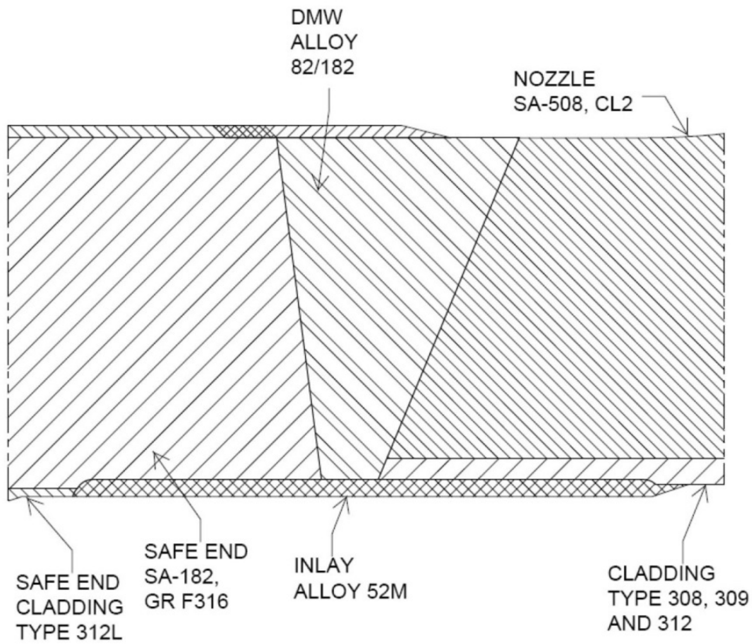
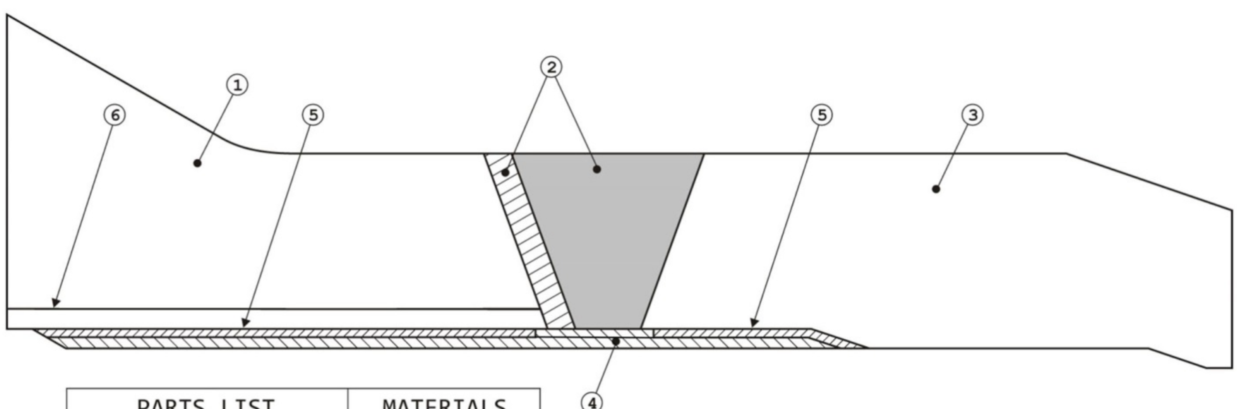


Figure 6.2 Weld Inlay Configuration Proposed by Industry (Tsao 2008c)



PARTS LIST		MATERIALS
1.	NOZZLE FORGING	A-508 CL.2
2.	WELD/BUTTER	ALLOY 82/182
3.	SAFE-END	SA-336 GR.F8M
4.	WELD ONLAY	ALLOY 52M
5.	BUFFER LAYER	ER308L
6.	CLADDING	ER308L

Figure 6.3 Weld Onlay Configuration Proposed by Industry (Tsao 2008b)

During the Fall 2009 refueling outage, Three Mile Island installed an Alloy 52 onlay over the core flood ‘A’ nozzle weld (Bellamy 2010). Attempts to mitigate the core flood ‘B’ nozzle-to-safe end Alloy 82/182 dissimilar metal weld (DMW) by onlay were unsuccessful.

The core flood 'B' nozzle-to-safe end mitigation process was abandoned due to an inability to reliably apply Alloy 52M weld material.(1) The weld configuration that was returned to service includes a new approximately 3-mm (1/8-in.) thick layer of Alloy 82 weld material over the DMW along with newly applied 309L SS weld build-up adjacent to the DMW to maintain a Performance Demonstration Initiative (PDI) ultrasonic testing (UT) inspectable configuration.

The dissimilar metal weld and required adjacent base material were UT, liquid penetrant testing (PT), and magnetic particle testing examined prior to performing any welding processes. There was no PWSCC identified during the examinations. Numerous small fabrication discontinuities that were acceptable to ASME Section III and Section XI were identified. These discontinuities and other unidentified original weld material impurities are believed to be the main cause of welding difficulties, because the most prevalent of these difficulties were encountered in the regions of NDE indications.

Sulfur mitigation layers of Alloy 82 filler metal were applied over the original DMW, which was the region requiring application of Alloy 52M weld material. In order to maintain an onlay configuration that was inspectable with a Supplement 10 procedure and had at least 3-mm (1/8-in.) thickness of PWSCC-resistant Alloy 52M material, the sulfur mitigation layer was limited to a thickness of 0.5 mm to 1 m (0.020 in. to 0.040 in.) in the dissimilar metal weld region. This thin sulfur mitigation layer allowed the Alloy 52M weld material to penetrate through the Alloy 82 sulfur mitigation layer and pick up original weld material contaminants that interfered with the normal weld puddle wetting process. The Alloy 52M weld beads were described as "ropey" and did not have good wetting and fluidity, resulting in unacceptable conditions. Attempts to dilute the original weld material contaminants resulted in similar unacceptable Alloy 52M welding results.

The root cause was concluded to be the incomplete consideration of the aggregate effect of material, geometry, and design on the 'B' core flood weld when developing the appropriate weld parameters. It was also determined that a contributing factor was inadequate pre-outage mockup fidelity. The welding techniques were not fully demonstrated on materials that possessed similar high sulfur conditions with simulated acceptable fabrication flaws using the designed thin Alloy 82 barrier layer.

In addition to the domestic use of inlays and onlays discussed above, weld inlays were applied on the reactor vessel-to-safe end welds at Ringhals 3 and 4 in Sweden. Inlays were applied at Ringhals 4 in 2002 and inspected with UT and eddy current testing (ET) in 2005. No indications were found. These welds were inspected again with UT and ET in 2010. No indications were found and these welds have now been placed on a 10-year re-inspection frequency (Hardies 2011).(2)

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(1) Information on Three Mile Island core flood 'B' nozzle onlay obtained by email on October 16, 2012, from Exelon Nuclear.

(2) Information on Ringhals is in slides presented at NRC/industry meeting summarized in Hardies (2011).

Inlays were applied at Ringhals 3 in 2003 and inspected with UT and ET in 2006. No indications were found. These welds were inspected with UT and ET in 2010. No indications were found and these welds have now been placed on a 10-year re-inspection frequency (Hardies 2011).

A summary of operating experience with PWSCC in butt welds in nuclear power plants that was compiled by the authors is provided in Appendix B. Based on this summary, the authors did not find any instances of leaks in welds with inlays or onlays. No service-related operating experience involving cracking in inlays or onlays was found. It should be noted, however, that the number of welds mitigated by inlays and onlays is small compared to the number of weld overlays and MSIP applied to butt welds susceptible to PWSCC, and information on inspections performed would not be available unless requested from each utility.

6.2 Code Case N-766 Design and Examination Requirements for Inlays and Onlays

Code Case N-766, "Nickel Alloy Reactor Coolant Inlay and Onlay for Mitigation of PWR Full Penetration Circumferential Nickel Alloy Dissimilar Metal Welds in Class 1 Items, Section XI, Division 1," was used as a source for the design requirements summarized in this section (ASME 2010). NRC concerns with two of the design requirements of this Case are noted in this section and discussed in Section 6.5.

For the final configuration, the applicable stress limits of the Construction Code have to be met. An inlay or onlay that is 10% or less of the design wall thickness may be neglected in the evaluation of the primary plus secondary stress intensity (NB-3222.2) and analysis for cyclic operation (NB-3222.4).

The Code Case requires that a fatigue crack growth evaluation be performed and specifies the assumptions to be used for initial flaw sizes for both circumferential and axial flaws. The acceptance standard for the fatigue crack growth evaluation is that a surface-connected flaw may not grow through the full thickness of the inlay or onlay, considering all applicable loads subject to Level A and B Service Limits.

The rules for performing fatigue crack growth evaluation are specified in Section XI, IWB-3640. The inlay and onlay designs are both required to be evaluated for fatigue crack growth. Two postulated cases are required for evaluation—one case for embedded planar flaws remaining within the DMW and one case for surface-connected planar flaws within the inlay/onlay.

Axial and circumferential flaw depths are assumed to be 10% of the original DMW thickness if as-left embedded flaw depths do not exceed 10% of the original DMW thickness, or if there are no embedded flaws. If as-left embedded flaw depths exceed 10% of the original DMW thickness, the actual as-left embedded flaw depths are to be used. The minimum initial flaw depth assumption of 10% through the DMW initiating at the inlay/onlay to DMW interface is based on the minimum detection capability inferred from Table IWB-3514-1 and is consistent with the crack growth and design requirements of Case N-740-2. For the circumferentially-oriented flaw, the postulated flaw length is the entire circumference of the DMW. For the axially-oriented flaw, the postulated flaw depth is the same, but the length is equal to the full DMW width plus any additional susceptible material.

In draft Code Case N-766-1, even if a flaw greater than 10% of the DMW thickness is detected and analyzed as an embedded flaw, as discussed below, the postulated 10% embedded flaw case is still required to be evaluated in order to cover undetected flaws that may be left between the inlay, or onlay, and the DMW at a location away from the detected flaw.

The weld inlay, or onlay, must also be evaluated for fatigue crack growth considering a postulated planar surface-connected flaw. The postulated initial flaw depth is specified to be 1.5 mm (1/16 in.). This postulated flaw size is specified to conservatively account for undetected flaws within the inlay or onlay based on current detection methods. The depth is equivalent to approximately one layer of weld material. The flaw lengths are specified to be 360° for circumferential flaws and the width of the DMW plus any additional susceptible material for axial flaws. For both the postulated embedded and surface-connected flaw cases, the flaw must not grow through the inlay, or onlay, for the remaining life of the plant, thereby maintaining its function as a barrier between the Alloy 82/182 material and reactor coolant (Marlette et al. 2012). Although much more resistant than Alloy 82, the NRC has concluded in its negative ballot on Code Case N-766 that, in addition to performing a design analysis for fatigue, Alloy 52 inlays and onlays should also be analyzed for PWSCC.

The effects of weld shrinkage on the component are generally not of great concern for inlay/onlay applications because the inlay/onlay thickness is so small compared to the overall DMW cross-sectional thickness. However, the Case requires that an inlay or onlay with a thickness greater than 12.5% of the original DMW thickness be evaluated for shrinkage effects. The thickness requirement is based on engineering judgment and the assumption that the inlay or onlay will be applied to a nozzle with a wall thickness of 50.8 mm (2 in.) or greater (Marlette et al. 2012).

Prior to installation of an inlay or onlay, the DMW and area to be welded has to be examined by volumetric and surface methods. Volumetric examinations have to be performed in accordance with the requirements of Code Case N-770-1 or later revisions. A surface examination has to be performed using liquid penetrant or ET on the area to be welded. Indications detected by volumetric examination that exceed IWB-3514 standards have to be corrected. Alternatively, the Code Case allows indications that do not meet the acceptance standards of IWB-3514 to be accepted by analytical evaluation in accordance with IWB-3600. The NRC disagreed with this provision and in its negative ballot on Code Case N-766 expressed a concern with returning to service welds with deep embedded flaws.

If a pre-existing flaw cannot be qualified to allow leaving it in place as an embedded flaw, the flaw has to be removed or reduced to an acceptable size by grinding out part or all of the material containing the flaw, and performing a localized welded repair prior to installing the inlay or onlay in accordance with IWA-4000 and IWB-3600. If weld repair of indications is required, the area where the weld inlay or onlay is to be deposited, including any local weld repairs, has to be examined using PT or ET. The area shall be free of surface indications with major dimensions greater than 1.5 mm (1/16 in.) prior to installation of the inlay or onlay. After installation, the inlay or onlay surface, including at least 13 mm (½ in.) of adjacent material has to receive a surface examination that may be performed by liquid penetrant or eddy current. Acceptance criteria for the surface examination of inlays or onlays has to satisfy Section III, NB-5352, except that indications with major dimensions greater than 1.5 mm (1/16 in.) have to be removed or reduced in size or repaired by welding and reexamined. The inlay or onlay volume, including the fusion zone, and ferritic steel heat-affected zone, when temper bead welding is used, has to be examined by UT. The volumetric examination performed after installation is for the purpose of detecting lack of bond and clad flaw indications only and is performed in accordance with Section V requirements. If temper bead welding is used, the examination shall be conducted no sooner than 48 hours after the completion of the third temper bead layer over the ferritic steel base material. Preservice and inservice examinations are required to be performed in accordance with Code Case N-770-1 or later.

To reduce the potential for hot cracking, the Code Case permits users to apply austenitic filler material over the austenitic stainless steel or ferritic steel materials. Surface examination of the seal layer(s) must also be performed using the same acceptance criteria as noted in the preceding paragraph. The location of the DMW fusion zones has to be identified and the accuracy of the locating technique has to be demonstrated on representative mockups and documented.

The Case specifies nickel alloy filler metal with a minimum 28% chromium content be used and an as-deposited weld metal with a minimum of 24% chromium content be achieved. Inlays and onlays have to be deposited using a Welding Procedure Specification qualified for groove welding in accordance with the Construction Code and Owner's Requirements identified in the Repair/Replacement Plan. Likewise, welders and welding operators have to be qualified in accordance with the Construction Code and Owner's Requirements identified in the Repair/Replacement Plan. The preheat and post-weld heat treatment requirements of the Construction Code and Owner's Requirements identified in the Repair/Replacement Plan have to be met if welding on ferritic base materials or if 3 mm (1/8 in.) or less of nonferritic weld deposit exists above the fusion line of the ferritic steel base material. Alternatively, the Code Case prescribes that ambient temperature temper bead welding may be performed in accordance with Appendix I of the Code Case.

Inlays and onlays are required to consist of at least two layers after final surface preparation. The minimum required thickness is 3 mm (1/8 in.) and all inlay and onlay layers credited toward the minimum thickness have to contain at least 24% chromium, as determined by chemical analysis of a representative mockup. Weld inlays and onlays are required to extend beyond the DMW and butter fusion zones by at least twice the demonstrated accuracy of the technique used for locating the fusion zones or 6 mm (¼ in.), whichever is greater.

6.3 NDE Reliability

6.3.1 Qualification and Acceptance Standards for Surface Examination

Code Cases N-770-1 (inspection of Alloy 82/182 butt welds) and N-766 (inlay/onlay mitigation technique) both use ET examinations to ensure the quality of welds. However, there are two issues with the application of ET as a surface examination method in these Code Cases.

The first issue pertains to ET acceptance standards prescribed in these Code Cases. Code Case N-770-1 states that the acceptance standards of NB-5352 apply for the surface examination of weld inlays or onlays, except that rounded indications with dimensions greater than the smaller of 1.5 mm (1/16 in.) or 50% of the thickness of the inlay or onlay are unacceptable. Code Case N-766 also invokes NB-5352 as the acceptance standard for surface examinations. Section III, NB-5352 contains acceptance standards for liquid penetrant. These standards are not applicable to ET. For example, the 1.5-mm (1/16-in.) dimension allowed for liquid penetrant would be indicative of a smaller flaw than 1.5-mm (1/16-in.) because of penetrant bleed-out.

The second issue pertains to ET qualification. Code Case N-770-1 states that the ET examination is required to be performed in accordance with IWA-2223. Code Case N-766 specifies that, "nondestructive examination methods shall meet the requirements of IWA-2200." Section XI, IWA-2223 requires that eddy current examination for detection of surface flaws be conducted in accordance with Appendix IV. Appendix IV, Supplement 2, contains requirements for qualification of ET techniques by demonstration for surface examination of piping and vessels. Supplement 2 allows notches with a maximum width of 0.25 mm (0.010 in.) to be used for the demonstration. The Appendix IV qualification is applicable only to materials whose acceptance standard is 3 mm (1/8 in.) or more in length. The width of a PWSCC flaw would be much smaller than a 0.25-mm (0.010-in.) wide notch allowed to be used in an Appendix IV, Supplement 2, demonstration and ET used for inlays and onlays has to be capable of reliably detecting rounded indications as small as 1.5 mm (1/16 in.).

At the ASME Code, Section XI meetings in Phoenix from November 5–8, 2012, the NRC staff (Collins et al. 2012) indicated that it is considering the adequacy of the ET qualification requirements of Appendix IV, Supplement 2, which are based on technique demonstration as opposed to performance demonstration techniques. ET performance demonstration techniques are provided in the recently approved Code Case N-773, "Alternative Requirements for Automated Eddy Current Examination of Class 1 Stainless Steel or Stainless Steel Clad Carbon Steel Piping from the Inside Surface." This Case provides an optional ET qualification program to that in Appendix IV, Supplement 2, and may serve as a guideline for a new Code Case for ET of inlays and onlays. At these meetings, the NRC staff also indicated an interest in performance qualification techniques that would address the possibility that very shallow subsurface defects will become exposed during operation. This has occurred at San Onofre, Unit 3, for upper head seal/cladding welds using Alloy 52 materials (Scherer 2008).

6.3.2 Ultrasonic Equivalency Testing of Weld Inlaid Components

The PWR Owners' Group (PWROG) sponsored testing to evaluate the effectiveness of current automated ultrasonic procedures applied to inner surface inspection of inlaid welds without modification of essential variables (Latiolais 2008).

The primary focus of this project was to evaluate the detection and sizing capabilities of Appendix VIII, Supplement 10, qualified procedures used for examination of DMWs from the inside surface on an inlaid component without changing the essential variables of the qualified procedure. ASME Section XI, Appendix VIII, Supplement 10, is not applicable to components with supplemental corrosion-resistant cladding applied to mitigate stress corrosion cracking

(SCC). Therefore, no PDI-qualified technique currently exists that can be used to inspect inlaid DMWs. The PWROG project was intended to show the effect of inlay material on the ability to ultrasonically detect and size flaws that might develop later in the service life of an inlaid component. It was the PWROG's plan for this testing that if equivalency was demonstrated, the need for additional qualification activities would not be necessary because currently available inspection procedures could be used.

An inlay test mockup was created that was identical to an existing PDI-601 series weld configuration. The PDI-601 series weld configuration is for the Westinghouse PWR vessel outlet shop weld, which has a SA-508 nozzle, an Inconel butter and weld to a SA182-316 safe end, which is welded to a wrought 308/316 stainless steel pipe (Latiolais 2002). This mockup is a full-scale representation. Both the 601 and the inlay mockup were fabricated from actual dropouts taken from a cancelled PWR to ensure that materials and welding processes are typical of those found in an operating plant. The inlay material was applied using welding techniques and hardware developed by AREVA NP. In order to identify welding imperfections that might exist in the DMW, AREVA NP ultrasonically inspected the inlay mockup by using a qualified Appendix VIII procedure before inlay material was applied.

The inlay test mockup has four 90° quadrants with varying inlay thicknesses that were blended smooth on the inner diameter surface. The first quadrant of the mockup was used for a baseline for noise comparison and had no weld inlay or flaws. The second and third quadrants have 0.508-cm and 0.178-cm (0.20-in. and 0.07-in.) thick inlays, respectively. In addition to the inlay, quadrants two, three, and four have the same set of four flaws identified as Flaws 1, 2, 3, and 12, which are identical to flaws contained in the 601 practice mockup. Flaws 1, 2, and 12 were circumferentially oriented with depths of 8.6 mm (0.339 in.), 8.9 mm (0.350 in.), and 9.5 mm (0.374 in.), respectively. Flaw 3 was axially oriented with a flaw depth of 20.7 mm (0.815 in.). In the fourth quadrant, an embedded flaw represents the partial removal and subsequent 25.4-mm (1-in.) deep inlay repair of a flaw. The flaws were implanted in the mockup using the same techniques used for the fabrication of the PDI-601 mockup.

Two vendors were contracted to inspect the inlay mockup. Previously collected data on similar flaws in the 601 mockup were used as a comparative reference. All data were collected following each vendor's applicable Appendix VIII-qualified automated ultrasonic procedure.

Both vendors performed an open procedure demonstration and reported similar findings with respect to flaw detection, sizing, and relative noise levels within the areas of the inlay. Both vendors observed an apparent increase in the noise level in the areas where the inlays were applied. For a given flaw, the signal-to-noise ratio was less in the Electric Power Research Institute (EPRI) block 601 when comparing the corresponding flaws in the inlayed areas. This reference noise level increased as the thickness of the inlay material increased. In the axially-oriented flaws, the signal-to-noise ratio was more noticeably affected, but it was not at a level that would impact the results of the examination. This increase in noise generally made flaw-depth sizing more difficult, but it had a lesser effect on detection capabilities. The increase in the relative noise within the areas of the inlays for circumferentially-oriented flaws depended upon the scanning direction. Based on discussions with multiple qualified UT inspectors, the increase in noise was attributable to the microstructure of the inlay and appeared to be affected by the orientation of the dendrites based on the direction of welding.

Each of the axially orientated flaws was sized using the 60° probe instead of the 45° probe, which is not the optimum angle for through-wall sizing but is allowed by procedure. Both vendors were able to detect, characterize, length size, and depth size all the implanted axial and circumferential flaws without deviating from the procedurally qualified techniques and the results were within the tolerances imposed by EPRI's PDI-qualified inspection procedures; that is, within the acceptance criteria in Section XI, Appendix VIII.

The reliability of UT is of interest to welds mitigated by weld inlays and onlays for several reasons. Pipe welds to be mitigated by weld inlays and onlays are required to be inspected immediately prior to the application, using an inspection technique qualified in accordance with ASME Section XI, Appendix VIII, and any flaws detected are to be evaluated in accordance with IWB-3600. Undetected or mischaracterized flaws could compromise the structural integrity of the weld. The calculated life of the inlay or onlay depends, in part, upon the reliability of the NDE performed. The reliability of NDE of post-mitigated welds is also important for determining whether any new flaws have initiated or existing flaws have propagated, and for assessing the effect of any potential flaws on the service life of the weld.

PNNL held a workshop in May 2012 with LMT, Inc., a commercial nuclear NDE vendor, to review UT data from service-induced flaws and to discuss factors that affect the reliability of various NDE techniques qualified in accordance with Section XI. The conclusions of this workshop, which relate to inspection of both pre- and post-inlay/onlay piping welds, are provided in Section 3.1.2.

6.4 Assessment of the Effectiveness of Weld Inlays/Onlays as a PWSCC Mitigation Strategy

In a study performed by Rudland et al. in 2010, confirmatory welding residual stress and flaw evaluation analyses were conducted to evaluate the inlay as a mitigation technique. Two large-bore, reactor coolant nozzle geometries were considered. The first was an 872-mm (34.3-in.) diameter, 68.1-mm (2.68-in.) thick reactor coolant outlet nozzle taken from an AREVA inlay submittal. The second was a 923-mm (36.3-in.) diameter, 83.8-mm (3.3-in.) thick reactor coolant nozzle used to develop welding residual stress results for probabilistic fracture mechanics calculations. For each of these geometries, detailed finite element simulations were conducted to predict the welding residual stress through the application of the inlay. The effects of temper bead welding and weld repairs were considered. The following repair sizes were considered:

- 50% deep ID preservice repair (before stainless steel safe end)
- 50% deep ID PWSCC repair (after stainless steel safe end but before inlay)
- 75% deep ID preservice repair
- 75% deep ID PWSCC repair
- 50% deep ID preservice repair and a 75% deep ID PWSCC repair
- 12% deep ID preservice repair

- 12% deep ID PWSCC repair
- 12% deep ID preservice repair and a 12% deep ID PWSCC repair

For each case, a final inlay thickness of 3 mm (0.125 in.) was considered because this corresponded to the minimum thickness required by Code Case N-766. In addition, an inlay with a thickness of 6 mm (0.25 in.) was considered for the 50% deep ID preservice and 50% deep ID PWSCC repair cases.

The results from the welding residual stress analyses suggest that regardless of the repair history, the ID stress state is driven by the inlay repair. In most cases analyzed, the ID axial stress due to the inlay was about 58 ksi (400 MPa), which is just above the yield strength for the DMW material. Even the beneficial effect of the SS safe end weld was eliminated by the thin layer of inlay material on the ID surface of the pipe. For all of the inlay cases with preservice repairs, the high axial stress on the ID dropped to zero at about 15% percent of the wall thickness for all repair depths. For the cases with PWSCC repairs, the axial stress dropped to zero between 40% and 50% of the wall thickness for repairs greater than 50% deep, and it dropped to zero at about 20% of the wall thickness for the 12% deep repair.

The results from the welding residual stress analyses were used in PWSCC growth analyses using both idealized-shaped and natural-shaped cracks assuming simulated crack growth rates.

The idealized flaw analyses followed the techniques documented in the ASME Section XI flaw evaluation guidelines. Sensitivity studies were conducted on crack growth rate, bending stress, operating temperature, initial flaw size and orientation, and inlay depth.

For the idealized flaw analyses, the ASME Section XI flaw evaluation guidelines were used in conducting PWSCC growth calculations. The effects of crack initiation were ignored and an initial surface-breaking defect was assumed in all analyses. This assumption is consistent with the Code Case N-766 requirement that a postulated surface-breaking planar flaw that is 1.5-mm (1/16-in.) deep will not grow through the full thickness of the inlay due to fatigue for the life of the inlay. Crack growth times through the inlay, to through-wall penetration, and to rupture were calculated. The following significant conclusions were obtained:

- The time for the initial defect to grow through-wall was dominated by the time for the initial defect to grow through the inlay; that is, a large portion of the crack growth time is spent in the first 3 mm of wall thickness. The only exception to this case was for the small weld repair (12%). In this case, the flaw arrested after passing through the inlay.
- For the 3-mm deep inlay, the time through the inlay was typically about 10 years. After that point, the time to leakage varied with repair size, ranging from an additional 5 years for a 50% deep repair to arrest for a 12% deep weld repair.
- For the 6-mm deep inlay, the time through the inlay was about 25 years, with the additional time to leakage the same as for the 3-mm cases.
- The crack growth times through the inlay are directly proportional to the crack growth rate used. More experimental data on Alloy 52 crack growth rates is needed to quantify the uncertainty in the crack growth rate.

- Bending stress did not have a large effect on the time for the crack to pass through the inlay, but had a large effect on time to leakage; that is, the lower bending stresses caused the crack to slow considerably near the middle of the wall thickness.
- Temperature had a large effect on the crack growth behavior. The time through the inlay, time to leakage, and time to rupture were increased by about a factor of 6 by reducing the temperatures from hot leg (327°C) to cold leg (288°C) conditions. Even for the fastest crack growth considered, the time to leakage was over 50 years at the cold leg temperatures.
- Initial crack length did not have a large impact on the time through the inlay or to leakage.
- Axial cracks grew faster than circumferential cracks due to the larger hoop stresses in the inlayed welds.

For the natural flaw growth analyses, the PipeFracCAE code, which was used in the Wolf Creek analyses, was modified to handle the unusual crack growth that may occur in an inlayed DMW. In a natural flaw growth analysis, the flaws are driven by PWSCC and tensile stresses caused by the weld residual stress and the service loading. A finite element analysis is performed at each increment of flaw growth to calculate stress intensity factors along the crack front. Because of the differences in the crack growth rates between the inlay material (Alloy 52) and the DMW (Alloy 82/182), a discontinuous, balloon-shaped crack forms. After modifications to the PipeFracCAE code were complete, several sample cases were run for comparisons to the idealized flaw analyses. The intent of these natural flaw analyses was to verify that the unusual flaw shapes did not highly impact the time through the inlay and leakage calculated using the idealized flaw assumption. The results from these runs illustrated that in some cases, the natural crack analyses gave slightly longer times to leakage, while in other cases the times to leakage were slightly shorter. The differences stemmed from the effect of the natural crack shape on the crack driving force and the more accurate representation of the welding residual stress field in the natural flaw analyses.

Overall, the natural crack shape analyses demonstrated that reasonable approximations of crack growth time through the inlay and to leakage can be made with idealized flaw analyses.

Several general conclusions can be made regarding the effectiveness of inlays as a mitigation technique. First, the sensitivity studies conducted assuming a postulated initial defect indicate that for the hot leg locations, the time to leakage values are less than the inlay design life even with Alloy 52 PWSCC crack growth rate improvement factors of 30–100. For the case of a 3-mm (0.125-in.) inlay, the times to leakage from the postulated defect ranged from about 12 years to 30 years. This conclusion assumes that the effect of crack initiation in Alloy 52 inlay materials is neglected and can be considered an additional conservatism in the results.

Second, the results presented in this report are highly influenced by the Alloy 52 crack growth rates assumed. Because of the limited Alloy 52 crack growth data, additional crack growth data is needed for these materials to fully understand and quantify the uncertainty in the results.

Third, the times to leakage calculated in this effort do not support sample inspections for inlay-mitigated hot leg temperature welds. However, the effect of temperature on the growth rates is dramatic and therefore the results from this study support sample inspection for inlay-mitigated cold leg temperature welds. As noted in Section 6.6 below, the NRC incorporated Code Case N-770-1 into 10 CFR 50.55a and imposed a condition prohibiting sample inspection of hot leg welds mitigated by inlays or onlays.

Finally, the results from this study suggest that a large portion of the time to leakage is spent growing the postulated defect through the inlay. Because the inlay may only be about three to five percent of the total wall thickness, the study performed by Rudland et al. (2010) recommended that both volumetric and ID surface examination be performed to locate a defect that may be present in the inlay material. Code Cases N-766 and N-770-1 require volumetric and surface examinations.

Regarding studies performed on cracking in inlay/onlay materials, Toloczko et al. (2010) provides the results of initial examinations to assess defects in prototypic industry-produced Alloy 52, 52M, and 152 mockup welds. Weld metals were characterized in three different mockup configurations including an Alloy 52M inlay mockup made by Ringhals AB. Most of the weld cracks were found near the final Alloy 52M weld pass in this thick inlay. Only isolated cracks were identified near the Alloy 52M-to-Alloy 82 interface and nearly all of these were in the Alloy 82 material. The weld cracks in the Alloy 52M were typically less than 100 µm in length, but there was one possible instance of an approximately 500-µm crack in the final weld pass.

Toloczko et al. (2010) reported that the preliminary weld crack examinations indicate that small intergranular weld cracks will be present in most Alloy 52, 52M, and 152 weldments. Brief comments can be made on implications to the use of thin, high-Cr inlays to provide corrosion resistance. The observed cracks do not appear to provide a continuous path for water to reach the more SCC-susceptible, lower-Cr Alloy 182 or 82 weld metal. While the typical crack size in all the welds was 100 µm or less, in three of the weld mockups, several 500-µm-long cracks were observed. This length is insufficient for a single crack to span even a thin overlay, but a clustering of interconnected cracks may potentially provide a path. This seems unlikely based on the current limited results; however, more detailed studies of crack size and three-dimensional distributions would need to be performed to better assess the probability that such interconnected cracks could exist.

Toloczko et al. (2010) reported further that the more important question is whether these pre-existing flaws can act as sites for accelerated crack growth during light-water reactor service. The location and length of a weld crack in the inlay or overlay would obviously have a strong effect on the local stress intensities. A long weld crack that intersects the surface of an inlay or overlay would be subject to higher fatigue-driven stresses, and clusters of cracks could more easily become interconnected. Similar issues can be envisioned for a weld crack on the surface acting as a nucleation site for the growth of an SCC crack. Measured SCC propagation rates of these materials are extremely slow, with perhaps a maximum rate of approximately 0.1 mm/year at relatively high stress intensity values. Relying on a simple calculation, it was estimated that it would take roughly 20 years for an SCC crack to span a 2-mm-thick inlay repair.

An update on Pacific Northwest National Laboratory SCC crack growth testing on Alloy 152, 52, 52M, and 52MSS welds is provided in Toloczko et al. (2011). These results support the crack growth rate results previously reported and discussed above and are consistent with or more conservative than the crack growth rates assumed in Rudland et al. (2010).

Based on the results of the 2010 assessment by Rudland et al., NRC developed condition 10 CFR 50.55a(g)(6)(ii)(F)(*5*) on the inspection requirements for inlays in Code Case N-770-1 that prohibits sample inspection of hot leg temperature inlays/onlays. Assuming that reliable NDE techniques are used to inspect inlays/onlays, inlays/onlays of appropriate thickness would be expected to provide effective mitigation against the growth of PWSCC into Alloy 82/182 welds to which they are attached.

6.5 Status of Code Case N-766, "Nickel Alloy Reactor Coolant Inlay and Onlay for Mitigation of PWR Full Penetration Circumferential Nickel Alloy Dissimilar Metal Welds of Class 1 Items"

ASME approved Code Case N-766, "Nickel Alloy Reactor Coolant Inlay and Cladding for Repair or Mitigation of PWR Full Penetration Circumferential Nickel Alloy Welds in Class 1 Items" on December 20, 2010, and issued it in Supplement 4 of the 2010 Edition of Section XI (ASME 2010). The NRC staff, in accordance with ASME voting procedures, submitted a negative ballot on this Code Case.

The staff presented its issues with the Code Case during discussions at the Code committee meetings and in writing with the negative ballot. The staff's major concerns were as follows.

