ELECTRIC POWER RESEARCH INSTITUTE

Materials Reliability Program: PWR Reactor Coolant System Cold-Loop Dissimilar Metal Butt Weld Reexamination Interval Extension (MRP-349)

A Basis for Revision to the Requirements of MRP- 139 and American Society of Mechanical Engineers Code Case N-770 for Large-Diameter Welds at Cold-Leg Temperatures

2012 TECHNICAL REPORT

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This document does NOT meet the requirements of 10CFR50 Appendix B, 10CFR Part 21, ANSI N45.2-1977 and/or the intent of ISO-9001 (1994).

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Product Description

A technical basis has been developed to support extension of the reexamination interval in Materials Reliability Program- (MRP-) 139, Revision 1, and American Society of Mechanical Engineers (ASME) Section XI Code Case N-770 for large-diameter (≥ 14 National Piping Standard [NPS]) cold-leg Alloy 82/182 dissimilar metal (DM) butt welds. This technical basis may be used for a revision to MRP-139 and Code Case N-770. Suggested revisions to these documents are included in this report.

Background

Alloy 82/182 welds have been shown to be susceptible to primary water stress corrosion cracking (PWSCC). Due to this, both MRP-139 and ASME Code Case N-770 require periodic volumetric reexamination of cold-leg Alloy 82/182 DM butt welds essentially every six or seven years, respectively. This population includes various branch connections, reactor coolant pump (RCP) inlet and outlet nozzles, steam generator (SG) outlet nozzles, and the reactor vessel (RV) cold-leg nozzles. The branch nozzles, typical of the Babcock and Wilcox and Combustion Engineering nuclear steam supply system designs, are generally inspected from the outside diameter (OD) and have varying accessibility and personnel radiation exposure issues, depending on plant design. Only a limited number of U.S. plants have DM welds in the SG nozzles that require inspection within the scope of MRP-139 or Code Case 770, but these welds will also typically be examined from the OD with plant-specific access and radiation exposure implications.

The RV cold-leg nozzles are typically inspected from the inside diameter, which requires that the core barrel be removed for access. This exam, under ASME Section XI inspection requirements, occurs once per interval, which coincides with the RV in-service inspection frequency, thus minimizing core barrel removal evolutions. While OD exams may be possible at some plants, additional accessibility issues arise for those plants where OD access is only through the floor of the refueling cavity, significantly limiting any benefits to this alternative. Although more frequent core barrel removal provides a significant incentive to perform mitigation of the affected DM welds and eliminate further PWSCC concern at that location, operating experience to date suggests that the susceptibility of the cold leg RV nozzles may not warrant urgent action.

Objective

The objective of this project is to develop a robust technical basis for extending the large-diameter Alloy 82/182 RV cold-leg, RCP, and SG cold-leg butt weld volumetric exam reexamination interval to at least 10 years. Extending past a 10-year interval would require changes to Section XI, and implementation of such changes is not within the scope of this program.

Approach

The approach to developing this technical basis was to use the results of previous analyses that had been performed for the MRP to develop the basis for MRP-139. Furthermore, service experience has been compiled and fitted to a Weibull distribution that can be used to predict the likelihood of future cracking for various butt weld locations. Work being performed for the Pressurized Water Reactor Owners Group to develop flaw tolerance evaluations for the RCP weld locations in the Combustion Engineering plants was also used. The technical basis for the extension of the reexamination interval is based on the information discussed above.

Results

This project required no new information or new analyses. Instead, the existing information was compiled and documented in one clear, concise technical basis document demonstrating that a 10-year interval provides an acceptable level of safety for large-diameter Alloy 82/182 butt weld locations at cold-leg temperatures.

Applications, Value, and Use

Extending the reexamination interval for large-diameter cold-leg Alloy 82/182 DM butt welds will enable the RV cold-leg exams to be performed on an interval that is consistent with the interval for the removal of the core internals and will provide additional flexibility in scheduling these exams.

Keywords

Alloy 600
Alloy 82/182
Butt welds
PWSCC
RCS piping
RV nozzle

Abstract

Both Materials Reliability Program- (MRP-) 139 and American Society of Mechanical Engineers (ASME) Code Case N-770 require periodic volumetric reexamination of cold-leg Alloy 82/182 dissimilar metal (DM) butt welds susceptible to primary water stress corrosion cracking (PWSCC) essentially every six or seven years, respectively. This population includes various branch connections, reactor coolant pump inlet and outlet nozzles, steam generator outlet nozzles, and the reactor vessel (RV) cold-leg nozzles. Inspection of the large-diameter weld locations on an interval that is inconsistent with the interval of 10 years required by ASME Section XI for other welds has resulted in hardship for utilities. While a consideration of selecting the six- or seven-year interval was to encourage utilities to perform mitigation of the affected DM welds and eliminate further PWSCC concern, operating experience to date suggests that the susceptibility of the cold leg RV nozzles may not warrant urgent action.

This technical basis demonstrates that the reexamination interval can be extended to 10 years while maintaining an acceptable level of quality and safety. This technical basis primarily uses existing work that has been extensively reviewed and accepted within the industry. Therefore, this technical basis is suitable for use as a justification for the revision to MRP-139 and ASME Code Case N-770.

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Section 1: Summary of Technical Basis

1.1 Approach

The approach to developing this technical basis was to utilize the results of previous deterministic and probabilistic analyses that had been performed for the Materials Reliability Program (MRP) to develop the basis for MRP-139 [1]. Furthermore, service experience has been compiled and used to predict the likelihood of future cracking for various butt weld locations. Work being performed for the Pressurized Water Reactor Owners Group (