1. The Code Case does not require a design analysis for flaw growth by PWSCC. The staff believes that an evaluation of PWSCC should be required for mitigative Alloy 52 inlays and onlays (Hardies 2011) to assure adequate thickness of the inlay/onlay for the Code Case inspection intervals requirements. In the staff's PWSCC flaw growth analysis for inlays/onlays (Rudland et al. 2010), the staff postulated an initial flaw size of 1.6 mm (1/16 in.) or 50% through the thickness of the inlay, as used in the Code Case for fatigue evaluation. The purpose of the staff's analysis was to evaluate the inspection intervals for inlays and onlays in Code Case N-770-1. As discussed in Section 6.4, the NRC staff concluded that from this analysis that the sample inspection provisions of Code Case N-770-1 inspection requirements were not acceptable for hot leg welds mitigated by inlays or onlays.
2. Another concern expressed by the NRC staff prior to approval of Code Case N-766 by the ASME pertains to the allowable size of embedded flaws that could be left in service after application of an inlay or onlay. The Code Case allows a flaw in the original Alloy 82/182 dissimilar metal weld to remain in service as long as IWB-3600 is satisfied. The NRC staff indicated that it does not find this to be acceptable for Class 1 piping. The NRC staff indicated its belief that Code Case N-766 must provide a limitation on the size of a flaw that is allowed to remain in service after an inlay is installed. The NRC staff indicated that it does not object to allowing flaws to remain in service after inlay or onlay installation. However, in casting its ballot on Code Case N-766, the NRC staff stated that it finds it to be unacceptable if a "large" flaw remains in service regardless of inlay repair and the requirements of the ASME Code, Section XI.

Regarding the first of the NRC staff's major concerns, industry developed a technical basis to justify a small initial flaw size for a PWSCC evaluation (Marlette et al. 2012). Marlette et al. report that the initial flaw size for the crack growth analysis was conservatively based on known eddy current detection capabilities. The ASME Boiler and Pressure Vessel Code contains qualification requirements for eddy current examination with specified flaw depths of 0.5 mm (0.02 in.) and less. For example, Supplement 2, Appendix IV of Section XI specifies a maximum depth of 0.5 mm (0.02 in.) for machined notches within a specimen to be used in eddy current qualification testing. They also report that eddy current testing documented in Kobayashi (2010) has demonstrated the ability to detect surface flaws as shallow as 0.3-mm (0.012-in.) deep within a weld inlay surface. Results are documented for several test specimens within the paper. Underwater laser beam welding was used to fill an inlay groove in one specimen. Surface slits with depths of 0.3 mm (0.012 in.), 0.5 mm (0.020 in.) and 1 mm (0.04 in.) were placed in the inlay surface. The length and width of all the surface flaws were 1.5 mm (0.06 in.) and 0.2 mm (0.008 in.), respectively. The test results demonstrated that eddy current is capable of detecting flaws as shallow as 0.3 mm (0.012 in.) deep within an inlay surface.

Accordingly, Marlette et al. (2012) assumed an initial surface flaw with a depth of 0.5 mm (0.02 in.) and a length-to-depth aspect ratio of 6, as used by Rudland et al. (2010). The analysis also assumed the same crack growth rate for the Alloy 52 weld inlay material that was used in Rudland et al. (2010); namely, a PWSCC crack growth rate for Alloy 52 weld material of one hundredth of the growth rate for Alloy 182. Marlette et al. (2012) report that the new analysis used the same two physical models, worst-case repair cases, residual stress models, bending and axial stresses, stress intensity factor calculation methodology, and crack paths as used by Rudland et al. (2010). Benchmarking runs were performed in order to provide validation that the generic analysis would produce similar results to the methods used by Rudland et al. (2010). All of the key parameters used in Rudland et al. (2010) including the 1.5-mm (1/16-in.) initial flaw depth were used for the benchmarking. Once the benchmark results were verified to be in good agreement with the results reported in Rudland et al. (2010), the new analysis was run using the 0.5-mm (0.02-in.) initial flaw depth.

Marlette et al. (2012) report that the results of the new analysis demonstrate that a postulated flaw will not grow through the remaining inlay thickness within an inspection interval; that is, a 10-year period. The analysis shows that the worst-case result is for axial flaw growth, which still provides over 15 years of operation before the postulated flaw would grow though the minimum inlay thickness. The authors indicate that the results from this analysis demonstrate that even in the unlikely case that PWSCC would become an active mechanism for crack growth within the resistant inlay material, it would not grow through the minimum required thickness within a 10-year inspection interval.

ASME, Section XI, developed a revision to Code Case N-766 that was intended to address the NRC staff's concerns and other issues that need to be clarified. Nevertheless, Code Case N-766-1 does not address either of the staff's concerns. For example, regarding a design analysis for flaw growth, the revised Code Case does not require users to perform a case-specific analysis or verify that the industry's generic analysis bounds weld-specific conditions. Final resolution of the staff positions on Code Case N-766 and Code Case N-766-1 will be developed as part of a future revision to Regulatory Guide 1.147 (Hardies 2011).

6.6 Assessment of Code Case N-770-1 Inspection Requirements

An overview of Code Case N-770-1 inspection requirements is contained in Section 3.4.1. The paragraphs that follow in this section describe the Code Case N-770-1 requirements for inlays and onlays and the conditions that NRC imposed on the examination of inlays and onlays when the NRC incorporated ASME Code Case N-770-1 by reference into 10 CFR 50.55a (76 FR 36232) in June 2011.

Inspection Item G welds are uncracked butt welds mitigated with an inlay and Inspection Item J welds are cracked butt welds mitigated with an inlay. Figure 3 of the Case shows the examination volume in weld inlays and indicates that inlays shall be constructed of an Alloy 52 material. Inspection Item H welds are uncracked butt welds mitigated with an onlay and Inspection Item K welds are cracked butt welds mitigated with an onlay. Figure 4 of the Case shows the examination volume in weld onlays and indicates that onlays shall be constructed of an Alloy 52 material.

Table 1 of the Case provides requirements for the examination methods, acceptance standards, and extent and frequency of examination of unmitigated and mitigated welds. For Inspection Items G and H, Table 1 requires inservice volumetric and surface examinations to be performed no sooner than the shorter of 10 years following the application of the inlay or onlay and the design life of the inlay or onlay. Examination volumes that show no indication of cracking are to be placed into a population to be examined on a sample basis. For Inspection Items J and K, Table 1 requires inservice volumetric and surface examinations to be performed once during the first or second refueling outage following application of the inlay or onlay. Examination volumes that show no indication of cracking are to be placed into a population to be examined on a sample basis. Based on the analysis performed by Rudland et al. (2010), the NRC disagreed with sample inspection provisions of Inspection Items G, H, J, and K and imposed condition 10 CFR 50.55a(g)(6)(ii)(F)(*5*). This condition is discussed below. The Code's once-per-interval inspection frequency reflects an implicit conclusion by the ASME and, in imposing the Code Case, by the NRC that inlays and onlays are expected to result in effective mitigation and that inspection serves a defense-in-depth monitoring function rather than a degradation management function.

Table 1 indicates that Notes (15), (16), and (17) apply to weld inlays and onlays. A discussion of these Notes follows.

Note (15)(a) requires a volumetric examination to be performed immediately before application of inlays or onlays and after application as a preservice baseline inspection. This requirement is consistent with Section XI requirements in IWA-4000 for activities involving welding on pressure boundary components.

Notes (15)(b) and (c) indicate that if an inlay or onlay weld does not permit acceptable weld inspection coverage as defined in the paragraph -2500(c) of the Case or if the capabilities of the volumetric examination for detection, length or depth sizing are adversely affected by the inlay or onlay, the weld shall be examined as an unmitigated weld in accordance with the requirements of Inspection Items A or B. These requirements are needed to be able to monitor weld inlays and onlays and ensure they remain capable of isolating the susceptible Alloy 82/182 weld from the reactor coolant and preventing potential PWSCC from occurring in the Alloy 82/182 weld.

Notes (15)(d) requires preservice surface examination to be performed and defines the surface examination requirements and the acceptance criteria. Note (15)(e) requires preservice volumetric examination to be performed and defines the volumetric examination requirements and acceptance criteria.

The examination requirements and acceptance criteria of Notes (15)(d) and (e) draw on existing ASME Code, Section XI, rules except that rounded indications found by surface examination to be larger than 1.5 mm (1/16 in.) or 50% of the thickness of the inlay or onlay are unacceptable. The acceptance standards of NB-5352 would allow rounded indications as large as 3 mm (1/8 in.).

Note (15)(f) allows welds, with cracks that have been detected and completely removed and repaired in accordance with IWA-4000 before application of the inlay or onlay, to be reclassified as Inspection Item G or H, respectively. This note clarifies the status of welds with cracks that have been completely removed and repaired and subsequently mitigated by inlays or onlays.

Note (16) applies to inservice volumetric examination of weld inlays and onlays that reveal crack growth or new cracking. Note (16)(a) requires subsequent volumetric examinations if the cracking meets the acceptance standards of -3132.3, “Acceptance by Evaluation,” of the Case. Note (16)(b) requires surface examinations in addition to the subsequent volumetric examinations required by Note (16)(a). These surface examinations are required to be performed in accordance with Note (17). Note (16)(c) states that if examinations required by Note (16)(a) reveal that the flaws remain essentially unchanged for three successive examinations, the weld examination schedule may revert to the sample and schedule of examinations identified in Table 1. These rules are consistent with ASME Code, Section XI, requirements for subsequent examinations except that they also require a surface examination if crack growth or new cracking is revealed by a volumetric examination. Note (16)(c) also requires that if cracking penetrates beyond the thickness of the inlay or onlay, the weld shall be reclassified as Inspection Item A-1, A-2, or B, as appropriate, until corrected. This requirement is needed because loss of integrity of the inlay or onlay would expose the underlying Alloy 82/182 material to reactor coolant and the potential for PWSCC to occur.

Note (17) pertains to inservice examination requirements for surface examinations of weld inlays and onlays and provides qualification requirements and acceptance standards for surface examinations by liquid penetrant and ET. As in Note (15)(d), these examination requirements and acceptance criteria draw on existing ASME Code, Section XI, rules except that rounded indications found by surface examination to be larger than 1.5 mm (1/16 in.) or 50% of the thickness of the inlay or onlay are unacceptable. The acceptance standards of NB-5352 would allow rounded indications as large as 3 mm (1/8 in.).

The rule imposing Code Case N-770-1 (76 FR 36232) imposed conditions (F)(*1*), (2), (*4*), (*5*), (*6*), and (*7*), which apply or may apply to welds modified by inlays or onlays. The NRC imposed these conditions, which are in addition to the Code Case requirements, to ensure that, in combination with the Code Case, adequate protection is provided for monitoring Alloy 82/182 welds.

Condition §50.55a(g)(6)(ii)(F)(*1*) of the rule requires licensees of existing operating PWRs as of July 21, 2011, to implement the requirements of ASME Code Case N-770-1, subject to the conditions specified in paragraphs (g)(6)(ii)(F)(*2*) through (g)(6)(ii)(F)(*10*) by the first refueling outage after August 22, 2011. This is the basic implementing requirement imposing Code Case N-770-1 with conditions.

Condition §50.55a(g)(6)(ii)(F)(*2*) of the rule requires butt welds that rely on Alloy 82/182 for structural integrity that have been modified by inlays or onlays to be categorized as Inspection Items A-1, A-2, or B until the NRC staff has reviewed the mitigation and authorized an alternative Code Case for the mitigated weld or until an alternative Code Case Inspection Item is used based on conformance with an ASME mitigation Code Case endorsed in Regulatory Guide 1.147 with conditions, if applicable, and incorporated into 10 CFR 50.55a. This condition is intended to ensure that inlay and onlay mitigations are designed, installed, and examined in a manner that will ensure an acceptable level of quality and safety before credit can be taken for the inspection frequencies of Inspection Items G, H, J, and K, as appropriate.

Condition §50.55a(g)(6)(ii)(F)(*3*) of the rule requires that welds in Inspection Items A-1, A-2, and B, that have not received a baseline examination using Section XI, Appendix VIII requirements, shall be examined at the next refueling outage after January 20, 2012. The rule also provides provisions for when previous examinations can be credited for baseline examinations. Among other welds, this condition applies to butt welds modified by inlays or onlays that are required by §50.55a(g)(6)(ii)(F)(*2*) to be categorized as Inspection items A-1, A-2, or B.

Code Case N-770-1, paragraph -2500(c) states that, "For axial and circumferential flaws, examination shall be performed to the maximum extent practical using qualified personnel and procedures. If essentially 100% coverage for circumferential flaws (100% of the susceptible material volume) can be achieved, the examination for axial flaws shall be completed to achieve the maximum coverage practical." The NRC disagreed with this provision. Axial flaws can lead to through-wall cracks and leakage of reactor coolant, which is a safety concern. Condition §50.55a(g)(6)(ii)(F)(*4*) requires that the axial (flaw) examination coverage requirements of -2500(c) may not be considered to be satisfied unless essentially 100% coverage is achieved. This condition was added for the NRC to ensure that, through NRC review of an authorization of alternative inspection coverage, appropriate actions are being taken to address potential inspection limitations for axial flaws. The industry guidelines of MRP-139 (EPRI 2005) allow less than essentially 100% coverage in some cases. This condition of the rule applies to the examination of all inspection items, including G, H, J, and K.

Condition §50.55a(g)(6)(ii)(F)(*5*) of the rule requires all hot leg operating temperature welds in Inspection Items G, H, J, or K to be inspected each interval and supersedes the provisions of Table 1 that allow a sample inspection plan to be used. Condition §50.55a(g)(6)(ii)(F)(*5*) also requires that a 25% sample of cold leg operating temperature welds must be inspected whenever the core barrel is removed (unless it has already been inspected within the past 10 years) or has reached 20 years, whichever is less.

Condition §50.55a(g)(6)(ii)(F)(*6*) is an inservice inspection reporting requirement for mitigated welds if growth of existing flaws is found that exceeds the previous IWB-3600 flaw evaluations or if new flaws are detected. In such cases, licensees are required to provide a report to the NRC, prior to entering Mode 4, that summarizes the licensee's flaw evaluation with inputs, methodologies, assumptions, and cause of the new flaw or flaw growth. This condition applies to inlays and onlays as well as welds mitigated by other techniques. If volumetric examination detects new flaws or growth of existing flaws in the required examination volume, the mitigation will not be performing as designed and the NRC will need to evaluate the licensee's actions to address the problem. Therefore, this condition was added to verify the acceptability of the weld prior to being placed back in service.

Condition §50.55a(g)(6)(ii)(F)(*7*) of the rule applies for Inspection Items G, H, J, and K when applying the acceptance standards of the ASME Code, Section XI, IWB-3514, Standards for Examination Category B-F, Pressure Retaining Dissimilar Metal Welds in Vessel Nozzles, and Examination Category B-J, Pressure Retaining Welds in Piping. For planar flaws contained within the inlay or onlay, the thickness "t" in IWB-3514 is the thickness of the inlay or onlay. For planar flaws in the balance of the DMW examination volume, the thickness "t" in IWB-3514 is the combined thickness of the inlay or onlay and the DMW. NRC added this condition to ensure that IWB-3514 was used correctly, because other interpretations may be non-conservative.

These conditions were developed by the NRC to ensure that the level of quality and safety provided by the requirements for inlays and onlays is consistent with that provided by existing ASME Code and NRC requirements for butt welds that are not susceptible to PWSCC.

The NRC staff became aware of the concerns discussed in Section 6.3.1 on ET qualification and acceptance criteria subsequent to incorporating Code Case N-770-1 in 10 CFR 50.55a. Once these NDE reliability issues are resolved, Code Case N-770-1, with the NRC conditions on inlays/onlays, would be expected to provide an acceptable approach for monitoring potential PWSCC in inlays and onlays.

6.7 Conclusions

Based on a survey of operating experience with Alloy 82/182 butt welds, the authors did not find any instances of leaks in welds with inlays or onlays or flaws. No service-related operating experience involving inlays or onlays indicating crack growth was found, although the number of welds mitigated with inlays and onlays is small compared to the number of welds mitigated by weld overlays and MSIP and information on inspections performed did not appear to be available unless requested from each utility.

The acceptance standards in Code Cases N-770-1 and N-766 for indications detected by ET were written for PT and are not applicable to ET.

The qualification requirements for ET in Code Cases N-770-1 and N-766 were not developed for flaws as small as may occur in inlays or onlays and, because they are based on technique demonstration rather than performance demonstration, are not considered by either NRC or PNNL to be as rigorous as needed to ensure effective surface inspections are performed.

The PWROG sponsored testing to evaluate the effectiveness of current automated UT procedures applied to inner surface inspection of inlaid welds without modification of essential variables. EPRI concluded from this evaluation that the currently available UT procedures for automated inspection of welds from the ID could be used for inlaid welds and that additional qualification activities would not be needed. The results of this evaluation should also be applicable to onlay welds of similar thickness to the inlay welds tested.

ASME, Section XI, developed a revision to Code Case N-766 that was intended to address the NRC staff's concerns and other issues that need to be clarified. Nevertheless, the revision does not address either of the staff's concerns. With respect to the Code Case N-770-1 requirements on inlays/onlays, there are significant regulatory concerns on ET qualification and acceptance criteria.

ASME approved Code Case N-766, "Nickel Alloy Reactor Coolant Inlay and Cladding for Repair or Mitigation of PWR Full Penetration Circumferential Nickel Alloy Welds in Class 1 Items" on December 20, 2010, and issued it in Supplement 4 of the 2010 Edition of Section XI. The NRC staff, in accordance with ASME voting procedures, submitted a negative ballot on this Code Case. The major concerns of the staff were that the Code Case does not require a design analysis for flaw growth by PWSCC to verify adequate thickness of the inlay/onlay and the Code Case allows welds mitigated by inlays and onlays with large embedded flaws to be returned to service. Industry performed a generic PWSCC evaluation to address the first concern. ASME, Section XI is working on a revision to Code Case N-766 to address the NRC staff's concerns and other issues that may need to be clarified.

Based on a review of the requirements of Code Case N-770-1, as implemented with NRC conditions, it is concluded that the inspection requirements for inlays and onlays, except for the outstanding issues noted above on ET qualification and acceptance criteria and on inlay/onlay thickness, provide an acceptable approach for monitoring potential PWSCC. For monitoring of potential PWSCC to perform as expected before and after mitigation by inlays and onlays, the NDE being applied has to be effective and reliable.

As noted, outstanding regulatory issues associated with the implementation of inlays and onlays as a mitigation method pertain principally to analyses to verify the adequacy of the thickness of inlays and onlays and the adequacy of the NDE to be used pre- and post-mitigation. These issues will have to be resolved for the industry to obtain regulatory credit for the reduced examination frequencies in Code Case N-770-1. Assuming that effective and reliable NDE techniques are used to inspect inlays/onlays, inlays/onlays of appropriate thickness would be expected to provide effective mitigation against the growth of PWSCC into Alloy 82/182 welds to which they are attached.

7 OVERALL CONCLUSIONS

In the United States, primary water stress corrosion cracking (PWSCC) in butt welds has been found in the range of piping systems and sizes from drain lines to reactor coolant loop piping and at all Class 1 temperature conditions, including a drain line at the reactor coolant loop cold leg temperature.

Leakage to date through piping dissimilar metal butt welds that has been attributed to PWSCC has only been observed from axial cracks in unmitigated pressurizer and hot leg temperature welds.

In assessing the overall reliability of the ultrasonic testing (UT) examinations to detect and accurately characterize service-induced stress corrosion cracking (SCC), there are a number of factors that must be considered, including inspection volume coverage, the presence of interfering signals, the use of non-encoded versus encoded techniques, relative experience and skill of the examiner, use of modeling to design examination parameters, and representativeness of mockups used for performance demonstration qualifications. The use of encoded UT techniques offers a distinct and significant advantage over non-encoded techniques in detection and characterization of flaws, because of the ability to review the UT data off-line and carefully determine the origin of the signals present in the images produced.

The examination requirements of ASME Code Case N-770-1 appear to be complete and parallel existing Section IWB Class 1 requirements. For unmitigated welds the requirements reflect a philosophy of more frequent monitoring for an active degradation mechanism. Deterministic flaw growth analyses for unmitigated welds generally showed times for crack growth of initiated flaws 10% to 25% through-wall to be shorter than Code Case N-770-1 inspection intervals. Baseline examinations have been completed and, although axial cracking and axial through-wall leakage have been found, no instances of circumferential or axial PWSCC have been observed that exceeded ASME Code structural factors. While deterministic analyses indicate that Code Case N-770-1 inspection intervals may be too long, additional bases would be needed to support a modification to Code Case N-770-1 inspection intervals. Such support could arise from unfavorable results of realistic probabilistic analyses and operating experience, including results of second and later rounds of examinations. Inspection limitations can alter the effectiveness of nondestructive examination (NDE). Geometry, surface conditions, or access may limit performing complete weld examinations. Information on geometric limitations to performing inspections of typical Westinghouse and Combustion Engineering plant reactor coolant system Alloy 82/182 welds is contained in Appendices C and D. This information is applicable to unmitigated welds as well as pre- and post-mechanical stress improvement process (MSIP), pre-weld overlay (WOL) examinations, and pre-inlay/onlay examinations.

Based on information searches, no instances of leaks were identified in welds mitigated by stress improvement. However, there have been instances in which cracks have been identified in boiling water reactor (BWR) welds previously mitigated by MSIP. Clearly these cracks were present when MSIP was applied. It is unclear whether these cracks continued to grow during subsequent plant operation. Operating experience with MSIP in BWRs highlights the importance of removing weld crowns and the benefit of performing effective and reliable examinations including, for example, the use of Appendix VIII-qualified, encoded phased-array UT techniques, prior to and subsequent to the application of MSIP.

Limited pre- and post-MSIP UT data from field welds with SCC indicates that MSIP may produce a decrease in flaw length measured by UT and a loss in UT flaw response as measured by signal-to-noise ratio.

Assuming that the performance criteria of Code Case N-770-1, Appendix I, are satisfied, it is reasonable to conclude that MSIP provides effective mitigation against the initiation of PWSCC and against the growth of any existing PWSCC that has been detected and allowed to remain in service. Therefore, based on a review of the requirements of Code Case N-770-1, as implemented with NRC conditions and the evaluation of MSIP as a mitigation strategy for PWSCC by Fredette and Scott (2009), it is concluded that these requirements for MSIP provide an acceptable approach for monitoring potential PWSCC.

Based on information searches, no instances of leaks in WOL welds or flaws propagating into overlays were identified. No service-related operating experience involving WOLs indicating additional crack growth was found.

In WOL mockup testing performed by Pacific Northwest National Laboratory all targeted flaws were detected in the pre- and post-WOL condition. Pre- and post-WOL length and depth-sizing root-mean-square error for flaws greater than 50% through the original wall thickness were found to be within the ASME depth-sizing qualification acceptance criterion.

An evaluation of WOLs using the criteria of Code Case N-770-1, Appendix I, has shown it to be reasonable to conclude that WOLs provide effective mitigation against the initiation of PWSCC and against the growth of any existing PWSCC that has been detected and allowed to remain in service. Therefore, based on a review of the requirements of Code Case N-770-1, as implemented with NRC conditions and the evaluation of full structural weld overlays and optimized weld overlays as mitigation strategies for PWSCC by Fredette and Scott (2010), it is concluded that these requirements for WOLs provide an acceptable approach for monitoring potential PWSCC.

During a survey of operating experience with Alloy 82/182 butt welds, the authors did not find any instances of leaks in welds with inlays or onlays, or unexpected flaws. No service-related operating experience involving inlays or onlays indicating crack growth was found, although the number of welds mitigated with inlays and onlays is very small compared to the number of welds mitigated by weld overlays and MSIP, and information on inspections performed would not be available unless requested from each plant owner.

There are a number of issues that need to be addressed for inlays and onlays in Code Cases N-766 and 770-1 concerning embedded flaws, the adequacy of inlay/onlay thickness for the prescribed inspection intervals, and qualification requirements and acceptance criteria for examinations by eddy current testing. Once these issues are resolved, the Code Cases would be expected to provide an acceptable approach for designing, installing, and examining welds mitigated by inlays/onlays and for monitoring potential PWSCC in inlays and onlays.

For monitoring of potential PWSCC in mitigated and unmitigated welds to perform as expected, the NDE applied has to be effective and reliable.

8 REQUIREMENTS SUMMARY

This section contains a tabular summary of applicable NRC regulatory requirements, ASME Code Cases, and the regulatory status of applicable ASME Code Cases applicable to Alloy 82/182 butt welds.

Applicable Requirement	Description and Status, if Applicable
10 CFR 50, Appendix A, GDC 14	*Reactor coolant pressure boundary (RCPB)* is to be designed, fabricated, erected, and tested so as to have an extremely low probability of abnormal leakage, rapidly propagating failure, and gross rupture.
10 CFR 50, Appendix A, GDC 31	*Fracture prevention of RCPB* requires that the probability of rapidly propagating fracture of the RCPB is to be minimized.
10 CFR 50, Appendix A, GDC 32	*Inspection of RCPB* requires that components that are part of the RCPB have the capability of being periodically inspected to assess their structural and leak-tight integrity.
10 CFR 50, Appendix B, Quality Assurance Requirements, Criterion V	*Instructions, Procedures, and Drawings* requires that activities affecting quality shall be prescribed by documented instructions, procedures, or drawings of a type appropriate to the circumstances and shall be accomplished in accordance with these instructions, procedures, or drawings.
10 CFR 50, Appendix B, Quality Assurance Requirements, Criterion IX	*Control of Special Processes* requires that special processes, including nondestructive testing, shall be controlled and accomplished by qualified personnel using qualified procedures in accordance with applicable Codes, standards, specifications, criteria, and other special requirements.
10 CFR 50, Appendix B, Quality Assurance Requirements, Criterion XVI	*Corrective Action* requires that measures be established to assure that conditions adverse to quality are promptly identified and corrected.
Plant Technical Specifications	*Reactor Coolant System Operational Leakage* shall be limited to no pressure boundary leakage.
10 CFR 50.55a	*Codes and standards rule* requires that ASME Code Class 1 components meet the requirements of Section XI of the ASME Code. Section XI contains requirements for inspection, evaluation of inspection results, acceptance criteria for inspection results, repair and replacement, pressure testing, and qualification of NDE methods. Section XI inspection requirements, beyond inspection requirements of Code Case N-770-1, continue to apply for the detection of degradation mechanisms, such as fatigue. Rules for evaluation of flaws are contained in Section XI, IWB-3600 and Appendix C.
10 CFR 50.55a(b)(5)	*In-service Inspection Code Cases* incorporates by reference Regulatory Guide 1.147, Revision 16, with conditions.
Code Case N-504-4	*Code Case N-504-4* provides alternative rules for repair of Class 1, 2, and 3 austenitic stainless steel piping by weld overlay. This Code Case was conditionally accepted by the NRC in Regulatory Guide 1.147, Revision 16. NRC imposed several conditions on the use of this Code Case.

Applicable Requirement	Description and Status, if Applicable
Code Case N-638-4	*Code Case N-638-4* provides rules of similar and dissimilar metal welding using the ambient temperature machine gas tungsten arc welding temper bead technique was conditionally accepted by the NRC in Regulatory Guide 1.147, Revision 16. NRC imposed two conditions on the use of this Code Case.
Code Case N-653-1	*Code Case N-653-1* provides qualification requirements for detection and length and depth sizing for both service-induced and fabrication-induced flaws. It is applicable for wrought austenitic, ferritic, or dissimilar metal welds (DMWs), overlaid with austenitic weld material. Code Case N-653-1 has not been addressed in either Regulatory Guide 1.147 or 1.193.
Code Case N-696-1	*Code Case N-696-1* modifies the ultrasonic depth-sizing qualification acceptance criterion for piping 2.1 in. (54 mm) and greater in wall thickness, for examinations performed from the inside surface. The RMS error acceptance criterion is changed from 0.125 in. (3.18 mm) to 0.250 in. (6.35 mm).
Code Case N-740-1	*Code Case N-740-1* provides rules for DMW overlay for repair of Class 1, 2, and 3 items. The NRC found Code Case N-740-1 unacceptable for use in Regulatory Guide 1.193, Revision 3. NRC listed Code Case N-740-2 in DG-1233 (Draft Regulatory Guide 1.193, Rev. 4), *ASME Code Cases Not Approved for Use*, which was issued in June 2013. The DG states that "(w)hile Revision 2 addresses some of the NRC staff concerns, significant issues remain."
Code Case N-754	*Code Case N-754* provides rules for optimized structural DMW overlays for mitigation of PWR Class 1 items. Code Case N-754 has not been addressed in either Regulatory Guide 1.147 or the draft Regulatory Guide on inservice inspection Code Case acceptability.
Code Case N-766-1	*Code Case N-766-1* provides alternative rules for the design, installation, and examination of a weld inlay or onlay onto full penetration, nickel alloy, DMWs associated with Class 1 component nozzles and piping in PWRs. Code Case N-766-1 has not been addressed in either Regulatory Guide 1.147 or 1.193.
Code Case N-770-1	*Code Case N-770-1* contains requirements for visual and ultrasonic testing (UT) inspection of mitigated and unmitigated Class 1 Alloy 82/182 butt welds and requirements for the evaluation of the inspection results. The NRC implementing requirements and conditions on the use of Code Case N-770-1 are contained in 10 CFR 50.55a(g)(6)(ii)(F)(*1-10*).
Code Case N-773	*Code Case N-773* contains eddy current testing (ET) performance demonstration requirements that may be used in lieu of Appendix IV, Supplement 2 when ET is used to complement UT performed on the inside surfaces of austenitic, DMW, and clad piping welds.
Code Case N-824	*Code Case N-824* provides rules that may be used in lieu of the requirements of the ASME Code, Appendix III, for ultrasonically examining cast austenitic piping welds from the outside surface.

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APPENDIX A

MAJOR EVENTS AND ACTIVITIES

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A.1 Summary of Major Events and Activities

A.1.1 Introduction

Reactor coolant systems (RCSs) in pressurized water reactors (PWRs) have a number of butt welds containing Alloy 82/182 materials that are used in joining components. Welds containing Alloy 82/182 may be used in the butt welds that join ferritic vessel nozzles to stainless steel RCS loop piping. Some PWR designs may use Alloy 82/182 butt welds to connect stainless steel clad ferritic reactor coolant loop piping to stainless steel branch piping, such as emergency core cooling system piping. Operating experience has demonstrated that Alloy 82/182 materials exposed to primary coolant water (or steam) under the normal operating conditions of PWR power plants are susceptible to primary water stress corrosion cracking (PWSCC).

PWSCC in dissimilar metal butt welds was first observed in 1993 at Palisades because of a leaking circumferentially-oriented crack in an Alloy 82/182 weld that joined a stainless steel clad ferritic power-operated relief valve nozzle to an Alloy 600 safe end (NRC 1993). The Palisades event in 1993 is the only plant to date with a leaking circumferential crack determined to be PWSCC. A limit load analyses based on the circumferential crack size measured at the inner diameter (ID) resulted in a margin-to-failure of about 5 for faulted loads (Rogers 1993).

The next occurrence of PWSCC was found in 2000 because of a leaking axially-oriented crack at the V.C. Summer plant (Casto 2001; Cotton 2001).

Leaks due to axial PWSCC in butt welds have also occurred at Tsuruga, Unit 2 in Japan (NRC 2004), at Davis-Besse in 2008 (NRC 2008a), and North Anna Power Station, Unit 1 (NAPS-1) in 2012 (Anderson et al. 2012).

Indications of cracking both circumferential and axial have been found in numerous plants since 2000. Domestic and foreign operating experience with PWSCC in butt welds is contained in Appendix B to this report.

Prior to 2005, inspection of dissimilar metal butt welds was performed under the ASME Code Section XI requirements. In September 2005, the industry was provided with the final guidelines on the implementation of an industry “mandatory” initiative for inspection of Alloy 82/182 butt welds in PWRs to be performed on a more frequent basis than the inspections required by the ASME Code (Hartz 2005). This initiative was developed by the industry Materials Reliability Program (MRP) and is documented in MRP-139, “Primary System Piping Butt Weld Inspection and Evaluation Guideline,” Electric Power Research Institute (EPRI) Report 1010087 (EPRI 2005). MRP-139 was issued under the implementation protocol of Nuclear Energy Institute (NEI) 03-08 (discussed below) as an industry mandatory initiative. MRP-139 provided industry guidance for the volumetric and visual inspections of butt welds in PWR primary systems, which augmented the inspections of these locations that were already required by Section XI of the ASME Code.

In about 2005 industry began to mitigate welds by techniques such as weld overlays and the mechanical stress improvement process (MSIP). MRP-139 specifies inspection intervals for mitigated welds that are longer than the intervals specified for unmitigated welds and provides for sample inspections of mitigated welds. MRP-139 also specified schedules for plants to complete baseline inspections of all Alloy 82/182 welds within the scope of MRP-139 based on system temperature and pipe diameter.

The U.S. Nuclear Regulatory Commission (NRC) staff reviewed the MRP-139 inspection program and provided comments to industry on its safety concerns in Mayfield (2005). One of the most important concerns the NRC staff raised dealt with MRP-139 not "requiring" volumetric inspections for piping less than 4-inches nominal pipe size (NPS). By issuing MRP-139: Interim Guidance, MRP 2007-038, on November 1, 2007, the MRP modified the MRP-139 guidelines to specify that Alloy 82/182 butt welds greater than or equal to 2-inches NPS but less than 4-inches NPS and either exposed to temperatures equivalent to the hot leg or serve an Emergency Core Cooling System function (e.g., Babcock & Wilcox [B&W] High Pressure Injection nozzles) will be volumetrically inspected (King 2007). A complete listing and brief explanation of the MRP responses to the NRC staff's concerns is contained in slides presented during a meeting between the EPRI MRP and the NRC staff held on February 21, 2008 (Kammerdeiner 2008).

EPRI issued MRP-139, Revision 1, in 2008, EPRI Report 1015009 (EPRI 2008a) to address concerns raised by industry in the implementation of MRP-139 and to address some of the concerns the NRC staff raised. The MRP-139 ultrasonic testing (UT) baseline inspection schedules were revised by MRP-139, Revision 1, to specify that Alloy 82/182 welds were to be completed per the following schedule:

- By December 31, 2007, all Alloy 82/182 butt welds greater than or equal to 2-inches NPS associated with the pressurizer and exposed to pressurizer-like temperatures will be volumetrically inspected per this guideline (includes B&W pressurizer safety relief valve nozzle welds). Note that this applies to surge line nozzle welds near the pressurizer because of the potential for fatigue synergy.
- By December 31, 2008, Alloy 82/182 butt welds that are greater than or equal to 4-inches NPS and less than or equal to 14-inches NPS and exposed to temperatures equivalent to the hot leg will be volumetrically inspected per this guideline. This implementation schedule also applies to the surge line nozzle weld at the hot leg and to the B&W makeup/high pressure injection nozzle weld.
- By December 31, 2009, Alloy 82/182 butt welds that are greater than 14-inches NPS and exposed to temperatures equivalent to the hot leg will be volumetrically inspected per this guideline.
- By December 31, 2010, Alloy 82/182 butt welds greater than or equal to 4-inches NPS that are exposed to temperatures equivalent to the cold leg will be volumetrically inspected per this guideline.

The NRC staff monitored industry's implementation of MRP-139 through NRC regional inspections conducted under Temporary Instruction (TI) 2515/172, "Reactor Coolant System Dissimilar Metal Butt Welds," which the NRC issued in 2008 (NRC 2008b). This TI was revised in May 2010 (NRC 2010c) and expired at the end of June 2011. The regional inspection reports for TI 2515/172 were issued in integrated inspection reports for each plant.

The industry actions to develop and implement the MRP-139 inspections allowed the NRC staff to pursue a process to codify requirements involving all stakeholders. The NRC concluded that the approach of working with ASME to revise inspection requirements and subsequently revise 10 CFR 50.55a was both necessary and in the best interest of protecting public health and safety (NRC 2008a).

The ASME Code inspection requirements, incorporated by reference in 10 CFR 50.55a, provide a regulatory foundation for ensuring the integrity of pressure-retaining components. The NRC concluded that the current ASME Code requirements for inspection of Alloy 82/182 butt welds are not frequent enough to ensure that ASME Code-allowable limits will continue to be met in the event that PWSCC initiates. This conclusion was based on MRP-55 and MRP-115 crack growth rates (discussed below) developed by the EPRI/MRP and on the ASME Code maximum flaw depth allowable limit of 75% through-wall. This issue was addressed in the short term by the MRP-139 examinations. However, the NRC concluded that the ASME Code requirements needed to be revised to provide a regulatory framework for ensuring that ASME Code-allowable limits would not be exceeded, leakage would not occur, and potential flaws would be detected before they challenged the structural or leakage integrity of piping welds. The NRC concluded that utility commitments to the industry initiative, MRP-139, would not provide a sufficient regulatory foundation for the long term (NRC 2008a).

In December 2005, the NRC sent a letter to ASME (Dyer 2005) requesting that the Section XI standards body address the inspection requirements for Class 1 PWR piping butt welds fabricated with Alloy 82/182 weld materials. In 2006 ASME approved the development of an ASME Code Case (Code Case N-770) on appropriate inspection requirements to address PWSCC in Class 1 butt welds containing Alloy 82/182 (Balkey 2006). ASME Code Case N-770 was approved by ASME on January 30, 2009, and was published in Supplement 8 of the 2007 Edition of the ASME Boiler and Pressure Vessel Code Nuclear Code Cases book. The title of ASME Code Case N-770 is "Alternative Examination Requirements and Acceptance Standards for Class 1 PWR Piping and Vessel Nozzle Butt Welds Fabricated with UNS N06082 or UNS W86182 Weld Filler Material With or Without the Application of Listed Mitigation Activities, Section XI, Division 1" (ASME 2009b).

Code Case N-770 was revised in response to a number of issues raised by the NRC. Code Case N-770-1 (ASME 2009a) was approved by the ASME in December 2009. On June 21, 2011, the NRC issued a final rule (76 FR 36232, p. 36278) incorporating ASME Code Case N-770-1 into the regulations by reference. The new rule is contained in 10 CFR 50.55a(g)(6)(ii)(F) and imposes Code Case N-770-1 with ten conditions the NRC concluded were necessary to ensure that these welds are appropriately monitored and assessed over their design life. This Code Case and the conditions imposed by the NRC in 10 CFR 50.55a(g)(6)(ii)(F) are discussed in detail in Chapters 3–6 of this report.

The sections that follow discuss each of the major events involving PWSCC in primary system Alloy 82/182 butt welds and other significant industry and regulatory activities related to PWSCC in butt welds.

A.1.2 V.C. Summer

On October 7, 2000, during a normally scheduled containment inspection after entering a refueling outage, the licensee for V.C. Summer Nuclear Power Station identified a circumferential indication of PWSCC in the first weld between the reactor vessel nozzle and the ‘A’ loop RCS hot leg piping. Specifically, the licensee found more than 200 pounds of boric acid crystals on the containment floor and protruding from the air boot around the ‘A’ loop RCS hot leg piping. Further examinations revealed a short through-wall crack in the hot leg nozzle safe end weld, approximately 0.9 m (3 ft) from the reactor vessel. Eddy current testing (ET) testing also identified similar small indications on the ID of four of the other five nozzle-to-pipe welds. The NRC issued Information Notice 2000-17 on October 18, 2000 (NRC 2000b) and supplemented the Information Notice on November 16, 2000 (NRC 2000a). The weld through-wall cracking was attributed to high residual stresses generated by extensive repairs made to this weld during fabrication. The reactor vessel nozzles at V.C. Summer are welded directly to reactor coolant piping, without safe ends. The hot leg and cold leg reactor vessel to piping welds were fabricated in the field (Casto 2001).

The licensee added a new section of stainless steel pipe with Alloy 52/152 welds to replace the 30.5-cm (12-in.) section of the hot leg pipe containing the leaking weld. The licensee performed an analysis of the weld indications found by inspection in the Loops ‘B’ and ‘C’ RPV hot leg nozzle welds and concluded from the analysis that the plant could be safely operated for a period of at least three years (Bamford et al. 2000). Hence, the licensee proposed to operate for two refueling cycles. The NRC staff performed an independent analysis of the flaws found by the licensee and determined that the licensee’s request for two fuel cycles of operation was not justified (Cotton 2001). The NRC concluded that the unit could be operated with ET indications in its Loops ‘B’ and ‘C’ RPV hot leg nozzle welds for one fuel cycle, at which time the weld indications would be re-examined. MSIP was subsequently applied to the Loops ‘B’ and ‘C’ RPV hot leg nozzle welds during Refueling Outage 13 (Stuart 2002).

In response to this event, the NRC formed a Special Inspection Team to determine the adequacy of the licensee's previous inspection, confirm that the licensee had completed an analysis and examination to determine the root cause, and review the overall corrective action plan and the extent of the condition. Through that Special Inspection Team, the NRC identified potentially generic issues involving limitations of required nondestructive examinations to detect certain small inside-diameter stress-corrosion cracks, and the potential for multiple weld repairs to result in high residual stresses, which can contribute to stress-corrosion cracking (Casto 2001).

In a letter dated December 14, 2000, the Nuclear Energy Institute informed the NRC that the Materials Reliability Project intended to lead the industry's actions to address the generic implications of the cracking experienced at V.C. Summer (Modeen 2000).

A.1.3 Wolf Creek

On October 13, 2006, the Wolf Creek Nuclear Operating Corporation performed pre-weld overlay UT inspections on the surge, spray, relief, and safety nozzle-to-safe end dissimilar metal and safe end-to-pipe stainless steel butt welds. The inspection identified five circumferential indications in the surge, relief, and safety nozzle-to-safe end dissimilar metal (DM) butt welds that the licensee attributed to PWSCC (Garrett 2006) and that were significantly larger and more extensive than previously seen in the industry (NRC 2007).

During a public meeting with the industry on December 20, 2006 (Mensah 2007), the NRC staff presented the results of a fracture mechanics-based scoping study that assessed the safety significance of the UT indications found at Wolf Creek. As a result of these analyses (Rudland et al. 2007a), the NRC staff concluded that there may be little or no time margin between the onset of leakage and rupture in pressurizer nozzle DM butt welds containing flaws similar to those found at Wolf Creek.

Over the course of many NRC staff discussions, the staff considered a number of options to assess what regulatory action to take to address this issue. The staff concluded that licensees needed to complete inspections or mitigations of the pressurizer nozzle Alloy 82/182 welds by the end of 2007 and implement interim enhanced leakage monitoring. This decision was based on the judgment that completing the actions by the end of 2007 would provide an appropriate balance of restoring safety margins within a time frame that would avoid compromising weld and inspection quality without placing undue reliance on the compensatory measure of enhanced leakage monitoring. A discussion of the risk-informed process used to recommend this decision is documented in Evans (2007c).

In March 2007, the NRC issued Confirmatory Action Letters (CALs) to 40 licensees with PWRs, confirming commitments from those licensees to resolve concerns regarding potential flaws in specific RCS Alloy 82/182 butt welds by performing inspections by the end of 2007. One example of the CALs issued was the CAL sent to Seabrook Station dated March 12, 2007 (Dyer 2007a). The remaining 29 PWR plants had either completed the requisite actions or do not have welds susceptible to these flaws (Evans 2008b).

Nine of the plants receiving CALs did not have outages scheduled in 2007. These plants committed to accelerate outages into 2007 if the industry was not able to demonstrate an adequate level of safety to the NRC. The nine plants were Braidwood 2, Comanche Peak 2, Diablo Canyon 2, Palo Verde 2, Seabrook, South Texas Project 1, V.C. Summer, Vogtle 1, and Waterford 3) (Evans 2008b).

By letter dated February 14, 2007, the Nuclear Energy Institute informed the NRC staff that the EPRI MRP would be undertaking a task to refine the crack growth analyses pertaining to the Wolf Creek pressurizer dissimilar metal weld (DMW) ultrasonic indications (Thayer 2007). These studies would reduce unnecessary conservatisms and address some of the uncertainties in previous analyses (Thayer 2007). In a response to the letter from Thayer (2007), the NRC staff indicated that results from the proposed improved modeling will be useful for regulatory purposes provided several areas of uncertainty and potential non-conservatism are also addressed (Dyer 2007b). A discussion of the NRC staff's concerns in the areas of uncertainty and potential non-conservatism is contained in the enclosure to Dyer (2007b). These refined crack growth analyses were referred to as advanced finite element analyses (AFEA) and were performed to address the NRC staff's concerns regarding the potential for rupture without prior evidence of leakage from circumferentially-oriented PWSCC in pressurizer nozzle welds. The goal of the AFEA was to demonstrate that PWSCC in pressurizer DM butt welds would progress through-wall and exhibit detectable leakage prior to causing a possible rupture event.

Industry took a two-phase approach to the AFE analyses. The Phase-I effort was conducted to establish the feasibility of using these uniquely developed crack growth codes by re-analyzing the critical case from the NRC staff's scoping analysis (Rudland et al. 2007a). The NRC staff transmitted concerns with the Phase-I effort in a letter to NEI from Evans (2007a). The Phase-II effort was conducted to assess the pressurizer nozzle integrity of the nine PWRs through over a hundred sensitivity cases by varying nozzle-specific loads, dimensions, geometries, weld residual stresses, PWSCC crack growth rates, initial flaw assumptions, and other parameters.

Industry completed these analyses and documented the results in MRP-216, Revision 1, "Advanced FEA Evaluation of Growth of Postulated Circumferential PWSCC Flaws in Pressurizer Nozzle Dissimilar Metal Welds: Evaluations Specific to Nine Subject Plants" (EPRI 2007a). MRP-216, Revision 1, concluded that PWSCC in pressurizer DM butt welds of the nine plants analyzed would progress through-wall and exhibit detectable leakage prior to causing a possible rupture event. These results were provided to the NRC staff by letter dated August 13, 2007 (Marion 2007).

The NRC's evaluation of MRP-216, Revision 1, concluded that there is reasonable assurance that the nine plants addressed by this evaluation would be able to operate safely until their next scheduled refueling outages in the spring of 2008. The NRC's safety assessment (NRC 2007) was transmitted to C. Haney, Director of the NRC Office of Nuclear Regulatory Research Division of Licensing, by a memorandum from Evans (2007b). This safety assessment provides the basis for notification letters sent to the licensees of the nine plants planning to inspect the pressurizer nozzle dissimilar metal butt welds in the spring of 2008. This safety assessment is supported by a report that contains the NRC staff's independent confirmatory analyses performed by the NRC Office of Nuclear Regulatory Research (Rudland et al. 2007b) . The NRC staff's independent analyses enabled the staff to perform an in-depth review and critique of the industry's analyses and to extend the industry's analyses in some key respects.

A.1.4 Davis-Besse

On January 4, 2008, while Davis-Besse was in cold shutdown with the reactor head in place and fuel in the reactor vessel, the licensee began to install a weld overlay on the decay heat removal drop line-to-RCS nozzle weld (NRC 2008a). This weld is located inside containment. The RCS was in a drained condition. During the first weld pass on the drop line weld, the welding operator noticed water seeping from the weld. Visual inspection revealed a small leak. Surface examinations before welding showed no abnormal conditions or leakage. The licensee subsequently determined that the leak was from an axial through-wall flaw that the licensee attributed to PWSCC. The licensee applied a full structural weld overlay (FSWOL) to this weld.

A.1.5 Inspection of a Retired Pressurizer

In mid-February 2008, the NRC staff received the results of initial inspections of the nozzles of a retired pressurizer. These initial inspections were provided in MRP 2008-012 (King 2008c) . This pressurizer was removed from service to eliminate the possibility of extended plant outages resulting from cracking associated with the heater sleeves and replaced with a new pressurizer fabricated with materials with increased resistance to PWSCC. The pressurizer was donated to NRC for research purposes and the inspections were performed by EPRI to assist in determining the research value of the nozzle welds. These inspections found indications by dye penetrant (PT) and manual-phased array ultrasonic examination (UT). Circumferential and axial indications were found in five of six nozzles. The nozzle welds of most interest were the three safety nozzles. The inspection concluded that these nozzles had 360°, circumferentially-oriented indications with non-uniform depths around the circumference. The deepest indications found were sized at 89% through-wall on the ‘A’ safety nozzle. The deepest indication found in the ‘B’ and ‘C’ safety nozzles were 75% and 69% through-wall, respectively.

Based on this information, NRC staff determined that the inspection results needed to be evaluated against the AFEA work the staff completed in September 2007 because the AFEA formed the basis for the continued operation of plants with pressurizer welds that had not yet been inspected, as mandated by industry guidelines. To help perform such an evaluation, the NRC staff requested that EPRI estimate the flaw profile for safety nozzle ‘A’ and provide some of the raw UT signals recorded during the inspection. EPRI provided this information to the NRC staff by letter MRP 2008-014, dated March 4, 2008 (King 2008a). EPRI estimated that the ‘A’ safety nozzle weld contained a continuous deep indication 360° around the circumference. This reported flaw profile was more severe than any of the predicted flaws in the above-referenced advanced finite element analyses that led to leakage that would be detected with sufficient time for plant shutdown prior to rupture. The flaw profile caused NRC staff to question whether the AFEAs would still support the spring 2008 pressurizer inspection schedules.

In making a regulatory decision to address the retired pressurizer nozzle weld inspection results in MRP 2008-012, the NRC staff considered three options. Option 1, the base case, would result in no change to existing regulatory and industry programs; that is, the affected plants would operate until their scheduled spring 2008 outage and inspect or mitigate the affected welds at that time. Option 2 would allow continued operation of the plants for a short time period while NRC staff gathered additional information. Option 3 would require all affected plants to shut down immediately and not restart until the basis for operation was reestablished or until inspection or mitigation activities were completed. The NRC staff based its regulatory decision on an assessment of the pros and cons of these options using the principles of risk-informed decision making.

On March 7, 2008, the NRC staff concluded that Option 2 was the appropriate decision; the staff judged that it had an appropriate basis to take a short period of time (e.g., within a week) to gather information to make a more informed decision. The initial inspection results were somewhat uncertain given that they were manual inspections with no recorded UT data. More refined inspection was judged to be prudent to reduce uncertainty regarding the results of the initial inspections. The NRC staff determined that the questions raised as a result of its review of the March 4, 2008, EPRI letter (King 2008a) were safety-significant questions and the NRC staff had verbally informed industry executives that it was considering regulatory action. A discussion of the risk-informed decision making process used to recommend Option 2 is documented in Evans (2008a).

Industry representatives took actions to rapidly put in place a comprehensive inspection effort that consisted of more advanced UT examinations, specifically ASME Code, Section XI, Appendix VIII-qualified encoded phased-array and radiographic testing (RT) examinations, followed a few days later by eddy current testing (ET) examinations. These inspections commenced on March 8, 2008, at the Studsvik-RACE facility in Memphis, the location of the nozzles from the retired pressurizer (Evans 2008b).

On March 9, 2008, an NRC inspector from Region I, and an expert in nondestructive examination (NDE) from PNNL, arrived at the Studsvik-RACE facility in Memphis. These NRC representatives immediately began auditing the weld inspection activities by the industry. Their audit included review of the UT inspection procedure, adherence to the UT procedure by the industry inspectors, the validity of the qualification of the inspection procedure by the Performance Demonstration Initiative (PDI) to ASME requirements, and evaluation of the UT inspection data. Their audit report also addressed the ET examinations performed on the inside surface of the safety nozzles. The inspectors concluded that the UT procedure was a qualified procedure with one exception that EPRI subsequently addressed. The NRC representatives verified that the industry inspectors followed the requirements of the UT procedure (Evans 2008b).

As recommended in the March 4, 2008, letter from EPRI (King 2008a), EPRI concluded that a PDI-qualified automated phased-array UT (PAUT) technique would provide a more accurate profile of any potential degradation in the welds than a PDI-qualified manual PAUT technique. The NRC staff agreed with this conclusion. Phased-array ultrasonic inspection is a good technique for detecting critical flaws especially in welds with limited access and difficult microstructures. As with conventional manual UT, with manual phased-array ultrasonics the inspector is physically scanning the weld while looking at the equipment screen and doing data evaluation in real time. Although screen shots of areas of interest can be recorded, all data analysis is done simultaneously with the manual UT scanning. In comparison with encoded PAUT examination, the weld is scanned and a full set of position encoded ultrasonic data is recorded. This means that the equipment is recording everything that the inspector performing the manual scan was seeing, but each ultrasonic waveform is recorded along with the position information. This is a critical difference between the two methods in that the inspector can go back and carefully process and review the data and create a set of images that enable clearer interpretations of the data. These images include "B," "C," and "D" scans where the "B" scan shows a projected side view of the weld, the "C" scan shows a projected top view of the weld, and the "D" scan shows a projected end view of the weld. In all three views, the software can project a more three-dimensional-like profile of the weld on top of the ultrasonic data so that using these views, the inspector can easily visualize and analyze the data (locate and size flaws in the material). Thus, the ability of the encoded PAUT inspection to provide accurate representations of any flaws in the inspection volume and to characterize indications is superior to that of the manual PAUT inspection (Evans 2008b).

The automated PAUT examinations began on the evening of Saturday, March 8, 2008, and continued into the following week. Each of the St. Lucie pressurizer safety nozzle dissimilar metal welds was inspected.

On March 13, 2008, EPRI provided to the NRC the draft automated PAUT examination results summary. This document stated, in part, that the retired pressurizer safety nozzle welds 'A,' 'B,' and 'C' had multiple embedded fabrication flaws. This document concluded that these fabrication flaws were attributed to slag, porosity, and/or lack of fusion. Also, these indications were found to be clustered as well as individual fabrication flaws. The document discussed that the ET examination identified several small circumferentially-oriented linear indications in safety nozzle weld 'A' located at intermittent circumferential weld positions which appear to originate in the weld near the weld-to-austenitic base material interface (on the opposite side of the weld to the buttering). There was also an indication from a machining flaw due to a fabrication boring operation done from both the vessel ID and the safe end. The boring operations were not aligned properly and resulted in an eccentric step. The indication from the eccentric step could be confused with a root signal, but it was about an inch away from the actual weld root. This eccentric step was confirmed by ET during the reexamination process and demonstrated to the PNNL NDE expert who observed the reexamination activity.

Based on the UT results, the EPRI document concluded that the inspection identified no flaws within the welds that were connected with the surface (Evans 2008b). The final report on the nondestructive examination summary of retired pressurizer safety nozzles was provided to the NRC staff on March 19, 2008 (King 2008b). This document concluded, in part, based on the results of the volumetric and surface examination methods employed that the pressurizer nozzle welds contain benign fabrication defects, but no specific indication of stress corrosion cracking. The final version of the summary reports was reviewed and determined to be essentially identical to the draft reports reviewed previously. In support of this document on March 13, 2008, EPRI provided a series of UT scans of the inspection data for independent NRC staff and contractor interpretation on site in Memphis (Evans 2008b).

NRC staff completed its review of the encoded PAUT results. The NRC staff found that there was sufficient data available to provide reasonable assurance that there were no structurally significant service-induced flaws within the retired pressurizer safety nozzle welds 'A,' 'B,' and 'C.' The NRC found that (1) the assumption made in the development of the manual flaw profile that the stacked indications identified in EPRI Letter 2008-012 were connected to the surface and (2) the determination that the flaw profile provided in EPRI letter MRP 2008-014 was potentially due to service-induced cracking, while conservatively based on the data available, were not supported by the evaluation of the encoded phased-array UT data (Evans 2008b). The NRC concluded that the AFEAs supported the continued operation of the nine plants beyond December 31, 2007, to their respective spring outages. Letters were sent to each operating PWR that had not yet completed inspections of the pressurizer safety valve Alloy 82/182 welds informing them of the NRC's decision. One example of the letters issued was the letter sent to Braidwood Station, Unit 2, dated March 14, 2008 (Haney 2008).

Upon completion of the nondestructive examinations, the portion of the 'Safety A' nozzle containing the DMW was removed and sent to a laboratory for destructive examination to verify the NDE results. The destructive evaluation confirmed the indications and flaws found within the retired pressurizer safety ‘A’ nozzle are fabrication defects with no evidence of PWSCC. The destructive evaluation confirmed the intermittent circumferentially-oriented linear indications identified by ET and showed these to be fabrication hot tears, including one which was depth-sized at approximately 17% through-wall. The flaws were confirmed to be non-safety significant and did not challenge the structural integrity of the component (Weakland 2008).

A.1.6 North Anna Power Station, Unit 1

During a spring 2012 inservice inspection of an Alloy 82/182 weld in an inlet (hot leg) steam generator nozzle at NAPS-1, several axially-oriented flaws were not detected by the licensee’s manual UT technique. The flaws were subsequently detected as a result of outer-diameter (OD) surface machining in preparation for a full structural weld overlay. The machining operation uncovered the existence of two through-wall flaws, based on the observance of primary water leaking from the DMW. Further ultrasonic tests were then performed, and a total of five axially-oriented flaws, classified as PWSCC, were detected in varied locations around the weld circumference (Anderson et al. 2012).

The North Anna hot leg safe end-to-nozzle weld configuration has an approximate 11° OD taper from the thinner austenitic piping side up to the thicker carbon steel nozzle, and is typical of a DMW created during steam generator replacement at Westinghouse-designed plants. However, the level of OD taper exhibited by this particular design is not included as a blind performance demonstration mockup used by the industry’s PDI, which is administered by EPRI. For this reason, the licensee engaged EPRI to assist in the development of a technical justification to support the basis for a site-specific qualification (Anderson et al. 2012).

The NRC Office of Research requested PNNL to assess the manual UT technique that was applied at North Anna, and evaluate potential causes for the failure of the examination to detect these significant flaws. The purpose of the PNNL assessment was to provide insights as to the nature of the event and provide a technical basis for regulatory consideration (Anderson et al. 2012).

To accomplish these objectives, PNNL was asked to perform the following activities:

- Model the acoustic performance of the manual UT probe arrangement used at North Anna to analyze its potential to detect inside diameter (ID) surface-connected, axially-oriented flaws, given predicted sound field characteristics;
- Visit the North Anna site to evaluate the actual probe and UT responses produced from site-specific DMW flaw mockups; and
- Assess the licensee’s technical justification, developed by EPRI, for qualification acceptance of the manual technique that was applied (Anderson et al. 2012).

PNNL determined from ultrasonic modeling of the specific probe parameters for the manual examinations employed on the subject DMW configuration at North Anna that insufficient acoustic energy would be available near the inner surface of the weld to assure detection of ID surface-connected axially-oriented flaws. These results further suggested inadequate performance for manual, real-time examinations to properly discriminate and characterize surface-connected flaws from other welding or metallurgical features in the inner one-third of the weld volume on these DMWs. This finding was corroborated by site observations that showed low signal-to-noise ratio (SNR) for the targeted mockup flaws in the presence of spurious indications that interfere with detection and classification of simulated ID-connected cracks. PNNL found the technical justification developed to extend PDI qualifications to the North Anna steam generator Alloy 82/182 welds to be inadequate to make a reasonable case for using the manual, non-encoded procedure that was employed (Anderson et al. 2012).

As a follow-on effort, Anderson et al. (2014) addressed remaining technical questions and issues that were raised during the first evaluation process. Anderson et al. (2014) assesses the failure of the licensee's applied UT technique to detect multiple flaws, describes subsequent studies conducted, and provides final results and conclusions. Conclusions from this follow-on effort include the following:

- The data acquired on the mockups show, in some cases, that weld fabrication and flaw implantation signal responses are higher in amplitude than nearby implanted target flaws. These conditions render assessments (detections) of flaw signal responses in the presence of such ambient noise highly improbable when using a manual non-encoded UT technique.

- Based on site observations and laboratory measurements of UT responses from the flaws and other artifacts during examinations conducted by PNNL on the mockups, one would not expect the manual, non-encoded technique employed to consistently detect axial flaws (with low numbers of false calls) without examiners having prior knowledge of where these flaws are located.

- The PNNL assessment of the EPRI NDE Center-developed Technical Justification supporting the manual ultrasonic examination demonstration at NAPS-1 shows that essential variables were changed, which contradict the requirements of Appendix VIII.

- The work conducted in assessing non-encoded and encoded examination techniques on the mockups indicates that encoded scans not only provide enhanced detection rates, but also allow for post-analysis and diagnosis of issues as well as appropriate oversight of examination records.

PNNL findings suggest that employment of a site-specific approach for an examination must have a solid technical basis to support the methodology and this basis would need to be rigorously and systematically developed in order to meet the intent of Appendix VIII. As a result of the PNNL findings, industry committed in a meeting on July 20, 2012, to take a broad look at the NAPS-1 and other operating experience, and work to understand its impact and determine the appropriate industry corrective actions. An initial action by industry was the formation of the NDE Improvement Focus Group (NIFG). The NIFG efforts focused on DMWs where site-specific mockups have been used and non-encoded examinations conducted.

In 2013, the Electric Power Research Institute published the following reports to provide guidance for nuclear power plant owners with respect to improving the reliability of NDE. These reports are available from the EPRI website.

- *Nondestructive Evaluation: Guideline for Conducting Ultrasonic Examinations of Dissimilar Metal Welds, Revision 1*, EPRI Report 3002000091 (EPRI 2013a), and
- *Nondestructive Evaluation: Performance Demonstration Initiative (PDI) Guidance for Improved Reliability in Ultrasonic Examinations – Guideline for Hands-on Practice PDI-GL-001 Revision B, Site Specific Mockup Requirements for Dissimilar Metal Welds*, EPRI Report 3002000204 (EPRI 2013b).

These reports include:

- Performance Demonstration Initiative (PDI), Site Specific Configuration Mockup Requirements for Dissimilar Metal Welds, Revision C; and
- Guidelines for the Application of Team Scanning for Ultrasonic Examination of Dissimilar Metal Welds (DMW).

NIFG requested that NRC staff review these guidance documents. The NRC staff provided comments to NIFG on these guidance documents, and these comments were discussed with NIFG prior to NIFG's issuance of these two reports. It appeared that NIFG chose not to address the NRC staff comments by revising the guidance documents. This matter was discussed during a public meeting held on January 8–9, 2014 (Hardies 2014). As an action item from the January 2014 meeting, NIFG requested the NRC staff to formally transmit their comments by letter to NIFG. The NRC staff's comments were transmitted to NIFG by letter to the industry MRP NDE Integration Committee dated June 9, 2014 (Lupold 2014). The NRC staff noted in this letter that it believes that these comments are substantive and necessary to improve the performance of NDE when using either site-specific mockups or team scanning. The NRC staff also requested that the NDE Integration Committee provide a response to these comments. At the time of issuance of this report, the NDE Integration Committee had not provided a response to the NRC staff's comments.

A.1.7 Other Significant Industry and Regulatory Activities

Industry and regulatory activities such as the development of MRP-139 and ASME Code Case N-770-1 and its codification in 10 CFR 50.55a were discussed in the Introduction to this appendix. The following paragraphs discuss other significant activities that have taken place related to management of PWSCC in butt welds.

A.1.7.1 NEI-03-08, Guideline for the Management of Materials Issues

In May 2003, the industry adopted an initiative on materials management and issued Nuclear Energy Institute (NEI) 03-08, "Guideline for the Management of Materials Issues" (NEI 2003). The industry initiative and the associated NEI 03-08 guidance document established policy, direction, oversight, and support for industry programs involving the management of materials issues. The initiative committed each nuclear utility to adopt the responsibilities and processes described in NEI 03-08.

Through the activities described in NEI 03-08, the industry stated that it would ensure that its management of materials degradation and aging would be forward-looking. In addition, the industry stated that it would continue to rapidly identify and effectively respond to emerging issues and would emphasize safety and operational risk significance. Guidelines developed for power plant licensees under NEI 03-08 address assessment, inspection, repair, mitigation, replacement, and regulatory interface.

A.1.7.2 MRP-55 and 115, Crack Growth Rate Studies

The incidence of PWSCC of Alloy 600 components in the PWR RCS highlighted the need for qualified equations for crack growth rates (CGRs) to evaluate flaws found by inservice inspection of thick-walled parts, including welds. In 2002, the MRP developed CGRs for PWSCC of thick-wall components fabricated from Alloy 600 base material, such as reactor vessel head nozzles. The Alloy 600 CGR were issued in MRP-55 (EPRI 2002).

In 2005, EPRI issued MRP-115NP (EPRI 2004b) to extend the MRP-55 work to cover crack growth rates in Alloy 82/182/132 welds.

The CGRs of MRP-55 and MRP-115 were incorporated into the 2010 Edition of Section XI of the ASME Code in Non-mandatory Appendix C, Section C-8500, "Stress Corrosion Cracking Growth Rate." The current Codes and Standards rule, 10 CFR 50.55a, incorporates by reference the ASME Code through the 2008 Addenda of Section XI. The 2010 Edition of the ASME Code Section XI, with possible conditions on the use of Section C-8500 SCC CGRs for PWRs, will be address in a future NRC rule.

A.1.7.3 MRP-169, Technical Basis for Preemptive Weld Overlays for Alloy 82/182 Butt Welds in PWRs

By letter dated September 7, 2005, the NEI submitted Topical Report (TR) Materials Reliability Program: Technical Basis for Preemptive Weld Overlays for Alloy 82/182 Butt Welds in Pressurized Water Reactors (MRP-169), Revision 0, to the NRC staff for review (Marion 2005). Information on meetings between industry and NRC staff on the review of MRP-169, correspondence related to the NRC staff's requests for additional information, and responses to those requests, including a revision to MRP-169 is provided in Blount (2010).

TR MRP-169, Revision 1, provides the technical basis for the design, analyses, and inspections of the FSWOL and optimized weld overlays (OWOL) in PWRs (EPRI 2008b). The weld overlays are used to repair degraded nickel-based Alloy 82/182 DMWs or piping components made of Alloy 600 material by depositing weld metal on the outside surface of the welds and piping components. In addition, the overlays may be used as a preemptive measure to mitigate PWSCC.

Various aspects of TR MRP-169 are discussed in Chapter 5 of this report, in particular Sections 5.2, WOL Design Requirements; 5.3.1, Inspection of Dissimilar Metal Weld Overlay Specimens; 5.5, Status of ASME Code Cases N-740-X, "Full Structural Dissimilar Metal Weld Overlay for Repair or Mitigation of Class 1, 2, and 3 Items, Section XI, Division 1," and N-754, "Optimized Structural Dissimilar Metal Weld Overlay for Mitigation of PWR Class 1, Section XI, Division 1; and 5.6, Assessment of ASME Code Case N-770-1 Inspection Requirements. The details of the NRC's safety evaluation of MRP-169 are contained in Blount (2010).

The NRC's safety evaluation of MRP-169 concluded, in part, that:

> "MRP-169, Revision 1, as revised by letter dated February 3, 2010 (Riley 2010), adequately describes the methods for the weld overlay design, the supporting analyses of the design, the experiments that verified the analyses, and the inspection requirements of the overlaid DMWs. The design of the FSWOL and OWOL follows the intent of the acceptance standards of the ASME Code, Sections III and XI. The effect of the weld overlay on the residual stress benefits has been demonstrated by the analysis and verified by the laboratory experiments with mockups.
>
> "The ASME Code, Section XI has not yet included requirements for the weld overlay application, and the NRC staff has not yet approved ASME weld overlay Code Cases N-740-2 and N-754 in 10 CFR 50.55a via Regulatory Guide 1.147. Therefore, licensees planning to install an FSWOL or an OWOL on DMWs need to request relief from the ASME Code requirements before overlay installation. Licensees may reference TR MRP-169 in their weld overlay relief request as the technical basis for the weld overlay design…. The NRC staff concludes that MRP-169 has provided an adequate technical basis to demonstrate that the DMW overlaid with either the FSWOL or the OWOL will provide reasonable assurance that the structural integrity of the piping system will be maintained to perform its intended function. Therefore, the NRC staff approves the use of MRP-169."

A.1.7.4 MRP-317, Welding Residual Stress Dissimilar Metal Butt-Weld Finite Element Modeling Handbook

In October 2009, the 10-year inservice inspection at Seabrook identified an axial indication in the DMW at one of the reactor outlet nozzles at 158°. The axial indication did not meet the acceptance standards of IWB-3514. An analytical evaluation was performed by the licensee per IWB-3640 to demonstrate how long the as-found flaw could be left in service before repair was required. The analysis concluded that the cracked weld would have an allowable service life of just under 36 months to remain in compliance with the requirements of Section XI (O'Keefe 2010), which would have provided a full operating cycle for the utility to plan for and mitigate the weld. However, the NRC staff raised questions about the weld residual stress analysis used in the licensee's flaw evaluation.

As a result of the NRC staff's questions, the industry undertook an effort to develop guidelines for a consistent approach for performing weld residual stress analyses. This effort resulted in the development of MRP-317, "Welding Residual Stress Dissimilar Metal Butt-Weld Finite Element Modeling Handbook" (EPRI 2011). This handbook addressed subjects such as model geometry issues (e.g., design versus fabrication, weld bead geometry and sequencing, finite element mesh considerations), material property considerations, thermal models and welding parameters, structural modeling considerations, and model validation and verification. The NRC staff did not provide any formal comments or conclusions on this report.

This Seabrook reactor vessel outlet nozzle weld was mitigated by MSIP during the Fall 2009 refueling outage on an emergent basis (NuVision 2009).

A.2 Timeline of Major Events and Activities

Date	Event or Activity
September 1993	Circumferential through-wall crack at Palisades in the heat-affected zone of the power-operated relief valve Alloy 600 safe end.
1999	Two part-through-wall axial flaws found by UT in Ringhals, Unit 3, in a reactor vessel hot leg nozzle-to-safe end weld.
2000	Four part-through-wall axial flaws found by UT in Ringhals, Unit 4, in a reactor vessel hot leg nozzle-to-safe end weld.
October 2000	Axial through-wall crack in a reactor vessel nozzle-to-loop piping weld occurs at V.C. Summer.
May 2003	NEI issues NEI 03-08, *Guidelines for the Management of Materials Issues*.
2003	Boric acid deposits from an axial through-wall flaw found on the pressurizer relief nozzle of Tsuruga, Unit 2, in Japan. Subsequent UT from the OD detected two axial linear indications in the relief nozzle-to-safe–end weld.
September 2005	Industry implemented an initiative for more frequent inspections of Alloy 82/182 butt welds in PWRs than inspections required by the ASME Code. Initiative documented in MRP-139, “Primary System Piping Butt Weld Inspection and Evaluation Guideline.”
December 2005	NRC staff sent a letter to ASME Section XI requesting Code development of rules for inspection of Alloy 82/182 butt welds.
October 2006	Wolf Creek UT inspections of pressurizer Alloy 82/182 butt welds identified five circumferential indications in surge, relief, and safety nozzle-to-safe–end butt welds that licensee attributed to PWSCC.
February 2007	EPRI MRP initiated a task to refine PWSC crack growth analyses of Wolf Creek pressurizer weld UT indications to address the NRC staff’s concerns regarding the potential for rupture without prior evidence of leakage. Refined analyses referred to as advanced finite element analyses (AFEA).
March 2007	NRC issued Confirmatory Action Letters to 40 licensees with PWRs, confirming commitments from those licensees to resolve concerns regarding potential flaws in specific RCS Alloy 82/182 butt welds by performing inspections by the end of 2007.
September 2007	NRC documented its safety assessment on the industry’s AFEAs. NRC staff performed independent AFEA and concluded that there was reasonable assurance that the nine plants addressed by the evaluation could operate safely until their next scheduled refueling outages in the spring of 2008.
January 2008	Leakage observed from the Davis-Besse decay heat removal drop line-to-RCS nozzle weld after application of the first weld pass for a weld overlay. Leaking flaw determined by UT to be axial.
Mid-February 2008	NRC staff received the results of initial inspections of the nozzle welds of a retired pressurizer that needed to be evaluated against the AFEA results completed in September 2007.
March 8, 2008	EPRI implemented Section XI, Appendix VIII-qualified encoded phased-array, radiographic testing, and eddy current examinations of the retired pressurizer nozzle welds.
March 14, 2008	NRC informed affected licensees of its findings that there was sufficient NDE data available to provide reasonable assurance that there were no structurally significant service-induced flaws within the retired pressurizer safety nozzle welds.
June 21, 2011	NRC issues final 10 CFR 50.55a rule that adopts the ASME Code through the 2008 Addenda and incorporates Code Case N-770-1 with conditions.
April 2012	As a result of OD surface machining in preparation for installation of a FSWOL, two axial flaws were found to be leaking in NAPS-1 steam generator hot leg nozzle-to-safe–end weld. Further ultrasonic tests were performed, and a total of five axially-oriented flaws, classified as PWSCC, were detected in varied locations around the weld circumference.

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APPENDIX B

OPERATING EXPERIENCE WITH BUTT WELD PWSCC

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B.1 U.S. Operating Experience

Operating experience has demonstrated that Alloy 82/182 materials exposed to primary coolant water (or steam) under the normal operating conditions of pressurized water reactor (PWR) power plants are susceptible to primary water stress corrosion cracking (PWSCC). The first incidence of PWSCC that was observed in a butt weld occurred at Palisades in 1993 in the heat-affected zone (HAZ) of the power-operated relief valve (PORV) Alloy 600 safe end. PWSCC had been identified earlier than 1993 in components such as Alloy 600 steam generator tubes and Alloy 82/182 pressurizer control rod drive partial penetration welds. PWSCC in butt welds was observed in 2000 at V.C. Summer in a field-welded Alloy 82/182 reactor vessel nozzle-to-reactor coolant system (RCS) piping weld. Since the V.C. Summer event, there have been well over a dozen indications recorded in butt welds in domestic PWRs that were attributed to PWSCC. Summaries of each event are provided below followed by an overview of U.S. operating experience event in Table B.1.

Palisades. On September 16, 1993, plant personnel identified a leak in the PORV line near the nozzle connection to the pressurizer (NRC 1993). The pressurizer had a stainless steel clad ferritic PORV nozzle joined by an Alloy 82/182 weld to an Alloy 600 safe end. The crack initiated in the HAZ of the Alloy 600 safe end. Nondestructive examination (NDE) and visual inspection found a circumferential crack approximately 76 mm (3 in.) in length, about 30% of the circumference.

Consumers Power indicated the crack initiated due to PWSCC in the HAZ of the PORV line-to-pressurizer nozzle safe end weld. The cracking mode was intergranular from the inside diameter pipe surface with the final 5% to 10% of crack growth being transgranular.

V.C. Summer. In 2000, a large accumulation of boric acid deposits observed during a refueling outage at V.C. Summer led to the discovery of cracking in the ‘A’ hot leg pipe-to-RPV nozzle Alloy 82/182 weld (Casto 2001; Cotton 2001; Byrne 2002; NRC 2008a). The weld had a through-wall axial flaw with a small circumferential component and other small part-through-wall axial flaws. Based on destructive examinations of the piping and the weld material that was removed, the licensee determined that PWSCC caused the flaws. The low-alloy (ferritic) steel and the stainless steel at the ends of the weld arrested the axial crack growth of the flaw.

The circumferential flaw grew a short distance through a portion of the nickel-based alloy butter on the inside of an undercut portion of the low-alloy steel nozzle. The circumferential flaw was arrested when it ran into the low-alloy steel nozzle. Because the sizes of the axial and circumferential cracks were bounded, it would not have been possible for these cracks to lead to a piping rupture. The safety significance of this occurrence was limited to leakage of primary coolant. If a circumferential flaw had initiated closer to the center of the weld, it could have caused a more safety-significant situation. An ultrasonic testing (UT) examination of the remaining nozzle-to-pipe welds in all the loops found no flaws.

The licensee performed eddy-current examinations of the vessel nozzle-to-pipe welds from the inside surface of the pipe. This technique is sensitive enough to find surface flaws but is not capable of determining their depth in thick-walled piping. Small axial and circumferential flaws were identified in the ‘B’ hot leg pipe-to-reactor pressure vessel (RPV) nozzle nickel-based alloy weld; a small circumferential flaw was identified in the ‘C’ hot leg pipe-to-RPV nozzle nickel-based alloy weld; and a small circumferential flaw was found in both the ‘A’ and ‘C’ cold leg pipe-to-RPV nozzle nickel-based alloy welds.

The staff of the U.S. Nuclear Regulatory Commission (NRC) reviewed the evaluation submitted by the licensee to justify the continued operation of V.C. Summer without repairing existing eddy current testing (ET) indications in the ‘B’ loop and ‘C’ loop welds. The Westinghouse evaluation concluded that V.C. Summer could be operated for at least two fuel cycles without repairing existing ET indications. The staff performed an independent evaluation using a bounding PWSCC growth rate and concluded that V.C. Summer could be operated with ET indications in the ‘B’ loop and ‘C’ loop hot leg welds for one fuel cycle.

The flawed region of the RPV ‘A’ nozzle weld was removed and a new spool piece welded in place with an Alloy 52 weld. The mechanical stress improvement process (MSIP) was applied to the RPV ‘B’ and ‘C’ nozzle welds. The UT and ET examinations performed by the licensee in subsequent refueling outages found no evidence of crack growth.

Three Mile Island, Unit 1. During a refueling outage in October 2003, an indication was detected in a surge line nozzle-to-safe–end Alloy 82/182 weld at Three Mile Island, Unit 1 (TMI-1) (NRC 2002). The nozzle is a 25.4-mm (10-in.) diameter, Schedule 140, American Society for Testing and Materials (ASTM) A-105, Grade 2, carbon steel product with an Alloy 82/182 filler metal butter and welded with Alloy 82/182 filler metal to an ASTM A-336 Class F8M forged stainless steel safe end. The surge line nozzle is connected to the steam generator ‘A’ hot leg of the primary coolant loop and normally is operating at 317°C (602°F).

TMI-1 was performing planned manual UT of the surge line nozzle-to-safe–end weld and found an axial indication in the weld material. The licensee characterized the indication as spanning the width of the weld on the inside surface and extending 12 mm (0.48 in.) into the weld.

The indication was confined in the Alloy 82/182 weld material and stopped at the base metal interface on either side of the weld. The indication was in a region that was repaired during original fabrication. Based on the location, acoustic response, and operating temperature, TMI-1 concluded that the indication was due to PWSCC.

TMI-1 installed an Alloy 52 full structural weld overlay repair to maintain weld integrity.

Calvert Cliffs, Unit 2. As a result of the UT inspections at Calvert Cliffs, Unit 2, in the spring of 2005, two reactor coolant system nozzles were identified with indications of flaws requiring disposition (Holm 2005). No through-wall leakage was detected during the inspections. Both nozzles were determined to have a flaw or flaws that could not be found acceptable under ASME Section XI, IWB-3600.

The RCS nozzles requiring repair were the 50-mm (2-in.) diameter 21 Hot Leg Drain Line and 22A Cold Leg Letdown Line. These are carbon steel nozzles buttered using Alloy 82/182, and a stainless steel safe end was welded to the buttered nozzle using Alloy 82/82. The 21 Hot Leg Drain Line Nozzle UT identified one circumferential indication and two axial indications in the dissimilar weld regions that required further disposition. An engineering evaluation of this nozzle determined that the circumferential indication was acceptable under ASME Section XI standards, while the axial indications were not. The results of this evaluation indicated repair would be required prior to returning Unit 2 to service. The 22A Cold Leg Letdown Nozzle UT identified one axial indication that required disposition. Evaluation of this nozzle determined that this indication could not be accurately sized in accordance with ASME Section XI requirements and repair was also required prior to returning Unit 2 to service. The welds were overlaid.

The licensee reported that the root cause of the 21 Hot Leg Drain Nozzle (circumferential indication) was an original fabrication defect, without evidence of having grown in service. This indication was determined to be acceptable under ASME Section XI standards. The two axial indications on the 21 Hot Leg Drain Nozzle were caused by primary water stress corrosion cracking.

The 22A Cold Leg Letdown Nozzle axial indication was not found to be a degraded condition, but was instead considered by the licensee to be a local ultrasonic anomaly. Repair was performed because of the inability to size the anomaly within ASME Section XI Code requirements.

D.C. Cook, Unit 1. Examinations performed at D.C. Cook, Unit 1, in spring 2005, detected unacceptable cracking in a pressurizer safety nozzle-to-safe–end Alloy 82/182 weld (1-PZR-23) (Fadel 2005a, b). The crack was oriented in the axial direction. The crack was contained within the Alloy 82/182 weld, and the characteristics were concluded to be consistent with stress corrosion cracking. The weld was overlaid.

Millstone, Unit 3. In October 2005, the licensee was performing UT examinations at Millstone, Unit 3, in accordance with ASME Code, Section XI, requirements (Price 2006; EPRI 2007b). The licensee identified an axial flaw in the pressurizer spray nozzle-to-safe–end weld 03-X-5641-E-T. Flaw sizing information was not available. The licensee applied a full structural weld overlay (FSWOL).

Calvert Cliffs, Unit 1. In 2006, during the spring outage season at Calvert Cliffs, Unit 1, a 25% through-wall circumferential indication was found in a hot leg surge nozzle-to-safe–end weld, a 20% through-wall circumferential indication was located in a hot leg drain line weld, and an 8% through-wall axial flaw was found in a pressurizer relief valve nozzle-to-safe–end weld (Spina 2006; NRC 2008a). The licensee addressed the potential for further growth of these flaws by PWSCC by application of MSIP to these welds..

Davis-Besse. During the 2006 spring outage season at Davis-Besse, an axial indication of an indeterminate depth was found in a cold leg drain nozzle weld (NRC 2008a). Geometric interference prevented the UT from measuring the depth of the flaw. The licensee assumed the flaw was the result of PWSCC. The licensee completed a FSWOL repair. Because of the nature of the phenomenon, PWSCC at cold leg temperatures has a lower probability of initiating than at hot leg temperatures.

Wolf Creek. On October 13, 2006, the Wolf Creek Nuclear Operating Corporation performed pre-weld overlay inspections using UT techniques on the pressurizer surge, spray, relief, and safety nozzle-to-safe end Alloy 82/182 and safe end-to-pipe stainless steel butt welds (Garrett 2006; NRC 2008a). The inspection identified three circumferential indications in the surge nozzle-to-safe end Alloy 82/182 butt weld, one in the relief nozzle-to-safe end Alloy 82/182 butt welds, and one in the safety nozzle-to-safe end Alloy 82/182 butt weld. The licensee attributed the indications to PWSCC. The sizing techniques used were not qualified; however, based on the sizes estimated by the examiners, some of the flaws were significantly longer circumferentially than flaws previously seen in the industry. All five flaws were estimated to be less than approximately one-third of the wall thickness in depth. The licensee applied FSWOLs to these welds.

Farley, Unit 2. The licensee performed manual UT of the pressurizer Alloy 82/182 butt welds during a Farley, Unit 2, refueling outage in April 2007. Examinations scanning the pressurizer surge nozzle-to-safe–end weld for axially-oriented flaws detected an unacceptable axial indication (George 2007; NRC 2008a). The licensee performed examinations for circumferentially-oriented indications but did not complete the manual data analysis, deciding rather to perform phased-array UT, which is better suited to the analysis of complex geometries. Subsequently, the licensee performed encoded PAUT examinations on the pressurizer surge nozzle weld. The scan for axially-oriented flaws revealed an axial indication in the same area as the manual call, characterized with a depth of 7.9 mm (0.31 in.), which is approximately 20% through-wall. The scan for circumferentially-oriented flaws detected an unacceptable circumferential indication, approximately 150 mm (6 in.) from the axial indication. It identified the circumferential indication as approximately 75-mm (3-in.) long (outside diameter dimension), with a maximum depth of 12.7 mm (0.5 in.), which is approximately 33% through-wall, and located the indication at or near the butter-to-Alloy 82/182 weld interface at or near the inside diameter surface. Because the indications were in PWSCC-susceptible material, the licensee based its corrective action on the assumption that the indications were the result of PWSCC. The licensee applied a FSWOL to this weld.

Davis-Besse. On January 4, 2008, while Davis-Besse was in cold shutdown with the reactor head in place and fuel in the reactor vessel, the licensee began to install a weld overlay on the decay heat removal (DHR) drop line-to-RCS nozzle weld (NRC 2008a). This weld is located inside containment. The RCS was in a drained condition. During the first weld pass on the drop line weld, the welding operator noticed water seeping from the weld. Visual inspection revealed a small leak. Surface examinations before welding showed no abnormal conditions or leakage. The licensee subsequently determined that the leak was from an axial through-wall flaw that the licensee attributed to PWSCC. The licensee applied a FSWOL to this weld.

Crystal River, Unit 3. During a March 2008 outage to replace a degrading reactor coolant pump seal at Crystal River, Unit 3, the licensee identified two circumferential indications in a weld that joins the DHR system drop line to an RCS hot leg (NRC 2008a). Further evaluation of the DHR hot leg nozzle connection determined that the two circumferential indications were actually one indication about 380-mm (15-in.) long. The UT measured the maximum through-wall depth of the flaw at 65% in one localized area. The licensee's fracture mechanics evaluation of the circumferential indication on the DHR drop line determined that the flaw did not exceed the structural requirements for pipe in ASME Code, Section XI. The licensee applied a FSWOL to this weld.

Salem, Unit 1. The licensee for Salem, Unit 1, performed examinations on all eight reactor vessel nozzle hot and cold leg Alloy 82/182 welds during a fall 2008 refueling outage. All examinations were performed from the outside surface using a combination of automated and manual phased-array techniques (Braun 2009; Burritt 2009). During the examinations, a circumferential inside surface-connected flaw was reported on one of the hot leg Alloy 82/182 welds. The flaw was measured to be 24% through-wall (16.1 mm [0.634 in.]) and 52.3-mm (2.06-in.) long on the inside surface.

The licensee analyzed the flaw in accordance with IWB-3600 and found it to be acceptable for up to 36 months of operation before repair or re-inspection. Further evaluation of the flaw size determined that it was within the acceptable limits of NUREG-0313 (Hazelton and Koo 1988) for the application of MSIP; that is, below 30% through-wall (24.2% actual) and less than 10% of the circumference (2.3% actual). All eight reactor vessel nozzle welds were mitigated by MSIP.

Seabrook. During the October 2009 refueling outage inservice inspection (ISI) examinations at Seabrook Station, an axial 21% through-wall flaw was reported in a reactor vessel hot leg nozzle-to-safe–end weld (O'Keefe 2010; Freeman 2011). The flaw was detected in the weld and did not meet the acceptance standards of IWB-3514. An analytical evaluation was performed per IWB-3640 to determine how long the as-found flaw could be left in service before repair was required. The analysis resulted in an allowable service life of less than 36 months to remain in compliance with the requirements of Section XI. The flaw was attributed to PWSCC. The licensee for Seabrook performed MSIP on this weld.

North Anna Power Station, Unit 1 (NAPS-1). On March 24, 2012, axial indications were found as a result of leakage in the 'B' reactor coolant loop hot–leg-to-steam generator nozzle weld (Anderson et al. 2012; Anderson et al. 2014). The leakage was found during the performance of work activities to support weld overlay work on the 'B' loop hot leg steam generator nozzle weld. The workers noted a small amount of water seeping from the indications in the nozzle weld area. The indications were in the area of excavation that was being performed prior to installing the weld overlay. Approximately 1 inch of weld material thickness 360° around the circumference had been removed prior to identification of the seepage.

An examination of this weld had been conducted prior to the weld excavation, and none of the five indications were detected. It has been determined that two of the cracks were greater than 80% through-wall and three were greater than 40% through-wall. A full structural weld overlay was applied to this weld.

Table B.1 U.S. Operating Experience with Butt Weld PWSCC

Plant	Year	System/Location	Flaw Orientation	Estimated Flaw Size	Comments
Palisades	1993	HAZ of the PORV Alloy 600 safe end	Circumferential	NDE and visual inspection found a circumferential crack ~76 mm (3 in.) in length, about 30% circumference	Weld replaced
V.C. Summer	2000	RPV nozzle-to-pipe weld	TW axial flaw spanning the width of the weld with a small circumferential component and other small part-TW axial flaws	TW axial flaw	Weld replaced with Alloy 52 weld
Three Mile Island 1	2003	Surge line safe end-to-RCS hot leg nozzle weld	Axial	Spanned the width of the weld on the inside surface, extending about 50% TW at the deepest location	FSWOL
Calvert Cliffs 2	2005	RCS hot leg drain nozzle-to-safe end weld	One circumferential and two axial	No sizing information available	FSWOL
D.C. Cook 1	2005	PZR safety valve nozzle-to-safe–end weld	Axial	Sizing information not found	FSWOL
Millstone 3	2005	PZR spray valve nozzle-to-safe–end weld	Axial	No sizing information available	FSWOL
Calvert Cliffs 1	2006	Surge line safe end-to-RCS hot leg nozzle weld	Circumferential	25% TW, 2.4-in. long with a 12¾ in. OD	MSIP
Calvert Cliffs 1	2006	RCS hot leg drain nozzle-to-safe end–weld	Circumferential	20% TW, 0.45-in. long with a 2-7/8 in. OD	MSIP
Calvert Cliffs 1	2006	PZR relief valve nozzle-to-safe–end weld	Axial	>10% TW, 0.6-in. long with a 6-1/6 in. OD	MSIP
Davis-Besse	2006	Cold leg drain nozzle weld	Axial	No sizing information available	FSWOL
Wolf Creek	2006	PZR surge, safety and relief valve nozzle-to-safe–end welds	Circumferential	Estimated sizes of the five flaws in NRC (2008b); sizing technique was not qualified	FSWOL
Farley 2	2007	PZR surge nozzle-to-safe–end weld	Axial and circumferential	Axial 20% TW; circumferential 33% TW, 3.5-in. long	FSWOL
Davis-Besse	2008	Decay heat removal to RCS nozzle weld	Axial	100% TW	FSWOL
Crystal River 3	2008	Decay heat removal to RCS nozzle weld	Circumferential	65% TW deep in one localized area; most of the flaw depth under 1/3 wall; 15-in. long	FSWOL
Salem 1	2008	Reactor vessel hot leg nozzle-to-safe–end weld	Circumferential	24% TW and 2-in. long on the inside diameter (ID)	MSIP
Seabrook	2009	Reactor vessel hot leg nozzle-to-safe–end weld	Axial	Sizing information not found	MSIP
North Anna	2012	Reactor vessel hot leg nozzle-to-safe–end weld	Axial	5 flaws with the deepest estimated at 80% TW prior to machining. Two flaws leaked after machining to prep for a FSWOL.	FSWOL

B.2 Foreign Operating Experience

As noted in Section B.1, operating experience has demonstrated that Alloy 82/182 materials exposed to primary coolant water (or steam) under the normal operating conditions of PWR power plants are susceptible to PWSCC. The first incidence of PWSCC in butt welds that was observed in a foreign plant occurred at Ringhals, Unit 3, in 1999 in a reactor vessel hot leg nozzle-to-safe–end weld. PWSCC had been identified earlier in foreign PWRs in components such as steam generator tube and pressurizer control rod drive penetrations made of Alloy 600 and in Alloy 82/182 partial penetration welds. Since the Ringhals, Unit 3, event, there have been a number of indications recorded in butt welds that were attributed to PWSCC. Summaries of each event are provided below followed by an overview of foreign operating experience event in Table B.2.

A summary of cracking in Japanese steam generator inlet nozzle-to-safe–end welds is contained in Table 4-3 of MRP-349 (EPRI 2012a). This table indicates that, in addition to the Japanese plants discussed below, cracking was found in the steam generator inlet nozzle-to-safe–end welds at Genkai, Unit 1, in 2008 and at Tomari, Unit 2, in 2008. No additional information on the cracking at these two plants beyond that contained in MRP-349 was located. The number and size of the cracks found in the steam generator inlet nozzle welds at these two plants is bounded by cracking found at other Japanese plants.

Mihama, Unit 2. Mihama, Unit 2, is a Westinghouse-type, two-loop 500-megawatt electric (MWe) PWR. In November 2007, it was reported that the licensee (Kansai Electric Power Co.) was preparing to shot peen the ID surface of steam generator (SG) nozzle dissimilar metal welds (DMWs) in September 2007 for preemptive mitigation against the effects of PWSCC. The licensee performed visual and ET of the weld ID surface in September 2007 and identified a number of axial indications—1 by visual examination and 13 by ET at the SG ‘A’ inlet nozzle (Nomura et al. 2007). Follow-up liquid penetrant testing (PT) confirmed the presence of the ET-detected indications. The maximum length of the largest indication (No. 4) was determined to be approximately 17 mm (0.75 in.). Follow-up UT estimated the depth to be approximately 13 mm (0.5 in.) and the crack was depth-sized at approximately 11.5 mm (0.45 in.) based on observation of the fracture surface. The 17-mm indication was comprised of intermittently connected multiple small axial cracks approximately 3–5 mm (0.12–0.2 in.) in length (Nomura 2008a). The axial indications were detected at various locations around the circumference, all of which with the exception of one indication (No. 13), exhibited PWSCC-like characteristics and were contained within the Alloy 600 butter and weld. Indication No. 13 was identified in the stainless steel safe end near the Alloy 600 weld and exhibited branching along the grain boundary. UT of this indication from the ID surface estimated the depth to be less than 5 mm (0.2 in.). Based on observation of the fracture surface, the crack depth was estimated to be approximately 0.9 mm (0.04 in.).

The SG inlet nozzle is low-alloy carbon steel with an Alloy 600 buttering and is stainless steel clad on the ID. The main loop piping is stainless steel, approximately 940-mm (37-in.) outer diameter (OD), 778-mm (30.6-in.) ID with an 81-mm (3.19-in.) wall thickness, and connects to the nozzle via a stainless steel safe end approximately 160 mm (6.3 in.) in length. The DMW joint is of a double-V configuration made with Alloy 600/82 filler material.

A circumferential ring containing the safe end, weld, and Alloy 600 butter, which contained the indications, was removed from the system for physical and chemical analysis. Detailed metallographic analyses were performed on indications Nos. 4 and 13. The licensee concluded that machining of the ID surface of the DMW and stainless steel safe end resulted in high residual tensile stresses on the ID surface, which caused PWSCC in the DMW and cracking to form near the safe end weld–to–safe end interface. A spool piece was used to replace the removed circumferential ring and was attached to the nozzle with Alloy 690 weld material (Nomura 2008b).

Ohi, Unit 3. Ohi, Unit 3, is a Westinghouse-type four-loop 1127-MWe PWR (ANS 2011). In November 2008, it was reported that ET of the RPV outlet nozzle weld was performed in March 2008 by the licensee (Kansai Electric Power Co.) prior to the water jet peening operation of DMWs. Japanese PWR utilities had been applying water jet peening to reactor vessel nozzle DMWs since 2004 to mitigate PWSCC at those locations (Nomura 2008a). During this examination, a small axial flaw was detected. Visual examination from the ID surface estimated the flaw to be approximately 3 mm (0.12 in.) in length. Follow-up UT sized the flaw to be approximately 10 mm (0.4 in.) in length and less than 5 mm (0.2 in.) in depth. A detailed visual examination revealed evidence of machining on the ID surface. The crack exhibited branching along the dendritic boundaries similar to those observed on SG nozzle inlet welds.

The Ohi, Unit 3, RPV outlet nozzle is made of low-alloy steel with Alloy 82 butter, clad with stainless steel. The adjoining safe end is stainless steel 316F, with dimensions of 882-mm (34.7-in.) OD, 736-mm (29-in.) ID, and approximately 74-mm (2.9-in.) wall thickness. The DMW is of a double-V configuration and is made with Alloy 600/82 weld filler material.

The crack was presumed by the licensee to be relatively shallow, so repair by defect removal was implemented. The repair involved excavation of material at 0.5-mm (0.2-in.) to 1.0-mm (0.04-in.) depth increments, followed by an overall depth measurement, and visual examination and ET of the excavation to verify the absence or presence of the crack. The location and length of the crack was mapped for each increment. The flaw was completely removed at a depth of 20.3 mm (0.8 in.) (Mensah 2007). The maximum length of the crack was 13.5 mm (0.53 in.) at a depth of 5.5 mm (0.22 in.). Throughout the entire depth of the excavation, the crack exhibited turns and branching similar to that associated with PWSCC and was contained within the Alloy 82 butter and weld.

Water jet peening was performed on the surface of the divot created by the excavation, and the plant was placed in service for one operating cycle without weld repair. At a later time, the divot was planned to be filled with Alloy 82 weld material; a groove would be machined around the circumference of the joint spanning the stainless steel clad nozzle, Alloy 600 butter, DMW and safe end; and an inlay of Alloy 52 would be applied within the machined groove.

Ringhals, Units 3 and 4. Ringhals, Units 3 and 4, are Westinghouse three-loop PWRs, 1051 MWe and 935 MWe, respectively (ANS 2011). There were no documented repairs of safe ends in Ringhals 3, but there were two extensive and one more confined safe end repairs documented on Ringhals 4 (Skanberg 2001; EPRI 2004a; Miteva and Taylor 2006; NRC 2008a).

In 1999 during regularly scheduled ISI of the Ringhals, Unit 3, RPV outlet nozzle-to-safe–end DMWs, two shallow axial indications were detected in one of the DMWs. These indications were flaws that were found to be acceptable by evaluation and were left in service. Follow-up examinations in 2000 and 2001 revealed crack growth as well as the presence of a new crack. The flaw at 265°/299° in 2000 measured 13 mm (0.5 in.) in length and 9 mm (0.35 in.) in depth; in 2001, the same flaw measured 18 mm (0.7 in.) in length and 13 mm (0.5 in.) in depth. The flaw at 265°/323° in 2000 measured 16 mm (0.63 in.) in length and 9 mm (0.35 in.) in depth; in 2001 the same flaw measured 20 mm (0.8 in.) in length and 16 mm (0.63) in depth. The new flaw detected in 2001 at the RPV outlet nozzle 25°/323° measured 8 mm (0.3 in.) in length and 8 mm (0.3 in.) in depth. These cracks were subsequently removed through a boat sample.

During regularly scheduled ISI in 2000 of Ringhals, Unit 4, RPV outlet nozzle-to-safe–end DMWs, four axial flaws were detected in one of the outlet nozzle-to-safe–end welds. Three were evaluated as subsurface planar flaws and one as a surface-breaking planer flaw. All four were removed by boat samples. Metallographic examination showed that all four cracks were surface-breaking. The two deepest flaws were determined by metallographic examination to be 22 ± 3-mm (0.87 ± 0.1-in.) deep. The depths of these flaws according to ultrasonic measurements were 13 ± 3 mm (0.5 ± 0.1 in.) and 16 ± 3 mm (0.63 ± 0.1 in.). Metallographic examination of the flaws determined that stress corrosion cracking (SCC) occurred in a weld-repaired Alloy 182 region, branching and crack-tip characteristics were similar to those associated with SCC, hot cracking and minor lack of fusion was evident, and propagation of the SCC crack into the carbon steel nozzle or stainless steel safe end materials did not occur. Alloy 52M was used at both plants to replace/repair the material removed through boat samples.

The RPV outlet nozzle DMW joint is of a double-V configuration and consists of a carbon steel SA508 Class 2 nozzle clad with stainless steel, with Alloy 182 buttering, connected to a stainless steel SA182 F316 safe end with Alloy 182 weld filler material.

Takahama, Units 2 and 3. Takahama, Units 2 and 3, are Westinghouse-type three-loop PWRs, 780 MWe and 830 MWe, respectively (ANS 2011). In August 2008, it was reported by the licensee (Kansai Electric Power Co.) that indications of PWSCC were detected in the SG inlet nozzles of Takahama, Units 2 and 3 (Nomura 2008a). For Takahama, Unit 2, SG ‘A’ inlet nozzle had 3 indications detected by ET that could not be confirmed with UT; SG ‘B’ inlet nozzle had 2 indications detected by ET for which UT sized to be up to 7 mm (0.28 in.) in length and 6 mm (0.24 in.) in depth; and SG ‘C’ inlet nozzle had 4 indications for which UT sized to be up to 14 mm (0.55 in.) in length and 8 mm (0.3 in.) in depth. For Takahama, Unit 3, SG ‘A’ inlet nozzle had 7 indications detected by ET for which UT sized to be up to 28 mm (1.1 in.) in length and 9 mm (0.35 in.) in depth; SG ‘B’ inlet nozzle had 16 indications detected by ET for which UT sized to be up to 38 mm (1.34 in.) in length and 15 mm (0.59 in.) in depth; and SG ‘C’ inlet nozzle had 9 indications detected by ET for which UT sized to be up to 14 mm (0.55 in.) in length and 9 mm (0.35 in.) in depth. For each of the Takahama steam generator inlet nozzles, the indications were distributed at various locations throughout the entire circumference of the DMW.

No weld joint details or component material specifications were provided for the original SG inlet nozzle weld, but the original DMW filler material used at Takahama, Unit 2, was Alloy 600/82, and at Takahama, Unit 3, was Alloy 600/132.

The repair methods reported to be used were dependent upon the significance of the indication detected. For relatively small and shallow cracks, the defects would be removed by fine grinding or electro-discharge machining, followed by ID surface stress mitigation using shot peening. For relatively large cracks, the elbow would be removed to facilitate weld repair of the defects, then reinstallation of the elbow using either Alloy 600 or Alloy 690 weld filler material followed by surface prepping and installation of a circumferential weld inlay of Alloy 690 material that spanned from the nozzle to safe end.

Takahama, Unit 4. Takahama, Unit 4, is a Westinghouse-type four-loop 830-MWe PWR (ANS 2011). In November 2008, it was reported by the licensee (Kansai Electric Power Co.) that indications of PWSCC were detected in the SG inlet nozzles of Takahama, Unit 4, during the performance of visual and ET examinations in preparation for shot peening of the DMW ID surface for preemptive mitigation against PWSCC (Nomura 2008b). In all, 36 indications were detected—7 in the inlet nozzle of SG ‘A’, 8 in the inlet nozzle SG ‘B’, and 21 in the inlet nozzle of SG ‘C’. UT sized the indications in SG ‘A’ to be up to 14 mm (0.55 in.) in length and 12 mm (0.47 in.) in depth; in SG ‘B’ to be up to 30 mm (1.2 in.) in length and 13 mm (0.5 in.) in depth; and in SG ‘C’ to be up to 33 mm (1.3 in.) in length and 16 mm (0.63 in.) in depth. For each of the SG inlet nozzles, the indications appeared to be contained within the Alloy 600 butter and Alloy 600/132 weld material, and were distributed over the circumference of the DMW joint.

No weld joint details or component material specifications were provided for the original SG inlet nozzle weld, but the original DMW filler material used at Takahama, Unit 4, was Alloy 600/132.

At the time this information was presented, it was the utility’s intent to remove the defects, fill the excavations as necessary, and apply a circumferential weld inlay of Alloy 690 material that would span the DMW joint from the stainless steel cladding on the SG inlet nozzle to the stainless steel safe end.

Tihange, Unit 2. Tihange, Unit 2, is a three-loop 1008-MWe PWR (ANS 2011). In October 2002, indications were detected in five areas on the ID surface of the pressurizer surge line nozzle-to-safe–end weld (Roussel 2005). Four of the indications detected were circumferential and were found to be within the acceptable size limits of Section XI. The fifth indication, an axial indication, could not be distinguished easily, but was ultimately sized to be approximately 26 mm (1 in.) in length and 4 mm (0.16 in.) in depth. The flaw was located close to a repair made during fabrication, and it was thought that the indication could be a fabrication flaw that went undetected at that time, but the possibility of PWSCC could not be excluded (Gérard and Daoust 2004a, b). The component was placed back in service without repair or mitigation and was reexamined, initially at six-month intervals, in May 2003 and October 2003, and then inspected again in May 2005. The results of those examinations did not differ from the October 2002 results.

At the time of the October 2002 examination, the 1992 Edition without Addenda of Section XI of the ASME Code was the applicable inservice inspection code for all Belgian plants. UT examination of the subject weld was required to be performed to the requirements of Section XI, Appendix VIII with the UT examination volume defined to be the inner one-third of the thickness of the weld over an axial length equal to the width of the weld projected radially from the weld crown plus 6 mm (¼ inch) from each side of the weld crown. The pressurizer surge line nozzle joint is composed of a SA508 Class 3 nozzle, which is connected to a stainless steel 316 safe end by an Alloy 600/182 weld (Miteva and Taylor 2006).

In May 2003, the RPV outlet nozzle-to-safe–end welds were inspected, and consisted of ID UT and ID ET examinations. The ID UT examination did not identify any significant indications, but the ET examination detected a 10-mm (0.4-in.) crack-like axial indication on the hot leg No. 2 nozzle weld. Follow-up UT examination of the indication using UT probes specifically focused to detect cracks within 1 mm (0.04 in.) of the surface could not detect the indication, so the indication was presumed to be 10 mm × 1 mm (0.4 in. × 0.04 in.). The weld was reexamined in May 2005 and the results did not differ from those of the May 2003 examination.

The ultrasonic inspection of the dissimilar welds at the RPV nozzles was performed from the ID of the vessel. Qualification of the procedure was based on the requirements of Appendix VIII to Section XI of the ASME Code, Edition 1992 without addenda, but the European (European Network for Inspection Qualification) methodology was also used as a guideline. The qualification program took place in 1999.

ID detection of circumferential indications in the first (inner) third of the weld thickness is achievable from 5-mm (0.2-in.) depth and characterization from 8-mm (0.3-in.) depth knowing that the dead zone can extend from 4 to 6 mm (0.16 to 0.24 in.). ID detection of axial indications in the first third of the weld is achievable from 5-mm (0.2-in.) depth and characterization from 5-mm (0.2-in.) depth.

The UT examination of DMWs of pressurizer nozzle-to-safe–end welds is performed from the OD using automated techniques, which are qualified to detect axial cracks from 2 mm (0.08 in.) in depth and to size them from 4 mm (0.16 in.) in depth.

Tsuruga, Unit 2. Tsuruga, Unit 2, is a Westinghouse-type four-loop 1160-MWe PWR. In 2003 during a regularly scheduled ISI, boric acid deposits were found on the pressurizer relief nozzle (NRC 2004; Yonazawa 2004). Subsequent UT from the OD of all of the pressurizer relief and safety nozzles detected two axial linear indications in the relief nozzle-to-safe–end weld, the longest of which was 35 mm (1.38 in.), and one axial linear indication in the ‘A’ safety nozzle-to-safe–end weld approximately 50 mm (1.97 in.) in length. These indications were confirmed with radiographic testing from the OD and PT from the ID. All of the indications were contained within the weld material, including a portion of the nickel-based alloy butter on the inside of an undercut portion of the low-alloy steel nozzle.

The configuration of the pressurizer safety and relief nozzles are all the same; a carbon steel nozzle clad with stainless steel, buttered with Alloy 600, and attached to a stainless steel Type 316 safe end with Alloy 600 weld filler material. The OD of the nozzle is approximately 190 mm (7.48 in.); ID is approximately 130 mm (5.12 in.) with a wall thickness approximately 30 mm (1.18 in.).

The samples removed for destructive examinations contained the entire weld and a portion of the base metal on each side of the weld.

Radiography was performed on the severed pieces, confirming the linear flaws. Metallurgical failure analysis was performed on these samples. The results showed that the cracks initiated from the inside diameter surface, were axially oriented, and were intergranular or interdendritic in nature. A through-wall crack was confirmed at the 90° location in the weld on the relief nozzle. The conclusion of the metallurgical analysis was that the nozzle failures were caused by PWSCC in the nozzle weld.

Plant personnel stated that no indications were detected during the previous inspections.

Tsuruga, Unit 2. In November 2007, it was reported that the licensee (Japan Atomic Power Co.) was preparing to shot peen the ID surface of SG nozzle DMWs for preemptive mitigation against the effects of PWSCC. In September 2007, the licensee performed ET of the weld ID surface and identified 29 indications by ET on the SGs 'A', 'B', and 'C' inlet nozzle DMWs—1 on SG 'A', 5 on SG 'B', and 23 on SG 'C' (Nomura et al. 2007). Follow-up UT was performed on the nozzles; UT did not detect the indication in SG 'A'. The largest indication in the SG 'B' inlet nozzle was sized to be approximately 21 mm (0.83 in.) in length and 12 mm (0.47 in.) in depth. The largest indication in the SG 'C' inlet nozzle was sized to be approximately 14 mm (0.55 in.) in length and 13 mm (0.5 in.) in depth. The axial indications in SGs 'B' and 'C' were detected at various locations around the circumference. The licensee indicated that the indication on SG 'A' and the largest indication on SG 'B' would be further investigated using Suzuki's Universal Micro-Printing method; however, no results were identified by our review.

The SG inlet nozzles are low-alloy carbon steel with an Alloy 600 buttering, and are stainless steel clad on the ID. The main loop piping is stainless steel, has an approximately 943-mm (37.1-in.) OD and 788-mm (31-in.) ID with a 77.5-mm (3.05-in.) wall thickness, and connects to the nozzle via a stainless steel safe end. The DMW joint is of a double-V configuration made with Alloy 600/132 filler material (Nomura 2008a).

The affected SG nozzles were not removed. Local weld repairs were performed on the indications using either Alloy 600 or Alloy 690 material, followed by the installation of a circumferential weld inlay of Alloy 690 over the repaired areas.

Table B.2 Foreign Operating Experience with Butt Weld PWSCC

Plant	Year	System/Location	Flaw Orientation	Estimated Flaw Size	Comments
Mihama Unit 2	2007	SG-A inlet nozzle-to-safe–end weld	Numerous axial indications in weld. Shallow flaw in SS safe end near nickel-based weld.	Largest flaw measured to be 17-mm long and 12-mm deep. Wall thickness is 81 mm.	2 samples removed for metallurgical analysis confirmed PWSCC in weld and butter and cracking near the safe end weld-to-safe–end interface.
Ohi Unit 3	2008	RPV outlet nozzle-to-safe–end weld	1 axial flaw identified.	Flaw removed by grinding. Maximum flaw length was 13.5-mm long at 5.5-mm depth and the final flaw depth was 20 mm. Wall thickness is 74 mm.	Returned to service after water jet peening. Long-term plan to install an inlay.
Ringhals Unit 3	1999	RPV outlet nozzle-to-safe–end weld	2 axial flaws in 1999. Additional axial flaw found in 2001.	Initial 2 flaws measured 9-mm deep in 2000 and 13- and 16-mm deep in 2001. New flaw found in 2001 measured 8-mm deep.	Left in service in 1999. All 3 removed by boat sample and repaired by Alloy 52 in 2001.
Ringhals Unit 4	2000	RPV outlet nozzle-to-safe–end weld	4 axial flaws found by UT. Confirmed to be surface-breaking by metallurgical examination.	2 deepest flaws determined to be 22-mm deep by destructive examination.	All 4 flaws removed by boat sample and repaired by Alloy 52M.
Takahama Units 2 & 3	2008	SG inlet nozzle-to-safe end–welds	Numerous indications in 3 nozzle welds. Orientation not specified.	Largest flaw in Unit 2 was 14-mm long and 8-mm deep and largest flaw in Unit 3 was 38-mm long and 15-mm deep. Wall thickness not provided.	Repair technique depended upon the flaw depth.
Takahama Unit 4	2008	SG inlet nozzle-to-safe–end welds	Numerous indications in 3 nozzle welds. Orientation not specified.	Largest flaw was 33-mm long and 16-mm deep. Wall thickness not provided.	At time of reference, plan was to remove and fill defects and apply Alloy 690 inlay.
Tihange Unit 2	2002	Pressurizer surge line nozzle-to-safe–end weld	Circumferential and axial	Circumferential < IWB-3514. Axial 26-mm long, 4-mm deep.	Left in service—no change in subsequent inspections.
Tihange Unit 2	2003	RPV outlet nozzle-to-safe–end weld	Axial by ET; not identified by UT	Estimated at 10-mm long and 1-mm deep.	Left in service—no change in subsequent inspections.
Tsuruga Unit 2	2003	Pressurizer relief and safety nozzle-to-safe–end welds	2 axial flaws in relief nozzle weld. 1 axial flaw in ‘A’ safety nozzle weld.	1 through-wall flaw in relief nozzle weld. Other depths not available.	Samples removed for metallurgical analysis confirmed PWSCC.
Tsuruga Unit 2	2007	SG inlet nozzle-to-safe–end welds	Numerous axial indications in 2 of 4 nozzle welds.	Largest flaw in ‘B’ nozzle weld was about 21-mm long and 12-mm deep. Largest flaw in ‘C’ nozzle weld was 14-mm long and 13-mm deep. Wall thickness is 77.5 mm.	Local repairs made followed by Alloy 690 inlays.

B.3 Conclusions

Based on a review of the available operating experience with PWSCC in butt welds, the following conclusions are provided.

- PNNL identified over two dozen occurrences of circumferential and axial PWSCC in Alloy 82/132/182 butt welds in U.S. and foreign plants since 1993. Some of these occurrences involved multiple cracks. Axial PWSCC has been observed more frequently than circumferential cracking.
- In the United States, PWSCC in butt welds has been found in the range of piping systems and sizes from drain lines to reactor coolant loop piping and at all Class 1 temperature conditions, including drain line piping at a reactor coolant loop cold leg temperature.
- The first incidence of PWSCC that was observed in a butt weld was a leaking through-wall circumferential crack at Palisades in 1993 in the HAZ of the PORV Alloy 600 safe end.
- Leakage to date from PWSCC has only been observed from axial cracks in pressurizer and hot leg temperature welds.
- From the data available, PWSCC in Japan has been observed in pressurizer valve nozzle welds, RPV outlet nozzle welds, and steam generator inlet nozzle welds. All of the occurrences that were identified in Japan have been axial cracking. Information on weld configuration was provided on some of these welds that indicated a double V-groove configuration.
- Comparison of UT-measured depth and the depth measured by metallurgical analysis in Ringhals 4 (2000) and Ohi 3 (2008) showed flaw depths by UT that were substantially undersized.
- Based on the information obtained on the events described above no circumferential or axial PWSCC has exceeded ASME Code structural factors.

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APPENDIX C

DISSIMILAR METAL WELD INSPECTION LIMITATIONS OF A TYPICAL WESTINGHOUSE PLANT

APPENDIX C

DISSIMILAR METAL WELD INSPECTION LIMITATIONS OF A TYPICAL WESTINGHOUSE PLANT

C.1 Introduction

The information contained in this appendix was obtained during a workshop held with LMT, Inc., an inspection vendor for the commercial nuclear power industry. This vendor uses ultrasonic testing (UT) inspection methods qualified under ASME Code, Section XI, Appendix VIII, including phased-array (PA) techniques and conventional UT techniques in encoded and non-encoded delivery modes, as specified by the utility. This workshop was held to discuss the characteristics of UT data of indications attributed to stress corrosion cracking (SCC). This data was from encoded examinations of piping welds acquired from scans of the outside diameter (OD) surface. This workshop was also held to discuss limitations to achieving Code-required volume (CRV) coverage on Alloy 82/182 butt welds in a typical Westinghouse plant and a typical Combustion Engineering plant. This appendix provides information on limitations to obtaining the CRV coverage that may be encountered during examinations of Alloy 82/182 butt welds in the reactor coolant system in a Westinghouse plant.

Table C.1 provides a listing of the Alloy 82/182 butt welds that are typically found in a Westinghouse plant. The location of these welds is depicted in Figure C.1. The CRV coverage for the Alloy 82/182 in butt welds in the piping systems in Table C.1 is dependent on site-specific configurations and allowable scan access thereof. Site-specific designs vary in regards to material and component configuration(s). Therefore, the coverage depicted is applicable only to the site-specific design used to prepare this document. Standard 45° and 60° angles were utilized for CRV coverage assessments unless specified otherwise in the illustrations.

Table C.1 Alloy 82/182 Butt Welds and Dimensions in Typical Westinghouse

Description	Quantity	Circumference (Weld Centerline)	Thickness (Weld Centerline)
PZR Surge Nozzle	1	47.5 in. (120.6 cm)	1.60 in. (4.06 cm)
PZR Spray Nozzle	1	18.7 in. (47.5 cm)	0.87 in. (2.21 cm)
PZR Safety and Relief Nozzle	4	25 in. (63.5 cm)	1.37 in. (3.48 cm)
RPV Hot Leg Nozzle	3/4	113 in. (287.0 cm)	2.50 in. (6.35 cm)
SG Hot Leg Nozzle	3/4	132.3 in. (336.0 cm)	4.90 in. (12.45 cm)
SG Cold Leg Nozzle	3/4	132.3 in. (336.0 cm)	4.90 in. (12.45 cm)
RPV Cold Leg Nozzle	3/4	113 in. (287.0 cm)	2.50 in. (6.35 cm)

PZR – pressurizer; RPV – reactor pressure vessel; SG – steam generator; 3/4 – 3 or 4 loops

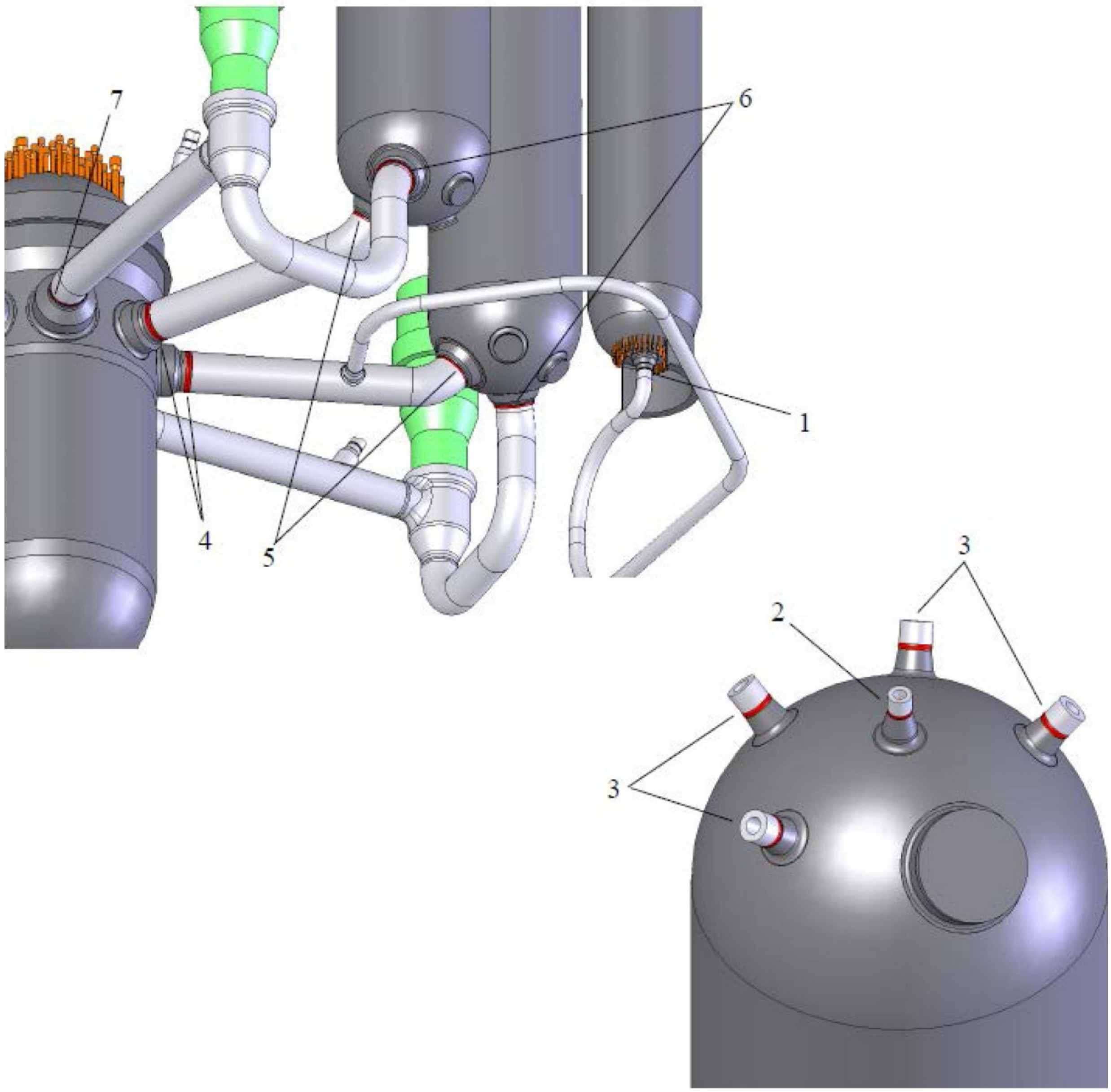


Figure C.1 Typical Locations of Alloy 82/182 Butt Welds in Westinghouse Design Plants

C.2 Pressurizer Surge Nozzle

Figure C.2 Photograph of Pressurizer Surge Nozzle, Nozzle Weld, and Safe End

The examination limitations for the pressurizer surge nozzle Alloy 82/182 butt weld were minimal scanning surface and the OD examination surface contour and condition.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure C.3. The axial scan direction CRV coverage achievable was 80%. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure C.4. The circumferential scan direction CRV coverage achievable was 100%.

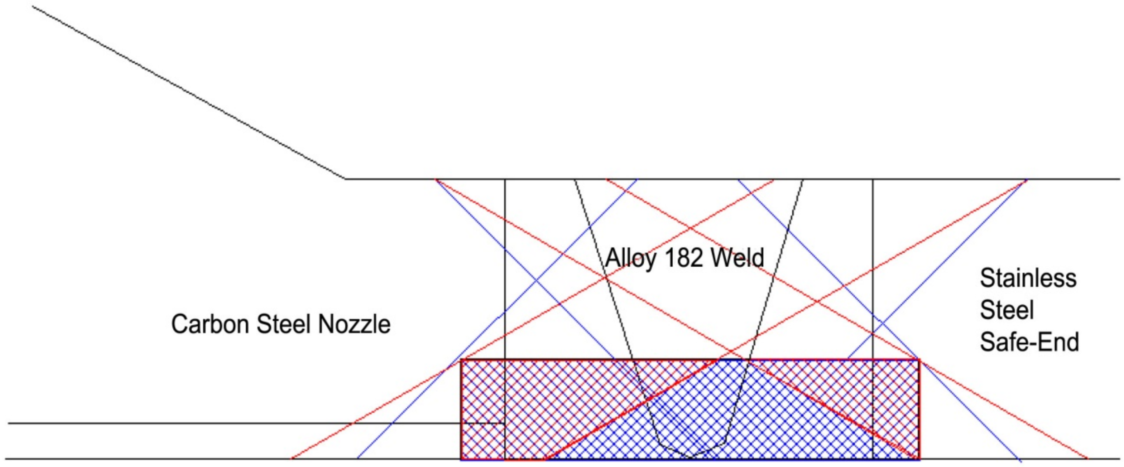


Figure C.3 Pressurizer Surge Nozzle Weld Axial Scan CRV Coverage Assessment

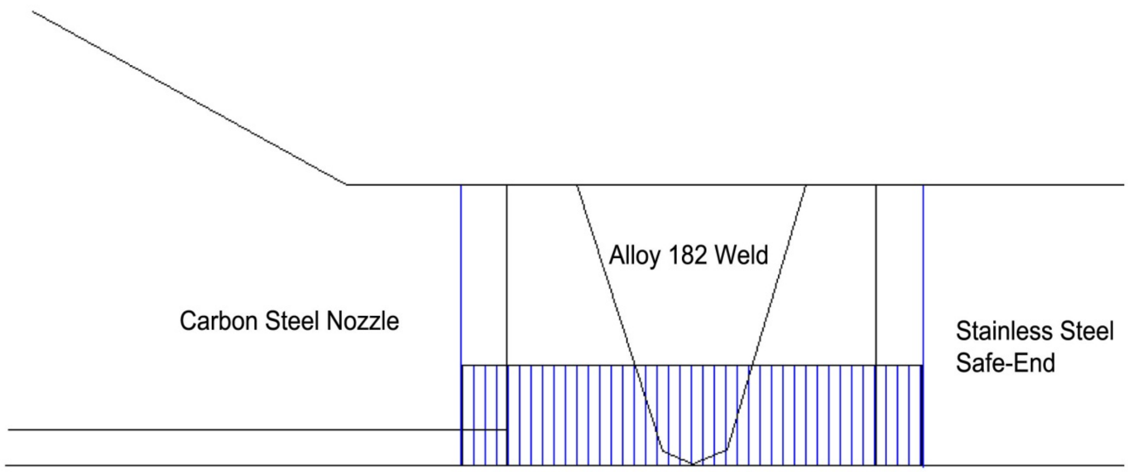


Figure C.4 Pressurizer Surge Nozzle Weld Circumferential Scan CRV Coverage Assessment

C.3 Pressurizer Spray Nozzle

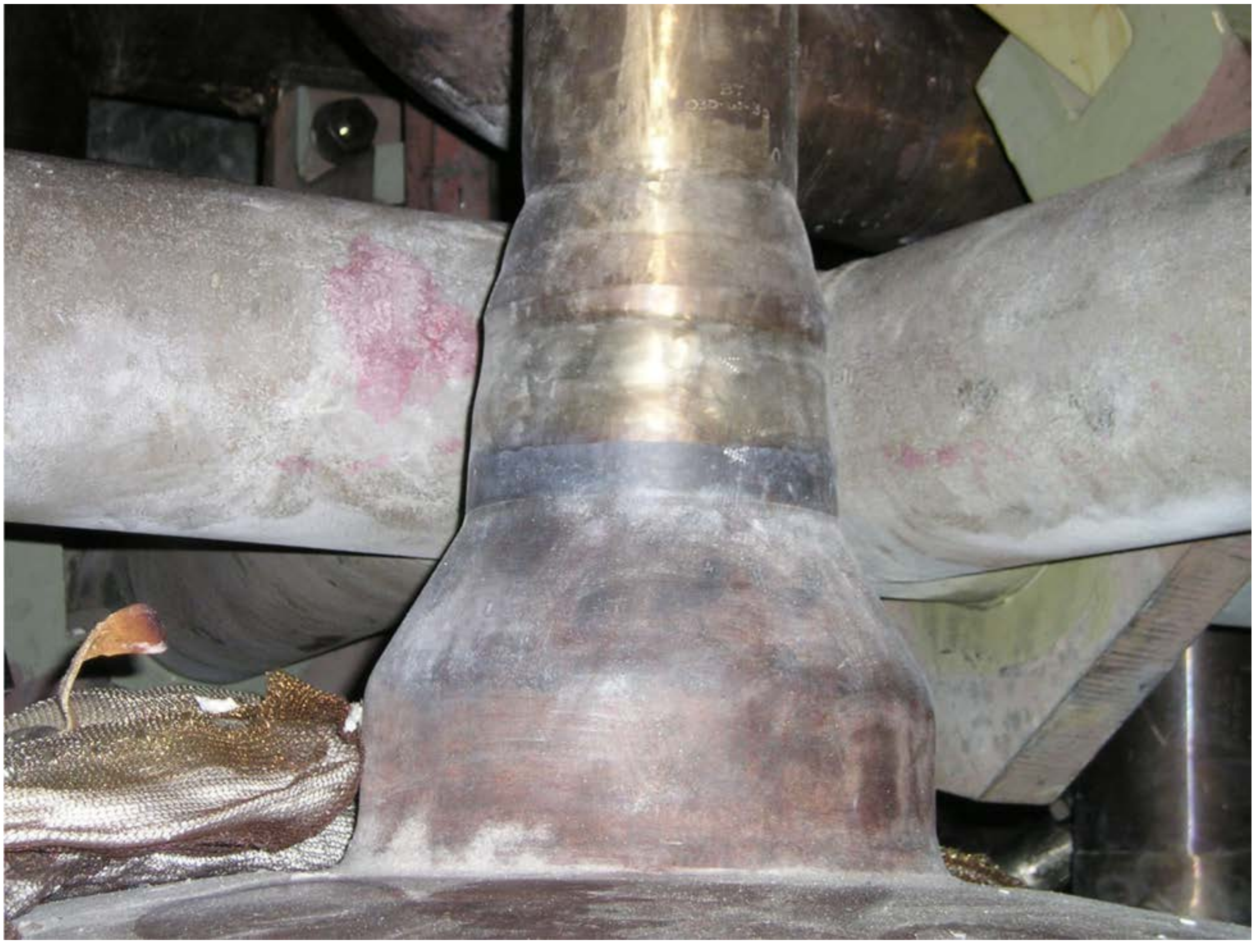


Figure C.5 Photograph of Pressurizer Spray Nozzle, Nozzle Weld, and Safe End

The examination limitations for the pressurizer spray nozzle Alloy 82/182 butt weld were minimal scanning surface and the OD examination surface contour and condition.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure C.6. The axial scan direction CRV coverage achievable was 40%. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure C.7. The circumferential scan direction CRV coverage achievable was 34%.

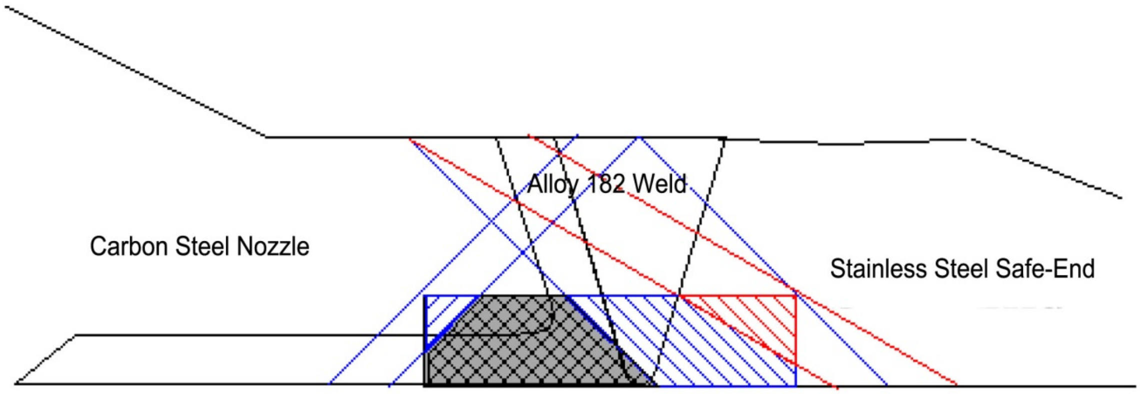


Figure C.6 Pressurizer Spray Nozzle Weld Axial Scan CRV Coverage Assessment

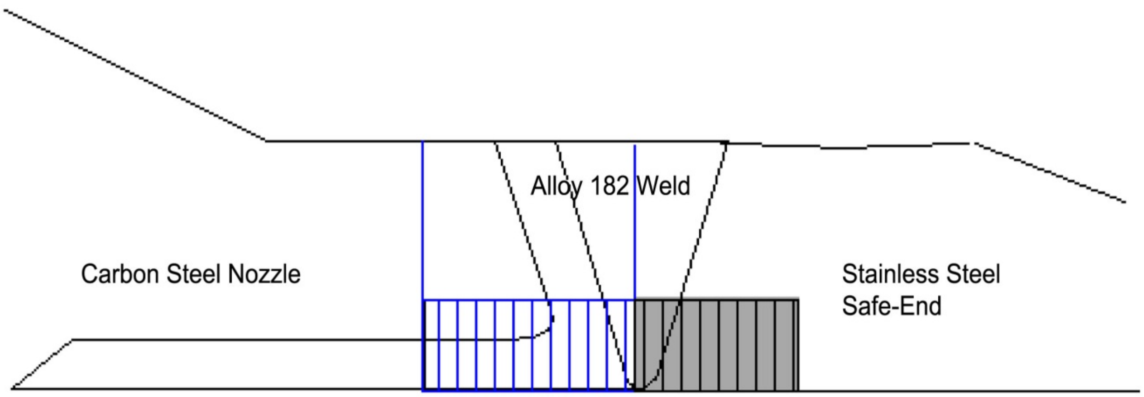


Figure C.7 Pressurizer Spray Nozzle Weld Circumferential Scan CRV Coverage Assessment

C.4 Pressurizer Safety and Relief Nozzle

Figure C.8 Photograph of Pressurizer Safety and Relief Nozzle, Nozzle Weld, and Safe End

The examination limitations for the pressurizer safety and relief nozzle Alloy 82/182 butt weld were minimal scanning surface and the OD examination surface contour and condition.

The cross-sectional examination coverage in both the axial scan direction for circumferential flaws and in the circumferential direction for axial flaws was 0%. This configuration does not allow a meaningful examination for either circumferential or axial flaws. The cross-sectional examination coverage for both scan directions is depicted in the assessment diagram in Figure C.9.

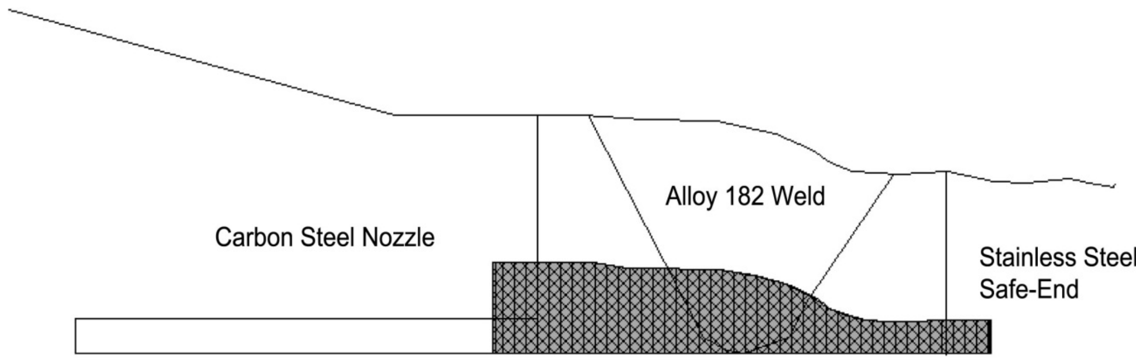


Figure C.9 Pressurizer Safety and Relief Nozzle Weld Axial Scan CRV Coverage Assessment

C.5 Reactor Pressure Vessel Hot Leg Nozzle

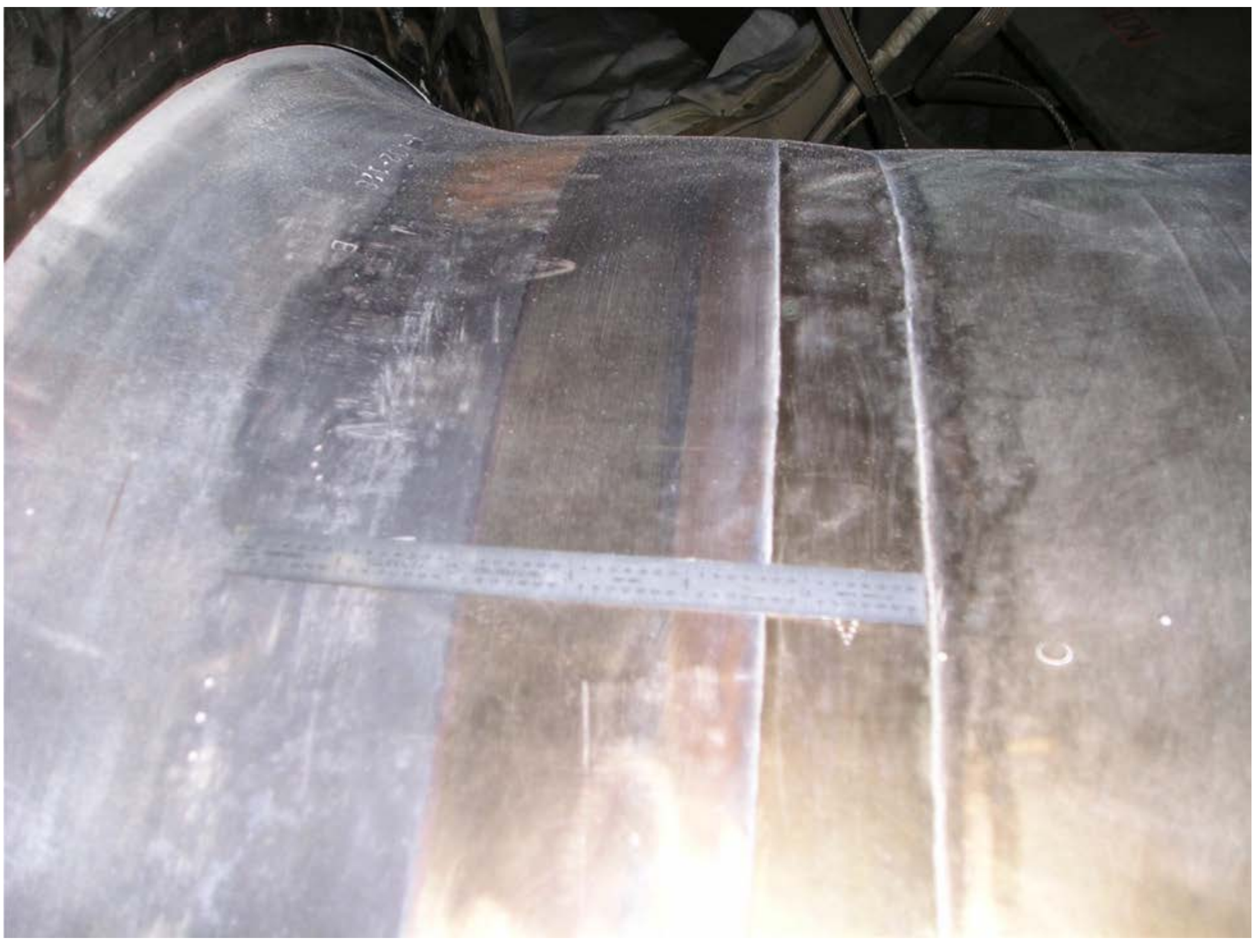


Figure C.10 RPV Hot Leg Nozzle, Nozzle Weld, and Safe End

The examination limitations for the RPV hot leg nozzle Alloy 82/182 butt weld were minimal scanning surface and OD examination surface contour and condition.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure C.11. The axial scan direction CRV coverage achievable was 28.8%. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure C.12. The circumferential scan direction CRV coverage achievable was 100%.

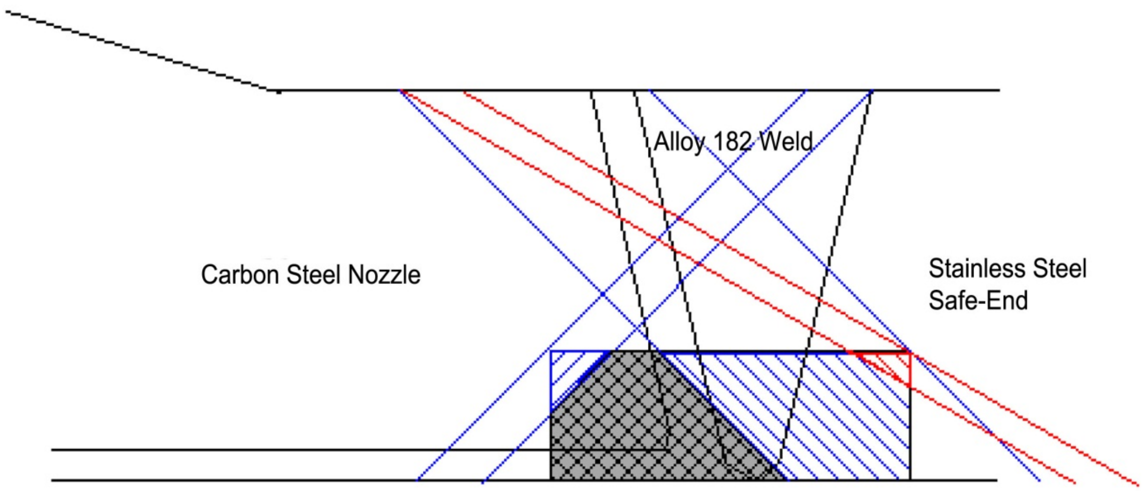


Figure C.11 RPV Hot Leg Nozzle Weld Axial Scan CRV Coverage Assessment

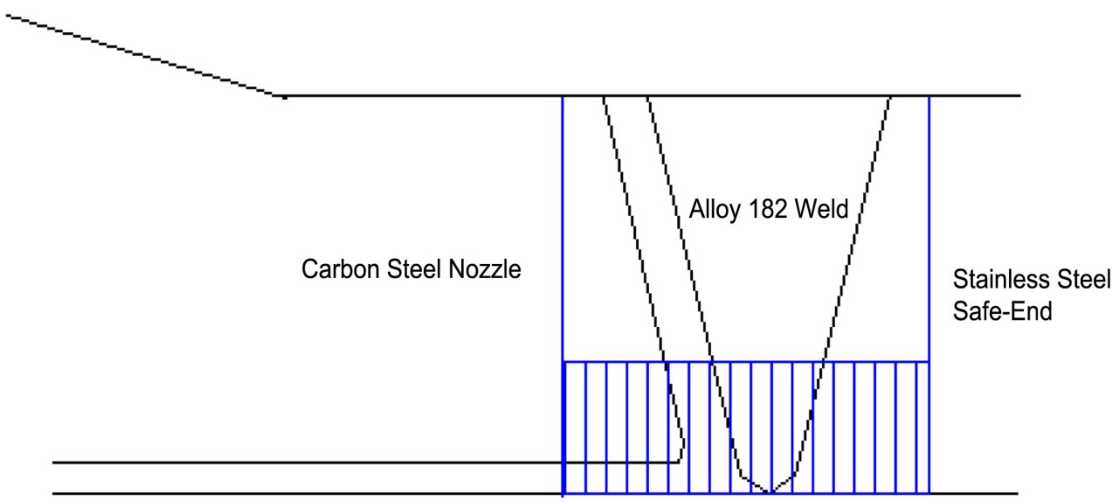


Figure C.12 RPV Hot Leg Nozzle Weld Circumferential Scan CRV Coverage Assessment

C.6 Steam Generator Hot Leg Nozzle

Figure C.13 Photograph of Steam Generator Hot Leg Nozzle, Nozzle Weld, and Safe End

The examination limitations for the steam generator hot leg nozzle Alloy 82/182 butt weld were minimal scanning surface and OD examination surface contour and condition.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure C.14. The axial scan direction CRV coverage achievable was 95.4%. This examination consisted, in part, of a phased-array ultrasonic testing (PAUT) technical justification of performance demonstration per site-specific mockup criteria. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure C.15. The axial scan direction CRV coverage achievable was 100%.

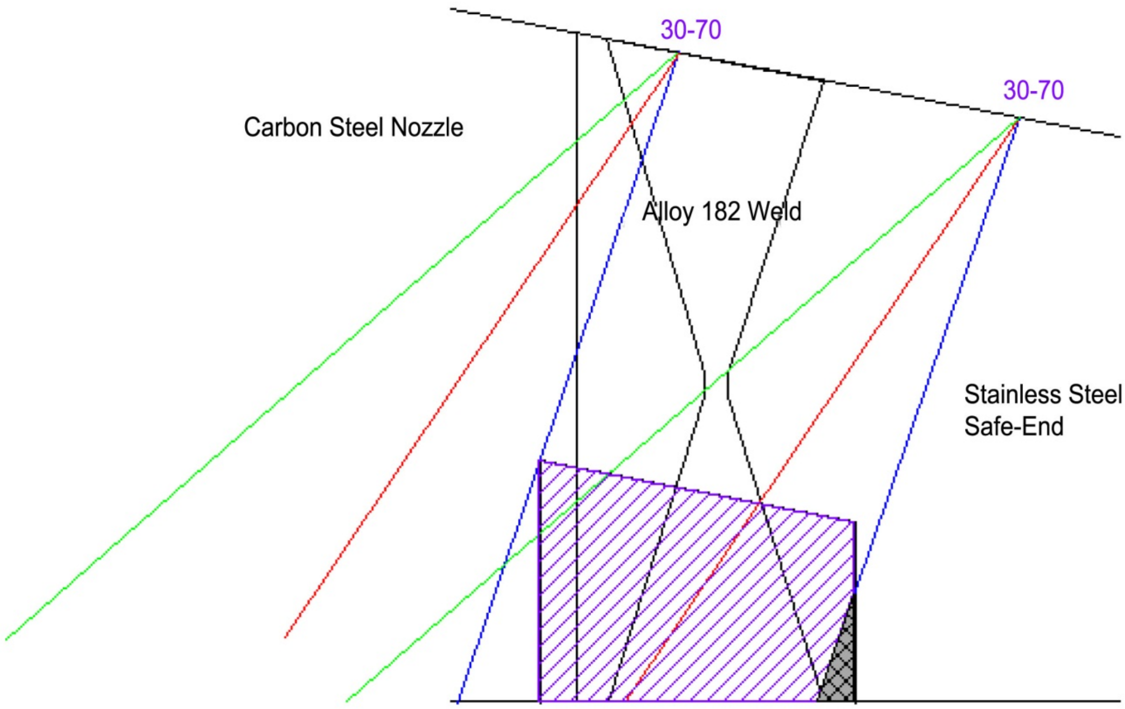


Figure C.14 **Steam Generator Hot Leg Nozzle Weld Axial Scan CRV Coverage Assessment**

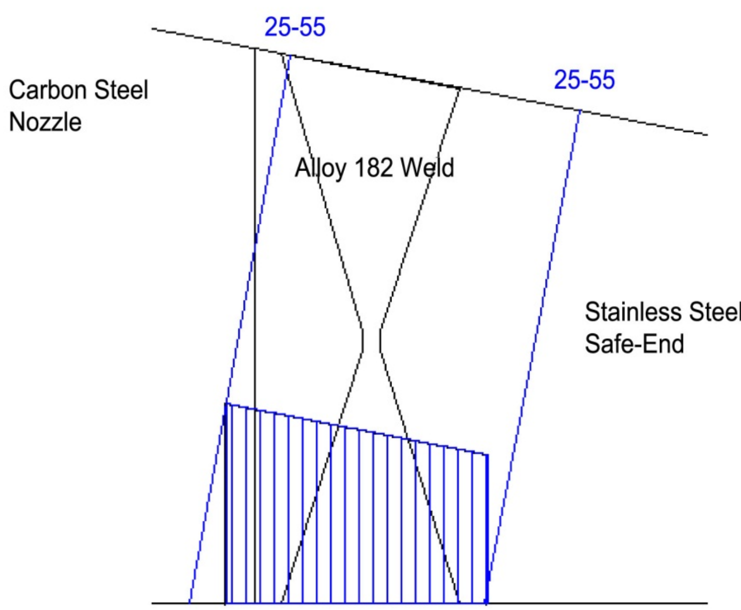


Figure C.15 **Steam Generator Hot Leg Nozzle Weld Circumferential Scan CRV Coverage Assessment**

C.7 Steam Generator Cold Leg Nozzle

Figure C.16 Photograph of Steam Generator Cold Leg Nozzle, Nozzle Weld, and Safe End

The examination limitations for the steam generator cold leg nozzle Alloy 82/182 butt weld were minimal scanning surface and OD examination surface contour and condition.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure C.17. The axial scan direction CRV coverage achievable was 95.4%. This examination consisted, in part, of a PAUT technical justification of performance demonstration per site-specific mockup criteria. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure C.18. The axial scan direction CRV coverage achievable was 100%.

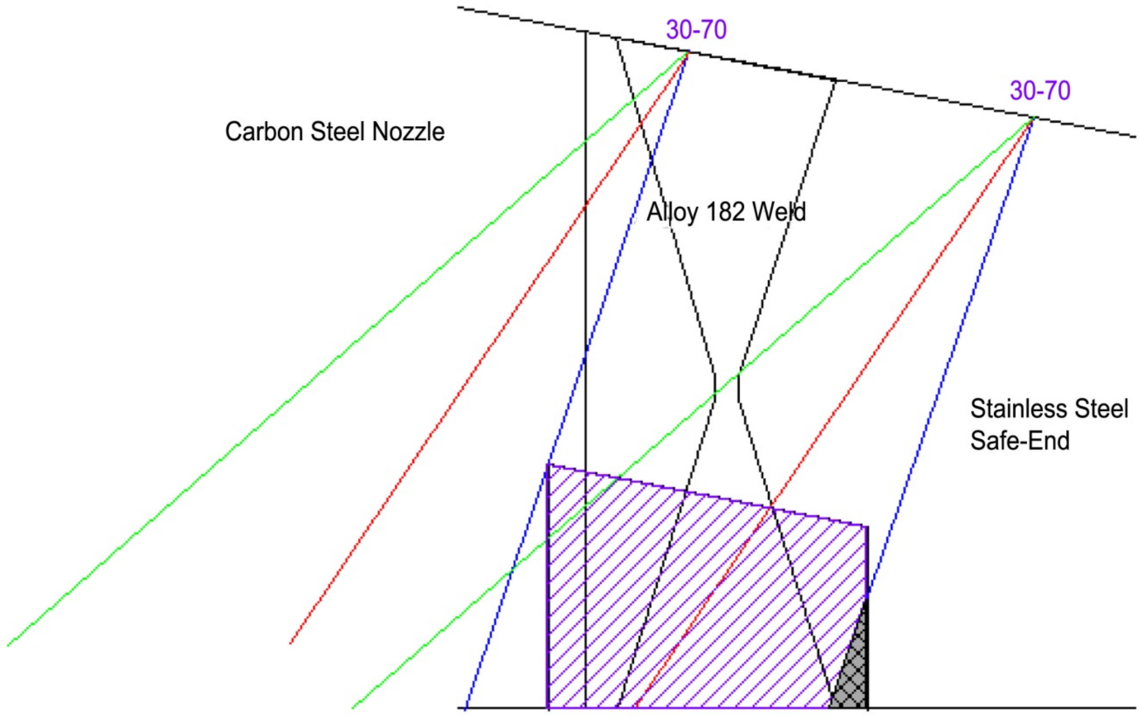


Figure C.17 Steam Generator Cold Leg Nozzle Weld Axial Scan CRV Coverage Assessment

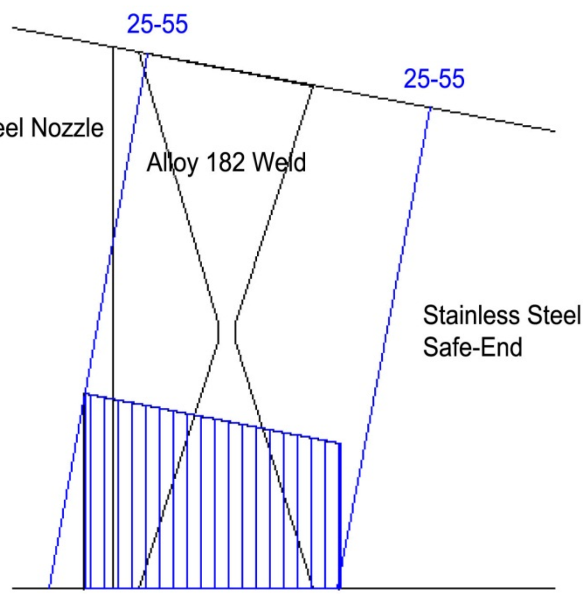


Figure C.18 Steam Generator Cold Leg Nozzle Weld Circumferential Scan CRV Coverage Assessment

C.8 RPV Cold Leg Nozzle

Figure C.19 Photograph of RPV Cold Leg Nozzle

The examination limitations for the RPV cold leg nozzle Alloy 82/182 butt weld were minimal scanning surface and OD examination surface contour and condition.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure C.20. The axial scan direction CRV coverage achievable was 100%. This examination consisted, in part, of a PAUT technical justification of performance demonstration per site-specific mockup criteria. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure C.21. The axial scan direction CRV coverage achievable was 100%.

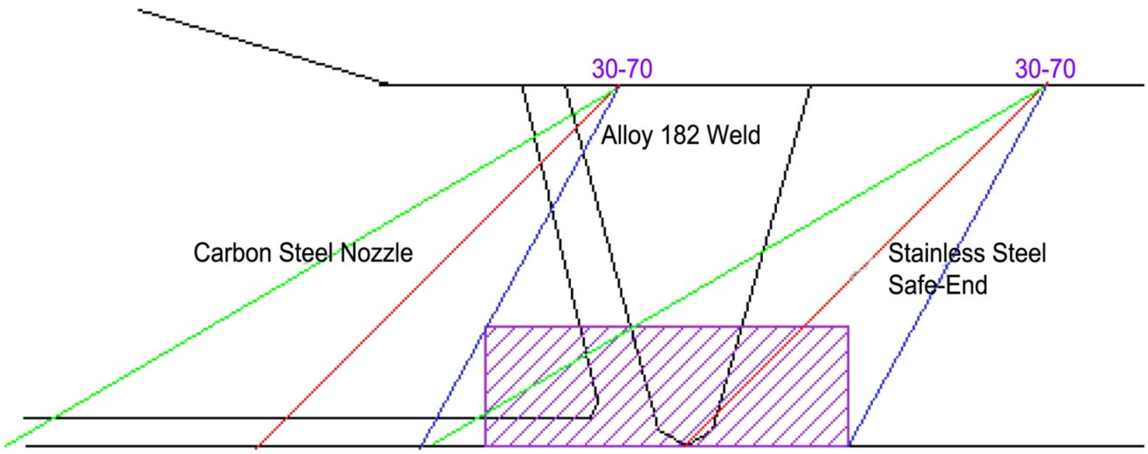


Figure C.20 RPV Cold Leg Nozzle Weld Axial Scan CRV Coverage

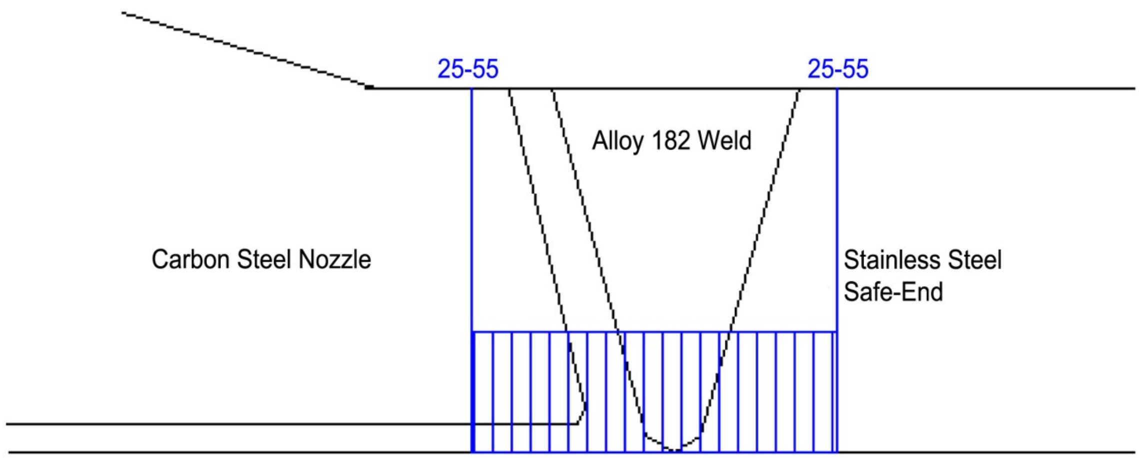


Figure C.21 RPV Cold Leg Nozzle Weld Circumferential Scan CRV Coverage

APPENDIX D

DISSIMILAR METAL WELD INSPECTION LIMITATIONS OF A TYPICAL COMBUSTION ENGINEERING PLANT

APPENDIX D

DISSIMILAR METAL WELD INSPECTION LIMITATIONS OF A TYPICAL COMBUSTION ENGINEERING PLANT

D.1 Introduction

The information contained in this appendix was obtained during a workshop held with LMT, Inc., an inspection vendor for the commercial nuclear power industry. This vendor uses ultrasonic testing (UT) inspection methods qualified under ASME Code, Section XI, Appendix VIII, including phased-array (PA) techniques and conventional UT techniques in encoded and non-encoded delivery modes, as specified by the utility. This workshop was held to discuss the characteristics of UT data of indications attributed to stress corrosion cracking (SCC). This data was from encoded examinations of piping welds acquired from scans of the outside diameter (OD) surface. This workshop was also held to discuss limitations to achieving Code-required volume (CRV) coverage on Alloy 82/182 butt welds in a typical Westinghouse plant and a typical Combustion Engineering (CE) plant. This appendix provides information on limitations to obtaining the CRV coverage that may be encountered during examinations of Alloy 82/182 butt welds in the reactor coolant system in a CE plant.

Table D.1 provides a listing of the Alloy 82/182 butt welds that are typically found in a CE plant. The location of these welds is depicted in Figure D.1. The CRV coverage for the Alloy 82/182 butt welds in the piping systems in Table D.1 is dependent on site-specific configurations and allowable scan access thereof. Site-specific designs vary in regards to material and component configuration(s). Therefore, the coverage depicted is applicable only to the site-specific design used to prepare this document. Standard 45° and 60° angles were utilized for CRV coverage assessments unless specified otherwise in the illustrations.

Table D.1 Alloy 82/182 Butt Welds and Dimensions in Typical CE Plant

Description	Quantity	Circumference (Weld Centerline)	Thickness (Weld Centerline)
RCP Suction to RC Pipe	4	36.60 in. (92.96 cm)	3.45 in. (8.76 cm)
RCP Discharge to RC Pipe	4	36.60 in. (92.96 cm)	3.35 in. (8.51 cm)
RC Loop Surge Nozzle	1	42.00 in. (106.68 cm)	1.57 in. (3.99 cm)
Letdown and Drain Nozzle	4	3.90 in. (9.91 cm)	0.90 in. (2.29 cm)
Hot Leg Drain Nozzle	1	3.90 in. (9.91 cm)	0.90 in. (2.29 cm)
Charging Inlet Nozzle	2	18.00 in. (45.72 cm)	1.20 in. (3.05 cm)
Safety Injection Nozzle	4	42.00 in. (106.68 cm)	1.55 in. (3.94 cm)
Shutdown Cooling Nozzle	1	50.25 in. (127.64 cm)	1.57 in. (3.99 cm)
Spray Nozzle	2	16.00 in. (40.64 cm)	0.93 in. (2.36 cm)
PZR Surge Nozzle	1	41.00 in. (104.14 cm)	1.59 in. (4.04 cm)
PZR Spray Nozzle	1	5.20 in. (13.21 cm)	0.83 in. (2.11 cm)
PZR Safety Nozzle	3	7.95 in. (20.19 cm)	1.40 in. (3.56 cm)

RCP – reactor coolant pump; RC – reactor coolant; PZR – pressurizer

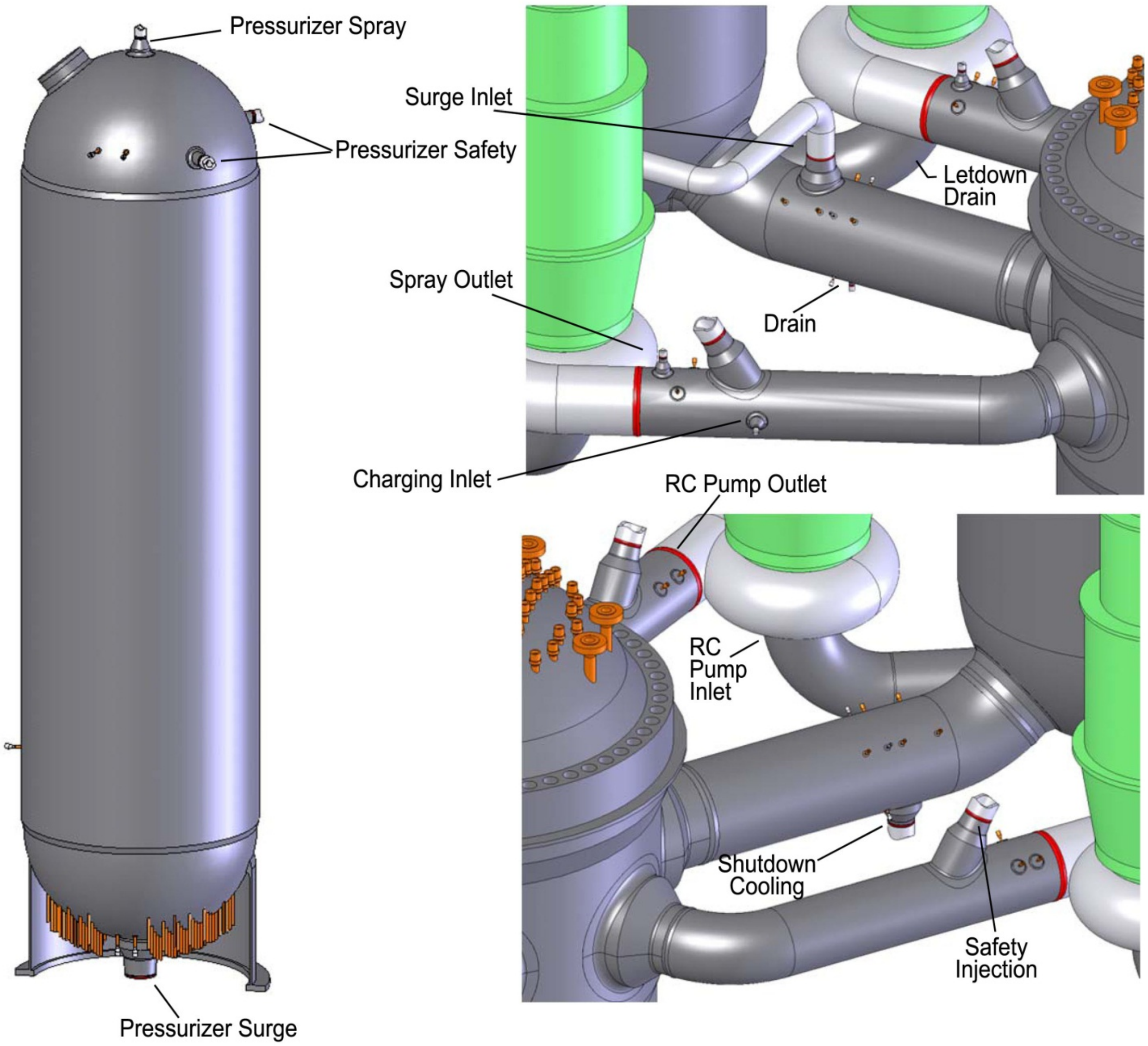


Figure D.1 Typical Locations of Alloy 82/182 Butt Welds in CE Design Plants

D.2 Reactor Coolant Pump (RCP) Suction

Figure D.2 Photograph of RCP Suction Nozzle, Nozzle Weld, and Safe End

The examination limitations for the RCP suction nozzle Alloy 82/182 butt weld were the cast austenitic stainless steel (CASS) pump nozzle material on the downstream side of the Alloy 82/182 weld and the examination surface (OD) contour /condition.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure D.3. The axial scan direction CRV coverage achievable was 100%. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure D.4. The circumferential scan direction CRV coverage achievable was 44.3%.

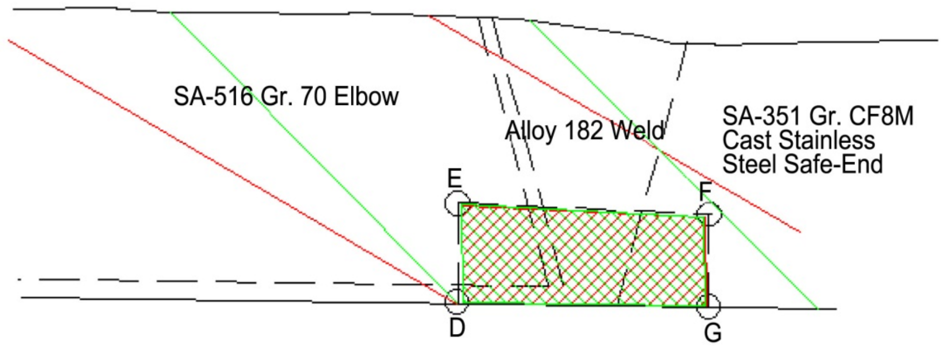


Figure D.3 RCP Suction Nozzle Weld Axial Scan Coverage Assessment

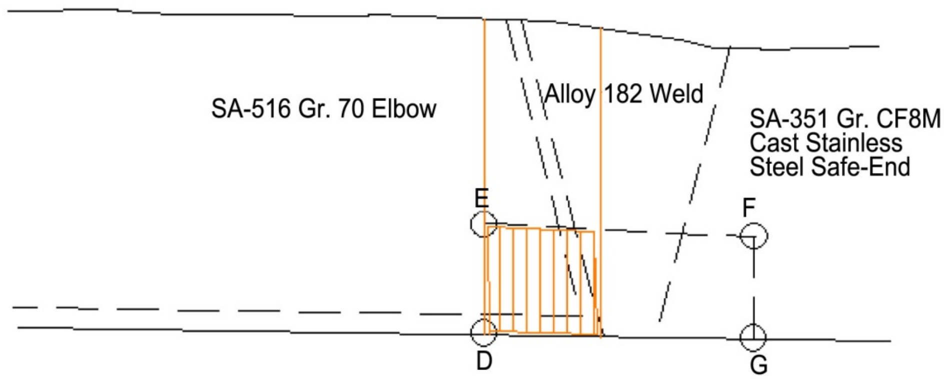


Figure D.4 RCP Suction Nozzle Weld Circumferential Scan Coverage Assessment

D.3 Reactor Coolant Pump Discharge

Figure D.5 Photograph of RCP Discharge Nozzle, Nozzle Weld, and Safe End

The examination limitations for the RCP discharge nozzle Alloy 82/182 butt weld were the CASS pump nozzle material on the upstream side of the Alloy 82/182 weld; the examination surface (OD) contour/condition; and instrumentation, safety injection, charging and spray nozzle connections. No coverage was obtainable in the locations where nozzle connections interfere with probe travel.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure D.6. The axial scan direction CRV coverage achievable was 77%. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure D.7. The circumferential scan direction CRV coverage achievable was 34%.

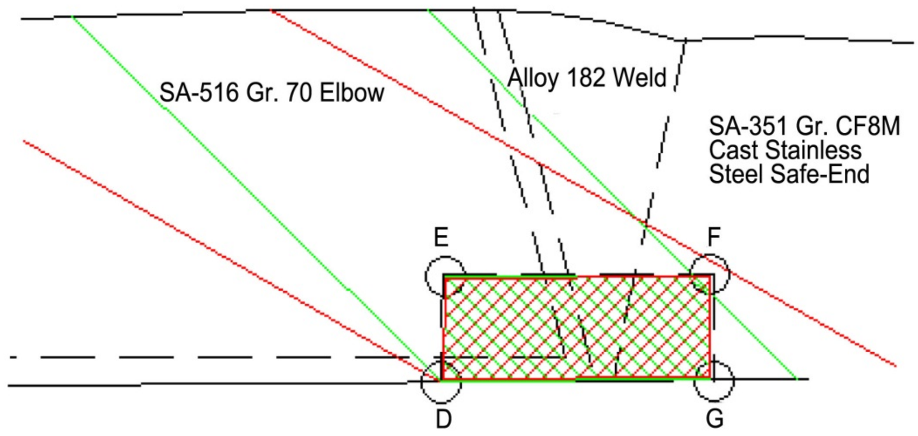


Figure D.6 RCP Discharge Nozzle Weld Axial Scan CRV Coverage Assessment

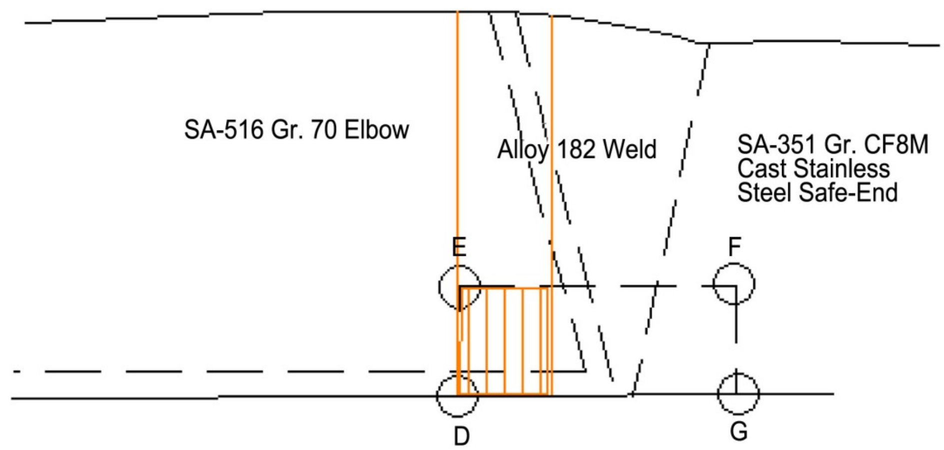


Figure D.7 RCP Discharge Nozzle Weld Circumferential Scan CRV Coverage Assessment

D.4 Reactor Coolant (RC) Loop Surge

Figure D.8 Photograph of Surge Nozzle, Nozzle Weld, and Safe End

The examination limitations for the surge nozzle Alloy 82/182 butt weld were the CASS safe end material on downstream side of the Alloy 82/182 weld and the examination surface (OD) contour/ condition.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure D.9. The axial scan direction CRV coverage achievable was 82.4%. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure D.10. The circumferential scan direction CRV coverage achievable was 31.3%.

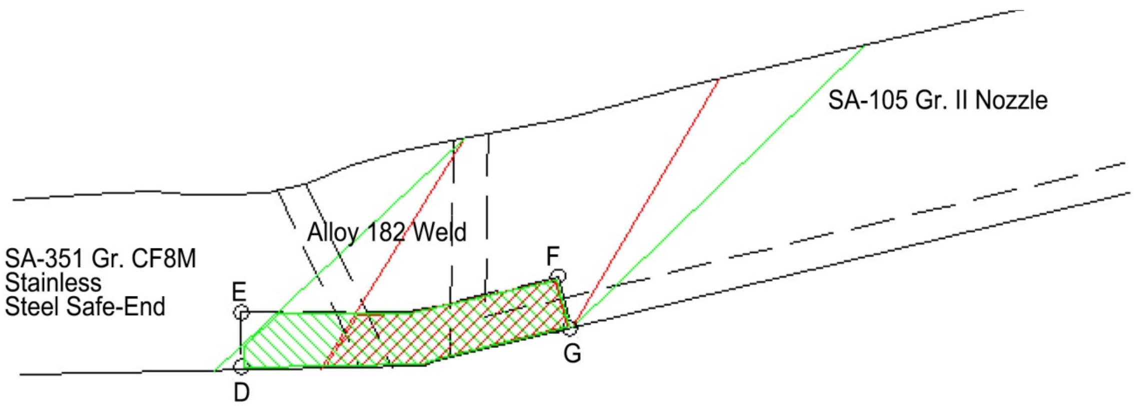


Figure D.9 Surge Nozzle Weld Axial Scan CRV Coverage Assessment

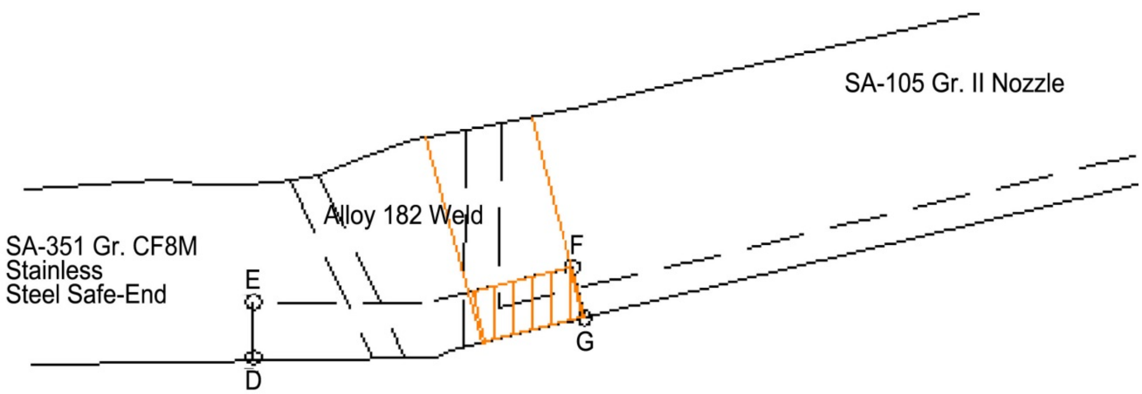


Figure D.10 Surge Nozzle Weld Circumferential Axial Scan CRV Coverage Assessment

D.5 Letdown and Drain

Figure D.11 Photograph of Letdown and Drain Nozzle, Nozzle Weld, and Safe End

There were no examination limitations for the letdown and drain nozzle Alloy 82/182 butt weld.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure D.12. The axial scan direction CRV coverage achievable was 100%. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure D.13. The circumferential scan direction CRV coverage achievable was 100%.

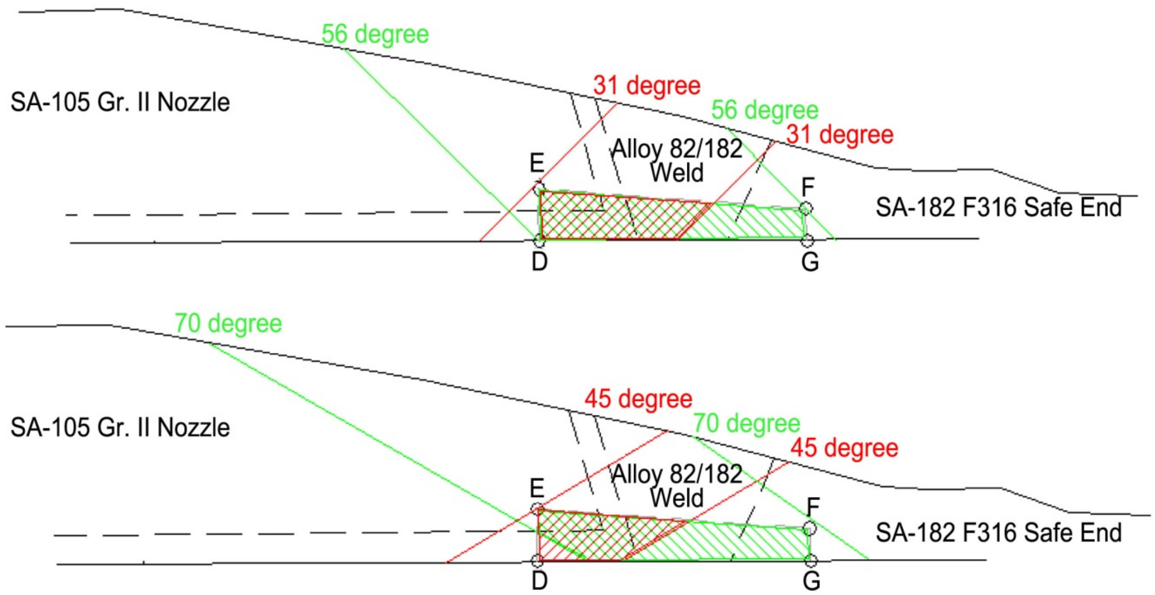


Figure D.12 Letdown and Drain Nozzle Weld Axial Scan CRV Coverage Assessment

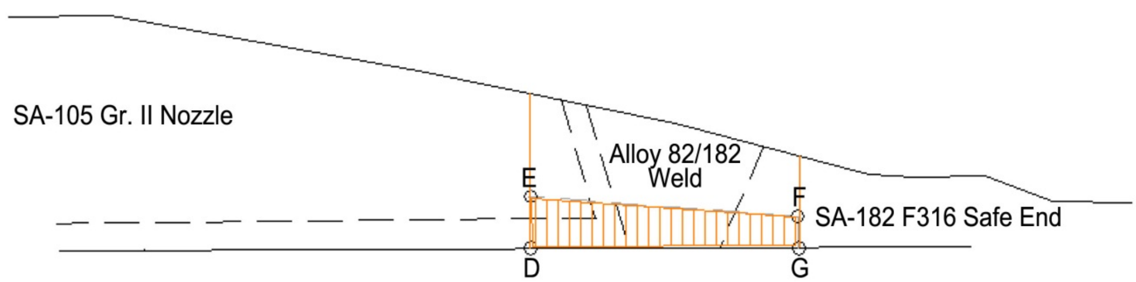


Figure D.13 Letdown and Drain Nozzle Weld Circumferential Scan CRV Coverage Assessment

D.6 Hot Leg Drain

Figure D.14 Photograph of Hot Leg Drain Nozzle, Nozzle Weld, and Safe End

There were no examination limitations for the hot leg drain nozzle Alloy 82/182 butt weld.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure D.15. The axial scan direction CRV coverage achievable was 100%. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure D.16. The circumferential scan direction CRV coverage achievable was 100%.

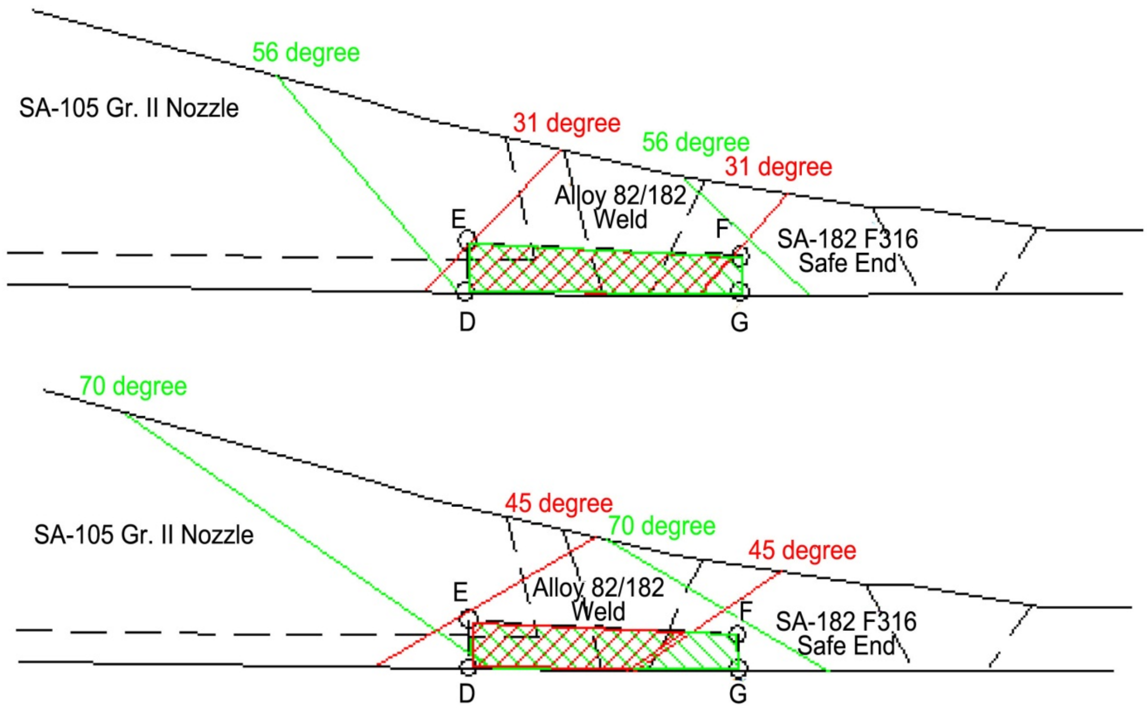


Figure D.15 Hot Leg Drain Nozzle Weld Axial Scan CRV Coverage Assessment

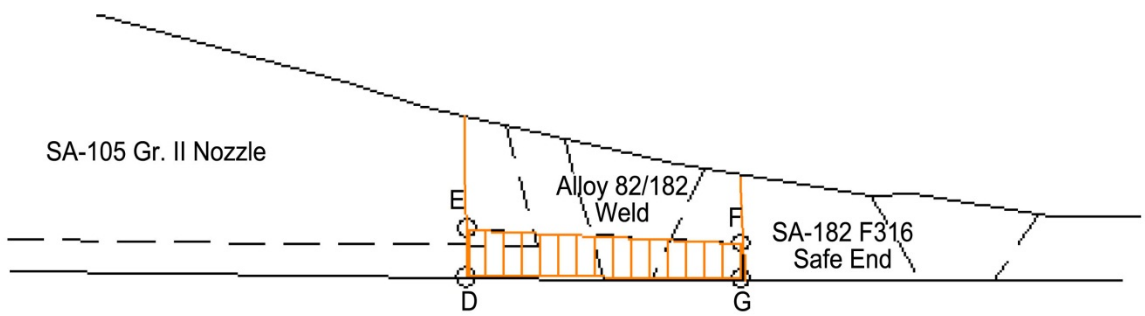


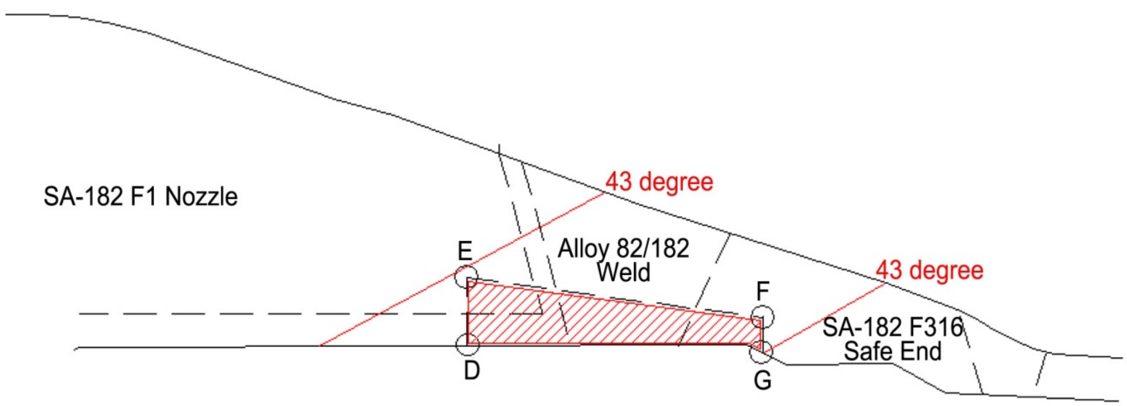
Figure D.16 Hot Leg Drain Nozzle Weld Circumferential Scan CRV Coverage Assessment

D.7 Charging Inlet

Figure D.17 Photograph of Charging Inlet Nozzle, Nozzle Weld, and Safe End

There were no examination limitations for the charging inlet nozzle Alloy 82/182 butt weld.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure D.18. The axial scan direction CRV coverage achievable was 100%. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure D.19. The circumferential scan direction CRV coverage achievable was 100%.



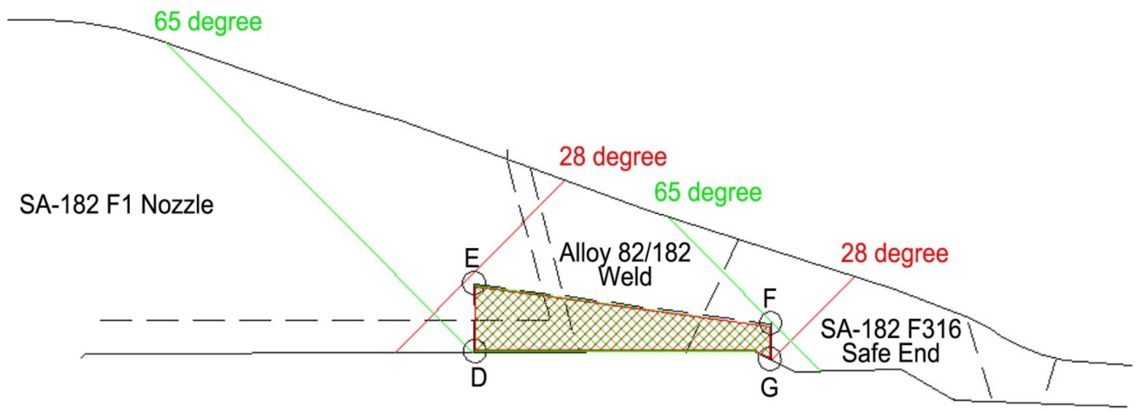


Figure D.18 Charging Inlet Nozzle Weld Axial Scan CRV Coverage Assessment

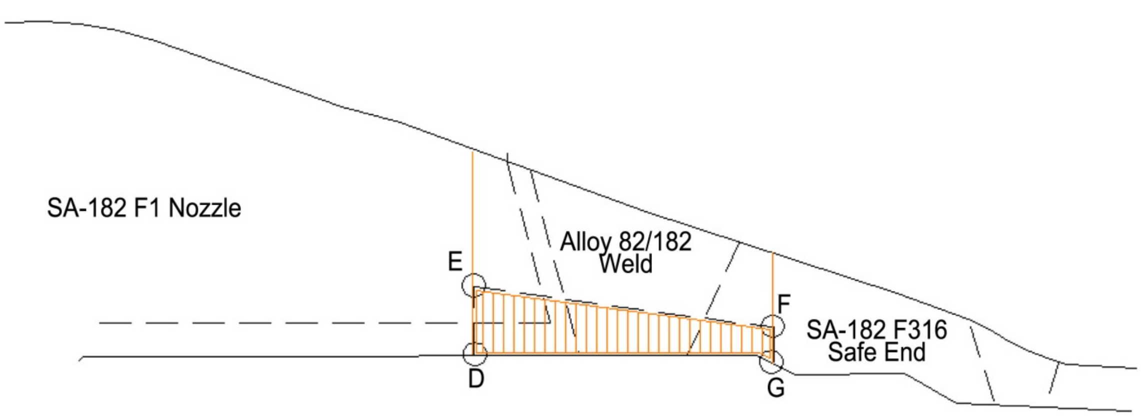


Figure D.19 Charging Inlet Nozzle Weld Circumferential Scan CRV Coverage Assessment

D.8 Safety Injection

Figure D.20 Photograph of Safety Injection Nozzle, Nozzle Weld, and Safe End

The examination limitations for the safety injection nozzle Alloy 82/182 butt weld were the CASS safe end material on upstream side of the Alloy 82/182 weld and the examination surface (OD) contour/ condition.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure D.21. The axial scan direction CRV coverage achievable was 94.3%. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure D.22. The circumferential scan direction CRV coverage achievable was 26.6%.

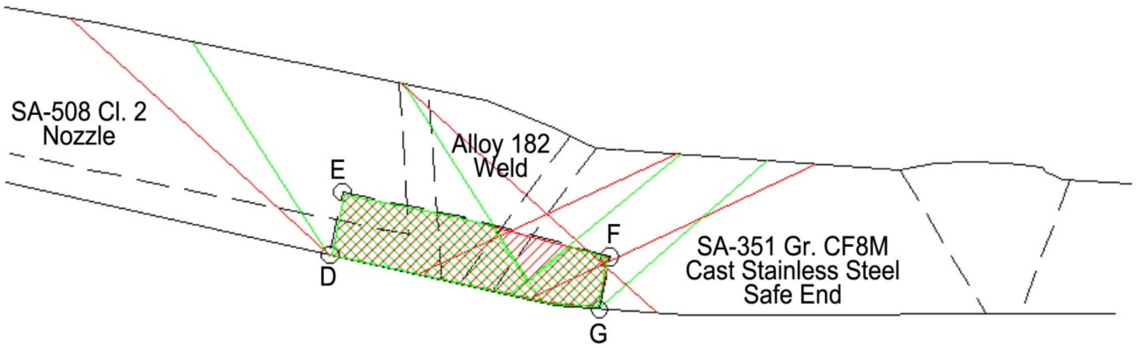


Figure D.21 Safety Injection Nozzle Weld Axial Scan CRV Coverage Assessment

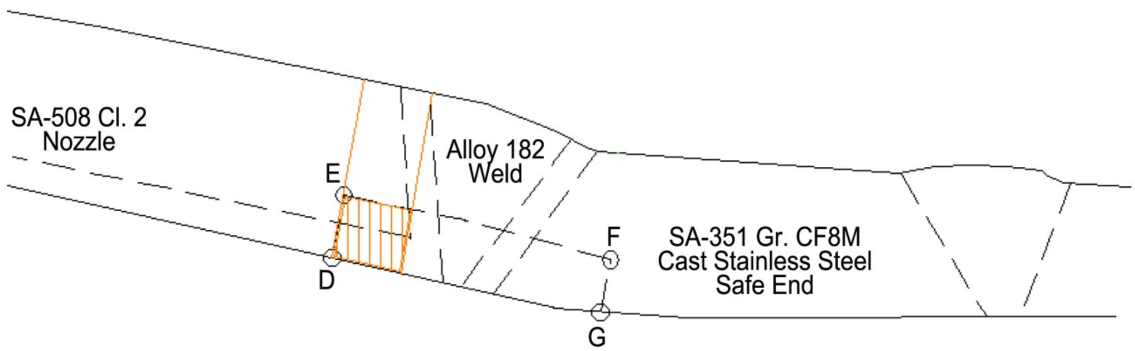


Figure D.22 Safety Injection Nozzle Weld Circumferential Scan CRV Coverage Assessment

D.9 Shutdown Cooling

Figure D.23 Photograph of Shutdown Cooling Nozzle, Nozzle Weld, and Safe End

The examination limitations for the shutdown cooling nozzle Alloy 82/182 butt weld were the CASS safe end material on the downstream side of the Alloy 82/182 weld and the examination surface (OD) contour /condition.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure D.24. The axial scan direction CRV coverage achievable was 98%. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure D.25. The circumferential scan direction CRV coverage achievable was 100%.

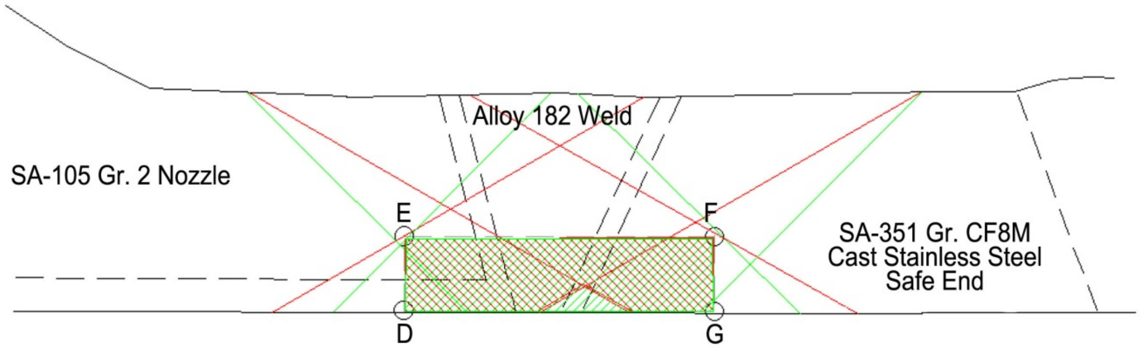


Figure D.24 Shutdown Cooling Nozzle Weld Axial Scan CRV Coverage Assessment

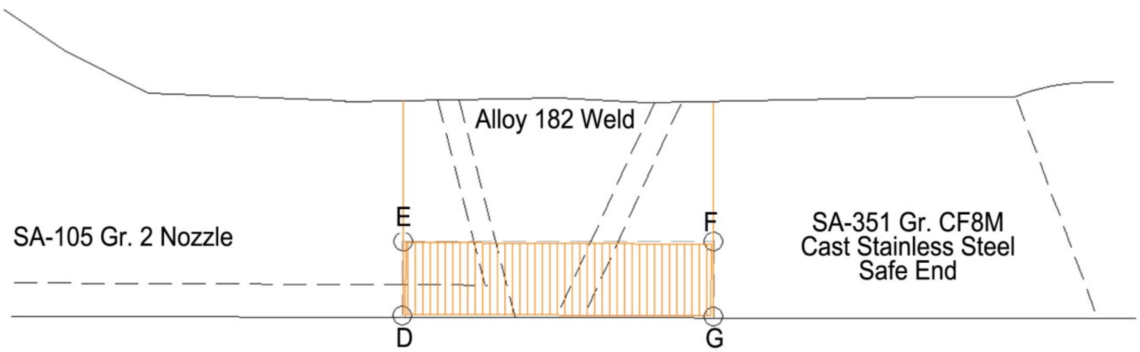


Figure D.25 Shutdown Cooling Nozzle Weld Circumferential Scan CRV Coverage Assessment

D.10 Spray

Figure D.26 Photograph of Spray Nozzle, Nozzle Weld, and Safe End

There were no examination limitations for the spray nozzle Alloy 82/182 butt.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure D.27. The axial scan direction CRV coverage achievable was 100%. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure D.28. The circumferential scan direction CRV coverage achievable was 100%.

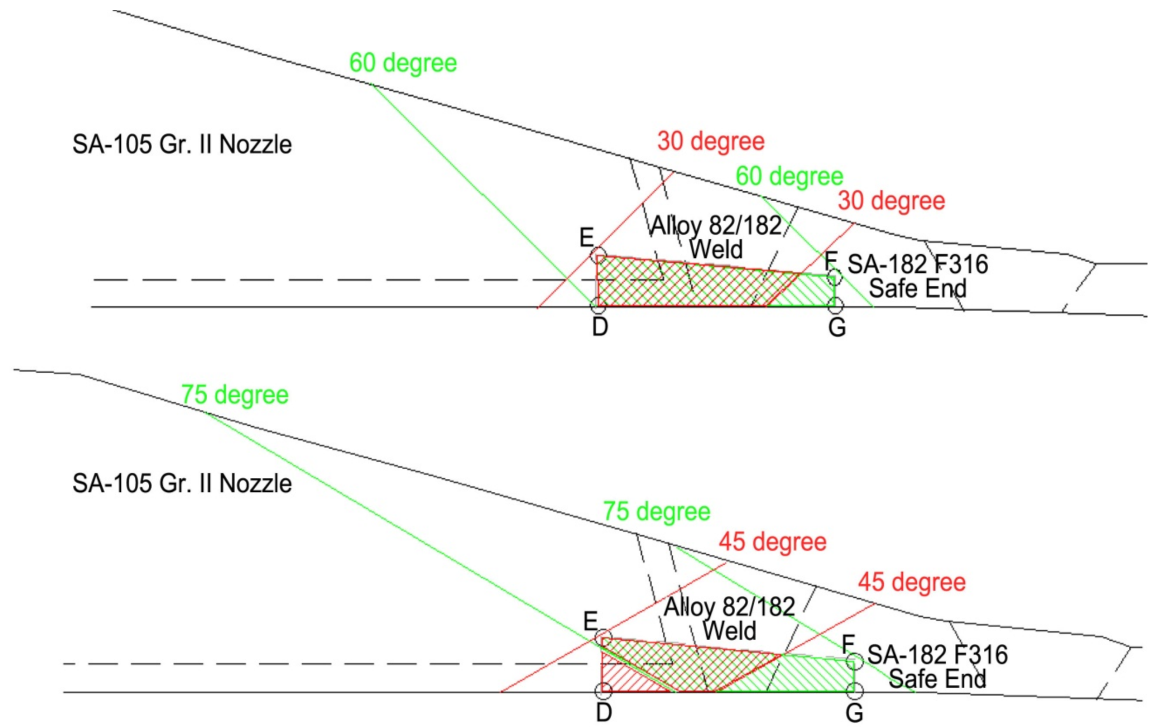


Figure D.27 Spray Nozzle Weld Axial Scan CRV Coverage Assessment

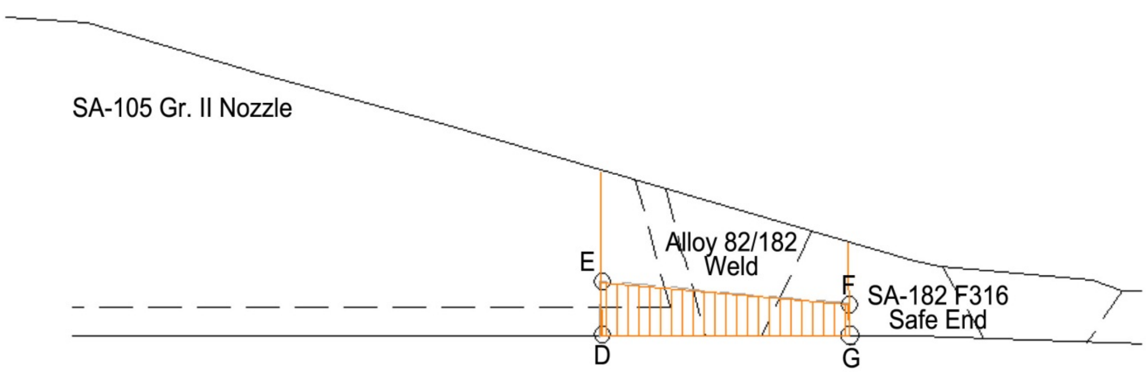


Figure D.28 Spray Nozzle Weld Circumferential Scan CRV Coverage Assessment

D.11 Pressurizer Surge

Figure D.29 Photograph of Pressurizer Surge Nozzle, Nozzle Weld, and Safe End

There were no examination limitations for the pressurizer surge nozzle Alloy 82/182 butt weld.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure D.30. The axial scan direction CRV coverage achievable was 100%. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure D.31. The circumferential scan direction CRV coverage achievable was 100%.

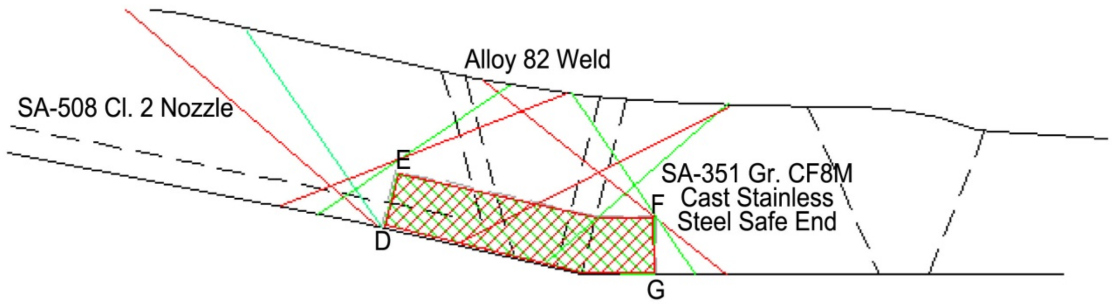


Figure D.30 Pressurizer Surge Nozzle Weld Axial Scan CRV Coverage Assessment

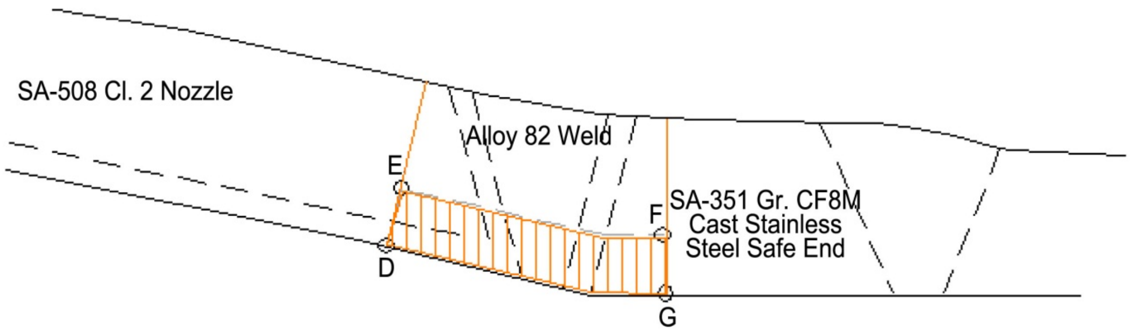


Figure D.31 Pressurizer Surge Nozzle Weld Circumferential Scan CRV Coverage Assessment

D.12 Pressurizer Spray

Figure D.32 Photograph of Pressurizer Spray Nozzle, Nozzle Weld, and Safe End

The examination limitation for the pressurizer spray nozzle Alloy 82/182 butt weld was the examination surface (OD) contour /condition.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure D.33. The axial scan direction CRV coverage achievable was 100%. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure D.34. The circumferential scan direction CRV coverage achievable was 68.9%.

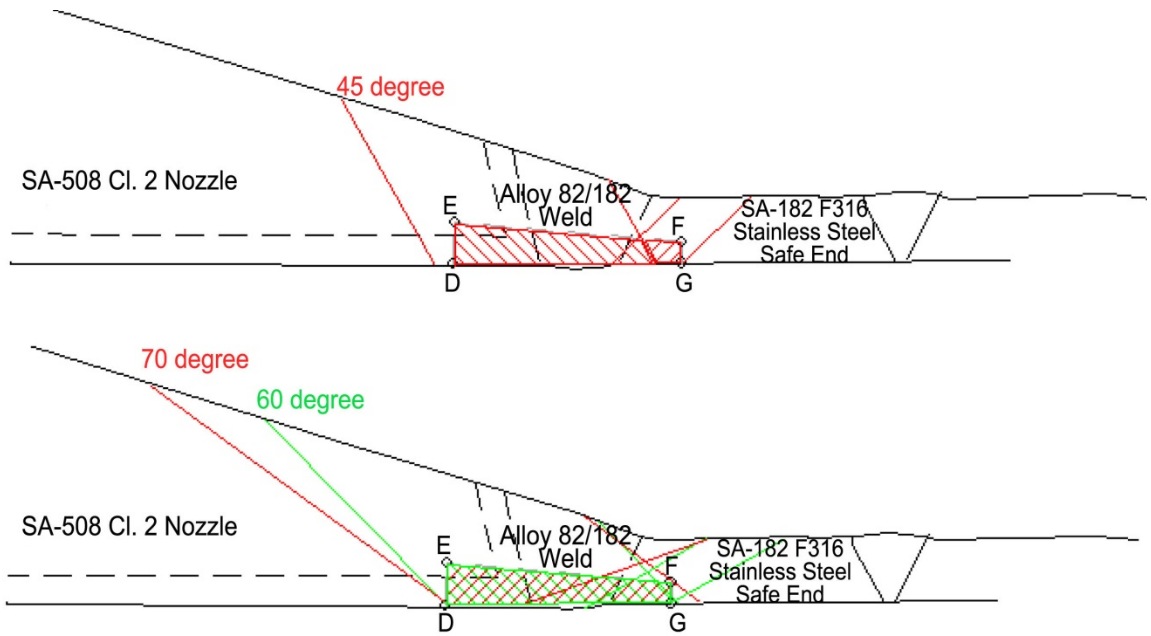


Figure D.33 Pressurizer Spray Nozzle Weld Axial Scan CRV Coverage Assessment

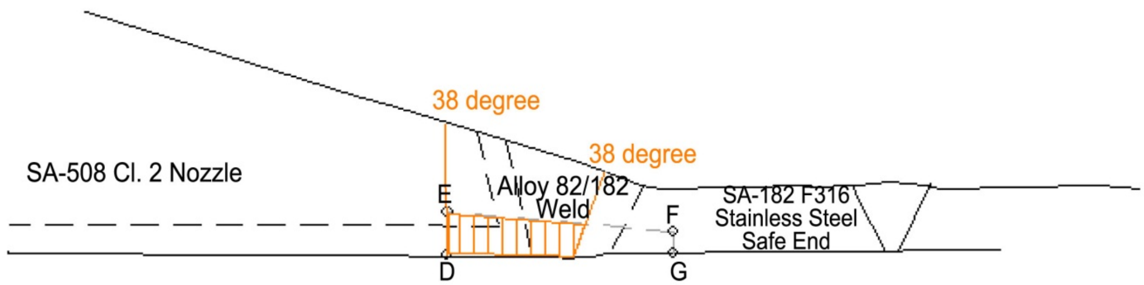


Figure D.34 Pressurizer Spray Nozzle Weld Circumferential Scan CRV Coverage Assessment

D.13 Pressurizer Safety & Relief

Figure D.35 Photograph of Pressurizer Safety & Relief Nozzle, Nozzle Weld, and Safe End

There were no examination limitations for the pressurizer safety and relief nozzle Alloy 82/182 butt weld.

The cross-sectional examination coverage in the axial scan direction for circumferential flaws is depicted in Figure D.36. The axial scan direction CRV coverage achievable was 100%. The cross-sectional examination coverage in the circumferential scan direction for axial flaws is depicted in Figure D.37. The circumferential scan direction CRV coverage achievable was 100%.

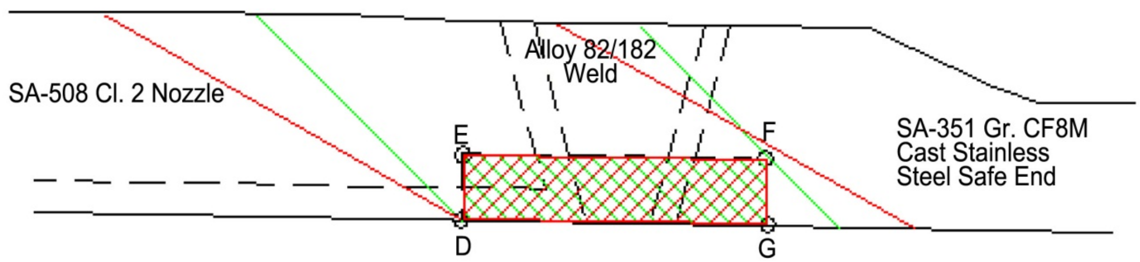


Figure D.36 Pressurizer Safety and Relief Nozzle Weld Axial Scan CRV Coverage Assessment

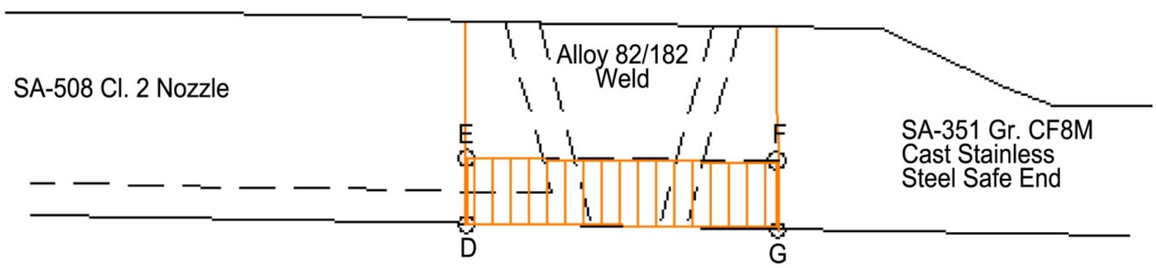


Figure D.37 Pressurizer Safety and Relief Nozzle Weld Circumferential Scan CRV Coverage Assessment

APPENDIX E

ASSESSMENT OF WELD RESIDUAL STRESS AND CRACK GROWTH ANALYSIS IN UNMITIGATED WELDS

APPENDIX E

ASSESSMENT OF WELD RESIDUAL STRESS AND CRACK GROWTH ANALYSES IN UNMITIGATED WELDS

This appendix contains a summary of the results of four crack growth studies that were assessed for insights they provide regarding the inspection intervals for unmitigated Alloy 82/182 welds specified in ASME Code Case N-770-1. The conclusions reached regarding the Code Case inspection intervals are reported in Section 3.4.4.

E.1 Results from BCL Mitigation Studies

U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research (RES) initiated a program entitled, "PWSCC in Leak-Before-Break Systems," to assess strategies for managing primary water stress corrosion cracking (PWSCC) in susceptible welds in leak-before-break systems. Under this RES program, Battelle Columbus Laboratory (BCL) performed two weld residual stress (WRS) and crack growth studies (Fredette and Scott 2009, 2010). The stress and crack growth results shown in Table E.1 are summarized from the studies performed by BCL under this program. Pacific Northwest National Laboratory (PNNL) assessed these results in an effort to gain insights on Code Case N-770-1 inspection intervals for unmitigated welds. Three dissimilar metal weld (DMW) pipe/nozzle geometries were considered in a BCL study on mitigation against PWSCC by the mechanical stress improvement process (MSIP) (Fredette and Scott 2009): (1) a large-diameter hot leg (HL) reactor pressure vessel (RPV) nozzle weld, (2) a medium-diameter pressurizer surge nozzle weld, and (3) a small-diameter pressurizer safety nozzle weld. In the second study, BCL analyzed welds being mitigated against PWSCC by weld overlays (Fredette and Scott 2010). However, crack growth results were only reported for the surge nozzle and the safety nozzle and, for unmitigated welds, were the same as provided in BCL's study on MSIP.

In modeling these pressurized water reactor (PWR) dissimilar metal welds, the application of the butter to the ferritic nozzle was modeled along with the post-weld heat treatment of the butter material. In addition, the weld root passes were ground out and re-welded as part of these analyses to simulate this common practice in the field. This full-circumferential grind-out/re-welding resulted in a residual stress field similar to that of a 360° inside surface repair weld. The results in Table E.1 are based on axisymmetric models. The stress intensities were calculated for normal operating pressure and temperature conditions and did not consider external bending moments.

Table E.1 Crack Growth Results from BCL Studies

System	Safe End	Crack Location	ID Axial Stress	K-Value (ksi-√in)[a]	Crack Growth Comments
Hot Leg RV Nozzle	No	Butter/Weld	40 ksi at weld centerline	17 ksi-√in at ID; 30 at 15%; 0 from 33% to 70% TW	Arrest by 33% TW
Hot Leg RV Nozzle	No	Ferritic/Butter	40 ksi at weld centerline	17 ksi-√in at ID; 25 at 11% TW; 0 from 33% on	Arrest by 33% TW
Surge Nozzle	Yes	Butter/Weld	–30 ksi at weld centerline	0 ksi-√in to 14% TW; 5 at 31% TW; 0 from 40% to 70% TW	Unlikely to initiate
Surge Nozzle	Yes	Ferritic/Weld	–30 ksi at weld centerline	0 ksi-√in to 14% TW; 8 at 22% TW; 0 from 36% to 68% TW	Unlikely to initiate
Safety Nozzle	Yes	Butter/Weld	–50 ksi at weld centerline	0 ksi-√in to 10% TW; 2.5 at 25% TW; 0 from 33% to 60% TW	Unlikely to initiate
Safety Nozzle	Yes	Ferritic/Butter	–50 ksi at weld centerline	0 ksi-√in to 64% TW	Unlikely to initiate

RV = reactor vessel; TW = through-wall
(a) 1 ksi-√in = 1.099 MPa-√m

The following concluding points can be made about this study.

- The analyses for the three nozzle welds shown in Table E.1 showed that if cracking were to initiate, it would arrest before cracking reached about one-third through-wall. This same result is shown even for the HL nozzle weld that does not have the beneficial compressive WRS effect of the secondary stainless steel safe end weld.
- These analyses were not conventional crack growth analyses and did not include external bending loads. Sensitivity analyses discussed below resulted in many fewer cases of arrested flaws.

E.2 Results from Pressurizer Nozzle Advanced Finite Element Analyses

Results were assessed of finite element analyses published in August 2007 by industry (EPRI 2007a) and by NRC staff (Rudland et al. 2007b). These results were used to assess Code Case N-770-1 ultrasonic testing (UT) inspection intervals for Inspection Item A-1, unmitigated butt welds at operating temperature greater than 625°F. This inspection item applies to welds attached to the pressurizer. Some of the finite element analyses were based on an initial flaw size derived from an inspection performed in October 2006 at the Wolf Creek plant on pressurizer nozzle Alloy 82/182 butt welds. Cracking in these welds at Wolf Creek was attributed to PWSCC.

The emphasis of the August 2007 analyses was to use advanced finite element analysis (AFEA) methods to remove the semi-elliptical flaw assumption that is typical in ASME Section XI flaw evaluations. Using this AFEA method, detailed sensitivity cases were analyzed to demonstrate that sufficient margins were available to allow pressurizer nozzle weld inspections of nine plants to be performed at their next refueling outages, rather than during forced mid-cycle outage shutdowns.

This assessment was based on the AFE sensitivity analyses performed on the surge nozzle welds. Table E.2 summarizes a number of the cases performed by both sets of analysts, industry, and the NRC. The first nine entries are from industry's analyses (EPRI 2007a) and the last seven entries are from the NRC staff's analyses (Rudland et al. 2007b).

Table E.2 Advanced Finite Element Analysis of Circumferential Flaw Growth in Surge Nozzle Welds

Case No.	Loads	Initial Flaw(s)	Safe End	Time to Leakage	Time from 1 gpm to Stability Margin = 1.2
18a	Low	10% TW, 360°	With safe end	Arrest	Not Applicable
19b	High	26% TW, 21/1 AR	With safe end	Arrest	Not Applicable
20b	Low	10% TW, 360°	With safe end	Arrest	Not Applicable
26a	Low, ID repair	10% TW, 360°	With safe end	2.2 years	>>40 days
17b	High	26% TW, 21/1 AR	Without safe end	1.2 years	35 days
18b	Low	10% TW, 360°	Without safe end	11.5 yrs	43 days
25b	High, ID repair	26% TW, 21/1 AR	Without safe end	0.5 year	68 days
S2b	High	10% TW, 360°	Without safe end	3.4 years	4 days[(a)]
S3b	High	10% TW, 5.6/1 AR	Without safe end	2.2 years	74 days
17-4	High, DEI WRS	10% TW, 360°	With safe end	5.8 years	1.07 month
17-6	High, Emc^2 WRS	10% TW, 360°	With safe end	Arrest	Not applicable
17-8	High, DEI WRS	26% TW, 21/1 AR	With safe end	6.15 years	Not calculated[(b)]
17-9	High, DEI WRS	10% TW, 360°	Without safe end	1.39 years	Not available[(c)]
17-10	Medium, DEI WRS	10% TW, 360°	Without safe end	2.84 years	0.64 month
17-11	High, DEI WRS, ID repair	10% TW, 360°	Without safe end	0.86 year	0.31 month
17	High, DEI WRS	10% TW, 360°	Without safe end	1.3 years	Not available[(c)]

AR = aspect ratio
DEI = industry analyst
Emc^2 = Engineering Mechanics Corporation of Columbus
(a) Initial leakage was calculated to be 4.9 gpm
(b) Relatively large margin so not calculated for this case
(c) Crack near critical at first leakage

All the finite element cases in Table E.2, except 19b and 20b, applied to a WRS model that included inner-diameter (ID) back-gouging and re-welding. Back gouging and re-welding increases the tensile stresses in the region of the ID. With the exception of Case 26a, cases with a safe end-to-pipe weld either arrest or have a time to through-wall (TW) leakage of about 6 years, which is longer than the Inspection Item A-1 inspection interval. Depending on the length of the safe end, installing a safe end-to-pipe weld introduces compressive residual stresses near the ID of the adjacent nozzle-to-safe end weld. Case 26a has low loads and a safe end-to-pipe weld and has a partial arc ID repair. The time to TW leakage for this case is 2.2 years. The AFEA showed that Case 25b with high loads and a limited-extent ID repair had a shorter time to TW leakage than the same case without repair (Case 17b). However, Case

25b with limited-extent ID repair had a longer time from initial through-wall leakage to failure than Case 17b without the repair.

Cases S2b, 17-10, and 18b with high, medium, and low loading, respectively, and without a safe end-to-pipe weld had times to through-wall leakage of 3.4 years, 2.84 years, and 11.5 years, respectively. These three cases had between 4 and 43 days for the plant to shut down before the stability margin established for this analysis was no longer satisfied. While the pressurizer surge nozzle configurations do have safe ends, the sensitivity cases analyzed without a safe end were included to account for uncertainties in the calculation of WRS and crack growth.

Case S2b, with 4 days calculated for the time between first leakage and crack instability, approximated a case with multiple shallow initial flaws around the ID. Because the external operating loading was medium, the long initial crack progressed through-wall around the circumference with a profile that left relatively little remaining wall ligament at first leakage.

The remaining six surge line cases included in Table E.2 were analyzed without safe end-to-pipe welds, with high loads, and with three different initial crack sizes. The times to leakage for the subset of cases without ID repairs (17b, S3b, 17-9, and 17) ranged from 1.2 years to 2.2 years. Two cases (17 and 17-9) had cracks near the critical size at first leakage. The two cases with ID repairs and high loads (25b and 17-11) had times to through-wall leakage of 0.5 year and 0.86 year but had adequate time between leakage and loss of stability margin to shut down the plant.

Code Case N-770-1 requires that an unmitigated pressurizer surge nozzle-to-safe–end weld be categorized as Inspection Item A-1 and requires that a volumetric examination of these welds be performed every second refueling outage. This interval would typically be about once every 3 years but could range from 2 to 4 years.

The following concluding points can be made about this study.

- Overall, the times-to-failure results of the AFEA shown in Table E.2 do not bound the inspection intervals in Code Case N-770-1 for Inspection Item A-1. The high load cases without a safe end may be considered bounding cases. These bounding cases would experience through-wall leakage before the typical 3-year interval between UT examinations of these welds.
- For the cases with a safe end, the times to through-wall leakage were longer than the Code Case N-770-1–required inspection interval, except for Case 26a, which has an ID repair. One would expect that ID repairs were fairly common and EPRI (2007a) indicates that five of the nine surge nozzle welds in the plants studied had documented ID repairs. Therefore, these analyses do not tend to support the Code Case N-770-1 inspection interval for Inspection Item A-1 welds.
- From a review of information on the NRC website pertaining to reactor coolant system weld issues (http://www.nrc.gov/reactors/operating/ops-experience/pressure-boundary-integrity/weld-issues/plant-specific-info.html) and Stall (2007), Wadley (2008), and King (2006), all the Alloy 82/182 pressurizer surge nozzle-to-safe–end welds have been mitigated by either full structural weld overlays or MSIP. With one exception, the NRC staff's

sensitivity cases for pressurizer safety, relief, and spray valve nozzle butt welds showed times to first leakage of longer than 4 years. One case resulted in time to first leakage of 3.3 years. All the cases showed considerable time between first leakage and crack instability. A number of sensitivity cases showed crack arrest.

- As of early 2013, there were unmitigated pressurizer safety, relief, and/or spray valve nozzle butt welds at three plants. These welds have all been inspected at least once and the plants have committed to re-inspect these unmitigated welds at least once every 4 years, consistent with the requirements of Code Case N-770-1. The authors are not aware of any operating experience that would challenge the Inspection Item A-1 re-inspection interval for these welds.

E.3 Hot Leg and Cold Leg Flaw Evaluation and Sensitivity Analyses

The NRC staff conducted a scoping evaluation to determine the leak and rupture characteristics of DMWs in primary piping containing a hypothetical pre-existing circumferential flaw at hot leg locations and at cold leg reactor coolant pump (RCP) nozzle locations (Wallace 2014). In conducting these analyses, it was assumed that the pre-existing flaws grew due to PWSCC and the analyses were based on ASME Boiler and Pressure Vessel Code, Section XI, IWB-3640, requirements. This analysis did not consider fatigue crack growth.

The NRC staff chose four representative hot leg cases that span the range of typical leak-before-break approved plants and three RCP suction and discharge nozzle bounding cases from Ganta and Bamford (2009). Table E.3 provides details of the geometry and conditions that were modeled. The NRC staff evaluated the time to leak and time to rupture for stresses resulting from Normal Operating (NO) conditions. For conservatism, as the bounding loading case, the NRC staff also evaluated the times to leak and rupture under Safe Shutdown Earthquake (SSE) conditions.

Table E.3 Summary of Geometries and Conditions

	Hot Leg	RCP Nozzle
Outside diameter (OD)	86.25 cm (33.96 in.)	91.44 cm (36.00 in.)
Wall thickness (t)	6.07 cm (2.39 in.)	7.62 cm (3.00 in.)
Temperature (T)	325°C (617°F)	286.11°C (547°F)
Pressure (P)	15.46 MPa (2243 psi)	15.49 MPa (2247 psi)
Initial flaw depth (a)	1.61 cm (0.634 in.)	1.61 cm (0.634 in.)
Initial flaw length (2c)	5.23 cm (2.06 in.)	5.23 cm (2.06 in.)

The NRC staff performed the evaluations for each of four different WRS distribution cases. Two of the cases are from values that NRC staff used for the hot leg geometry in the original Wolf Creek scoping analyses (Rudland et al. 2007a). The first case is for an as-welded Westinghouse-type outlet nozzle with no stainless steel safe end closure weld and no repair. Case 2 is the same geometry and conditions, but with a 15% inside diameter backchip and last pass weld. For Case 3, NRC staff developed a WRS profile from Dominion Engineering, Inc. (DEI) results presented in EPRI report MRP-216 (EPRI 2007a). In that report DEI took a 90-

degree partial arc deep weld repair and presented the results in the center of the repair, at the end of the repair, and far removed from the repair. NRC staff developed Case 4 from Case 2 as part of the inlay program (Rudland et al. 2010), but included the effect of a stainless steel safe end weld closure weld.

The NRC staff calculated the PWSCC growth of the assumed initial flaw using the 75^{th} percentile crack growth rates from EPRI MRP-115-NP (EPRI 2004b) for the different geometries, stress cases, and WRS cases. NRC staff also calculated the time to leakage and used the net-section collapse criteria and the Alloy 182 Z-factor to calculate time to rupture and the critical crack size for rupture.

In addition to those assumptions, the staff assumed idealized surface and through-wall flaw shapes. The work in the AFEA project showed this assumption to be typically conservative for the time between leakage and rupture, but reasonably accurate for time to leakage.

The results of these evaluations are shown in Tables E.4 and E.5.

Table E.4 Results of Hot Leg Evaluation for Time to Leak and Time to Rupture

		Normal Operation			Normal Operation + Safe Shutdown Earthquake	
Stress Case	**WRS Case**	**Time to Leak (year)**	**Time to Rupture (year)**	**Time between Leak and Rupture (year)**	**Time to Leak (year)**	**Time to Rupture (year)**
A	As-Welded	2.33	4.33	2.00	2.00	3.75
	15% Backchip	1.83	3.50	1.67	1.58	3.00
	Partial Arc Repair	0.83	3.08	2.25	0.75	2.67
	With Safe End	7.92	9.42	1.50	5.67	7.08
B	As-Welded	2.08	3.92	1.83	1.50	2.67
	15% Backchip	1.67	3.17	1.50	1.25	2.17
	Partial Arc Repair	0.75	2.83	2.08	0.67	1.83
	With Safe End	6.25	7.67	1.42	3.08	4.08
C	As-Welded	9.33	17.5	8.17	2.83	5.42
	15% Backchip	5.83	11.5	5.67	2.17	4.25
	Partial Arc Repair	0.33	16.2	14.8	0.92	3.83
	With Safe End	Arrest	-	-	15.3	17.0
D	As-Welded	2.67	5.08	2.42	1.25	2.17
	15% Backchip	2.08	4.00	1.92	1.08	1.75
	Partial Arc Repair	0.92	3.58	2.67	0.58	1.50
	With Safe End	12.5	14.2	1.67	2.25	3.08

Table E.5 Results of RCP Nozzle Evaluation for Time to Leak and Time to Rupture

		Normal Operation			Normal Operation + Safe Shutdown Earthquake	
Stress Case	WRS Case	Time to Leak (year)	Time to Rupture (year)	Time between Leak and Rupture (year)	Time to Leak (year)	Time to Rupture (year)
E	As-Welded	63.1	106.	42.9	15.2	25.1
	15% Backchip	38.6	63.2	24.6	11.3	19.4
	Partial Arc Repair	9.10	100.	90.9	5.19	16.8
	With Safe End	Arrest	-	-	47.8	54.9
F	As-Welded	83.8	136.	52.2	16.9	28.2
	15% Backchip	47.8	75.6	27.8	12.4	21.5
	Partial Arc Repair	9.80	165.	155.	5.48	18.9
	With Safe End	Arrest	-	-	62.6	70.2
G	As-Welded	26.5	45.1	18.6	14.2	23.5
	15% Backchip	18.2	32.8	14.6	10.7	18.2
	Partial Arc Repair	6.71	31.5	24.8	5.04	15.7
	With Safe End	400.0	407.0	7.40	41.3	48.0

Review of the results provided the following observations.

- The hot leg cases generally had shorter times to leak and rupture than those for the cold leg cases. This is the result of generally higher bending stresses as well as higher hot leg temperatures.
- For all cases where growth of the assumed flaw by PWSCC resulted in leakage in NO conditions, the time between leakage and rupture was well over 1 year, providing significant margin to identify the leak and safely shut down the reactor.
- Backchipping the weld root and rewelding decreased the time to leakage and the time between rupture and leakage as compared to the as-welded condition.
- Assuming that the NO+SSE loading could occur for extended time periods, the shortest time to rupture under NO+SSE loading conditions was 1.5 years.
- Addition of the residual stress because of the stainless steel safe end closure weld resulted in a significant increase in the time to leakage, sometimes even resulting in crack arrest, but decreased the time between leakage and rupture.
- The weld residual stresses that resulted from the partial arc repair resulted in the shortest times to leakage and rupture but did not generally result in the shortest times between leakage and rupture.

The following concluding points can be made about this study.

- The “time to rupture” calculations are probably conservative, but the level of conservatism is not quantified.

- In the hot leg weld case with the shortest time to leakage (Load Case B with a partial arc repair on a weld with high loads and no safe end closure weld), initial leakage would occur in 0.75 years. With an additional 2.08 years between leakage and rupture, even if such a weld condition were to exist and started to leak, sufficient time would exist to repair it before it becomes critical.
- In the hot leg weld with the lowest loading (Load Case C), the time to leakage for the as-welded case and the case with a 15% backchip without a safe end weld exceeded the 5-year inspection interval in Code Case N-770-1 for Inspection Item A-2, unmitigated butt welds at hot leg operating temperature less than or equal to 329°C (625°F). Load Case C with a partial arc repair, which did not have a safe end closure weld, does not bound the inspection interval for Inspection Item A-2. Load Case C with a 15% backchip and a safe end closure weld showed crack arrest.
- Overall, the time-to-initial leakage results for the hot leg temperature Load Cases A, B, and D analyzed without a safe end closure weld do not bound the 5-year inspection interval in Code Case N-770-1 for Inspection Item A-2. The times-to-initial leakage for all four hot leg temperature Load Cases analyzed with a safe end closure weld bound the inspection intervals in Code Case N-770-1 for Inspection Item A-2. The time between leakage and failure in all the cases analyzed would be sufficient to shut down a plant, assuming the leakage was detected. These sensitivity studies show the strong influence of weld residual stresses and external loading on the time-to-leakage, time-to-failure, and time between leakage and failure for the nozzle analyzed.
- In the cold leg case with the shortest time to leakage (Load Case G – partial arc repair on a weld with high loads and no safe end weld), initial leakage would occur in 6.71 years. This time to leakage is just short of the maximum inspection interval of 7 years in Code Case N-770-1 for Inspection Item B, unmitigated butt welds at cold leg operating temperature greater than or equal to 274°C (525°F) and less than 304°C (580°F). The time to leakage for the remainder of the cold leg cases were 9.1 years or longer. The times between leakage and rupture for the cold leg cases are equal to or longer than 7.4 years. The results of the cold leg analysis appear to support an inspection interval of at least 7 years.
- Ideally, results for time to reach the ASME Section XI maximum depth of 75% through-wall would bound the ASME Code Case inspection intervals, because this is the regulatory basis for degradation as opposed to showing that there is sufficient time to shut down a plant after leakage is discovered.

E.4 Results from the North Anna Power Station, Unit 1, Flaw Growth Analysis

The NRC staff and its contractor, Engineering Mechanics Corporation of Columbus, completed a flaw growth analysis (NRC 2012) of axially-orientated flaws found in the steam generator hot leg piping-to-steam generator nozzle DMW. Five axial flaws of varying depths were found in March 2012 (see Appendix B.1). A detailed weld residual stress analysis was performed using typical computational weld modeling processes that have been validated by mockup testing in the nuclear industry. The North Anna Power Station, Unit 1 (NAPS-1) hot leg to steam generator nozzle weld is a double-V groove weld with two repairs in the region where through-wall flaws were observed following pre-overlay machining. These repairs were a large inner-diameter repair and small outer-diameter repair. The weld material is Alloy 82 for the butter and Alloy 182 for the main weld and repair welds. The nozzle and safe end materials are assumed to be A508 and A316 stainless steel, respectively.

An axi-symmetric finite element model was used for the nozzle. The weld procedure simulated consisted of application of the Alloy 82 butter layer, post-weld heat treat, machining of the butter, application of the Alloy 182 weld, machining of the repair grooves followed by application of the repair welds, and then finally application of the closure stainless steel weld. The flaws found in the steam generator DMW were all axially orientated and varying depths. Because these are axially-orientated flaws, the loads that will affect the PWSCC growth will be the weld residual stress and hoop stress due to pressure.

The analysis considered idealized flaw growth and natural flaw growth models. The idealized flaw growth analysis was used to address questions such as, "What is the likelihood that a flaw was undetectable in the spring 2009 refueling outage and grew to the size observed in the early 2012 outage?" The staff concluded from this analysis that it is highly likely that a detectable flaw was present in the 2009 outage and grew to the size observed in 2012.

Natural flaw growth analyses were performed on the NAPS-1 steam generator nozzle DMW to obtain a deterministic estimate of the progress of an axial flaw through the weld from 2009 until the flaws were discovered in 2012. In a natural flaw growth analysis, the flaws are driven by PWSCC and tensile stresses caused by the WRS and the service loading. For axial flaw growth in the DMW, the loading consists of internal nozzle pressure and flaw face pressure of 2248 psi (15.5 Mpa) combined with the WRS. In the natural flaw growth analysis method, a finite element analysis is performed at each increment of flaw growth to calculate stress intensity factors along the crack front. Using the stress intensity factor results and the assumed flaw growth law and the 75-percentile flaw growth rate from EPRI MRP-115 (EPRI 2004b), an increment of crack advance is calculated and the procedure is repeated. For this study, PWSCC of DMW was the only subcritical cracking mechanism that was considered.

Typically, the flaw growth increments were kept less than 10 mm (0.4 in.), with smaller increments as the crack depth approached mid-thickness. For every crack growth step, the WRS were mapped to the flaw mesh and the WRS were compared to ensure accuracy and as a check of the proper boundary conditions and surface loading.

The evolution of the flaw and the corresponding complex flaw shapes can be seen in Figure 7 of (NRC 2012). The initial flaw shape (at time = 0 years) was assumed to be 6-mm (0.24-in.) deep and a total of 12 mm (0.48 in.) in width. The flaw reaches the right side weld butter line at about 0.46 years and then begins to grow slower in the butter. The flaw begins to touch the safe end at about 0.64 years and then the flaw follows the fusion boundary between the weld and safe end as it grows deeper. At 1.17 years, the flaw nearly reaches the butter-nozzle line and then can only grow vertically from that point on. The flaw depth growth slows down just past the neck area after about 1.76 years to 4 years. This is the region of the weld shape neck down where most of the material is represented by Alloy 82 butter. In addition, this is the region where the weld residual stresses become slightly negative, also contributing to a slower growth rate.

Figure E.1 shows the flaw depth at the deepest point versus time. The flaw growth rate falls near the narrow region between the double-Vs where the weld residual stress is lower, and a larger portion of the flaw is in the weld butter (with corresponding lower flaw growth). Later, the flaw growth rate increases as the deepest point in the main DMW with higher flaw growth rate experiences higher weld residual stress.

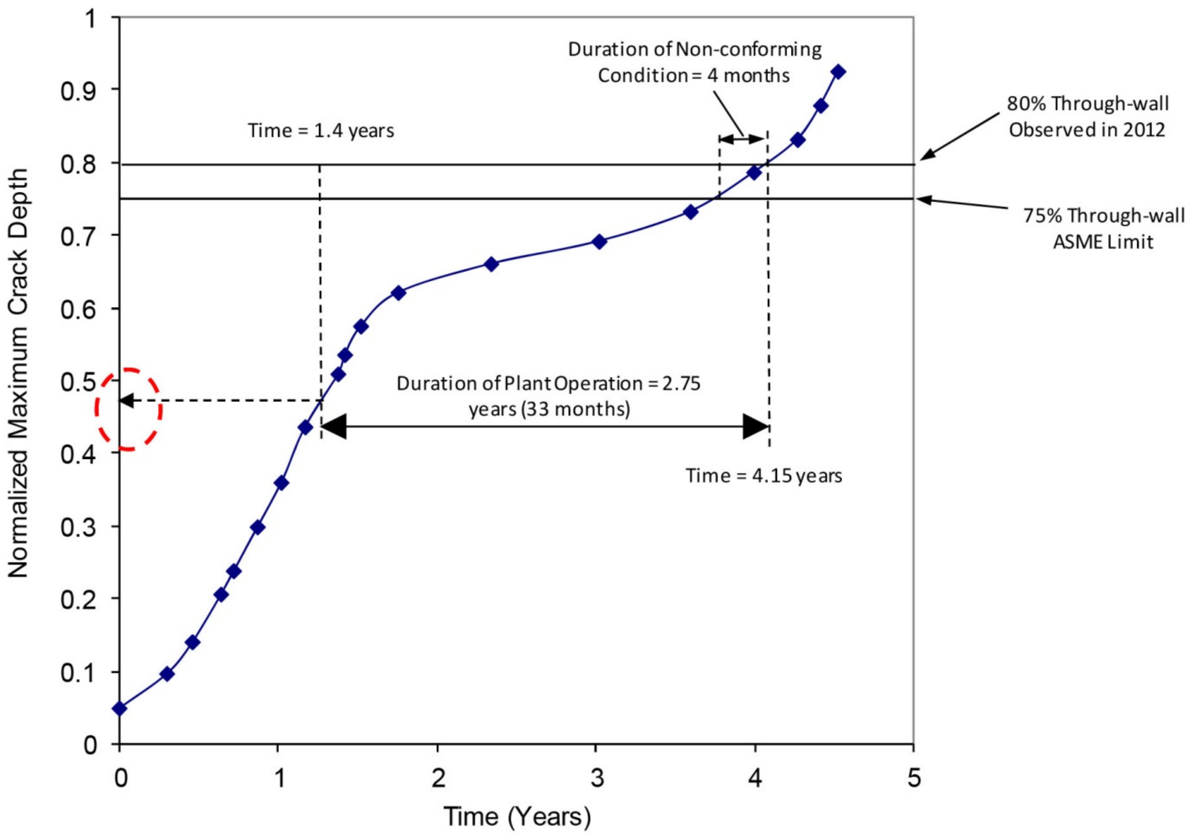


Figure E.1 Flaw Growth Estimate from 2009 Outage to 2012 (NRC 2012)

Figure E.1 allows an estimate of the time that the flaw grew during the 2.75 years from the 2009 inspection to 80% this spring. Starting with the observed 80% through-wall flaw in 2012, and moving back in time 33 months (corresponding to the preceding operating cycle), Figure E.1 shows that the estimated flaw depth was 47% in the 2009 outage. Similarly, starting with the 80% flaw in 2012, it is seen that the 75% ASME Code acceptability limit would have been reached about 4 months prior. The NRC staff concluded that this “more accurate deterministic natural flaw growth analysis indicates with greater likelihood (than from the idealized flaw growth analysis) that a flaw was present and detectable in 2009 and grew to the size observed in 2012.”

The following observations can be made from the results of this study.

- If the threshold of detection is conservatively (for this case) assumed to be 10% through-wall, Figure E.1 shows that the time to grow from 10% to 75% through-wall in this example is approximately 3-1/3 years or 40 months.
- This interval of 3-1/3 years is considerably shorter than the required UT inspection interval of once every 5 years for Code Case N-770-1 Inspection Item A-2 welds.

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11. ABSTRACT (200 words or less)

Operating experience has shown that Alloy 82/182/600 materials exposed to primary coolant water (or steam) under the normal operating conditions of PWRs are susceptible to PWSCC. These materials were widely used in the original construction of domestic PWR RCS. Cracking typically initiates at the inside surface of these materials when exposed to reactor coolant and in the presence of high tensile residual stresses introduced by welding. The locations in which PWSCC has been identified include partial penetration nozzles, nozzle welds, and piping butt welds. PWSCC increases the probability of a loss-of-coolant accident. This NUREG/CR pertains to managing PWSCC in Alloy 82/182 butt welds.
In response to this degradation mechanism, the nuclear industry and the NRC undertook a variety of actions. These actions included conducting crack growth rate studies for Alloy 82/182/600 materials, developing augmented inspection programs for varied component configurations, and establishing an improved regulatory environment for addressing PWSCC. In Alloy 82/182 butt welds, the nuclear industry began implementing mitigation strategies for the most susceptible of these welds.
This report provides a summary of the operating experience with PWSCC in Alloy 82/182 butt welds and an overview of industry and regulatory activities to address the safety concern.

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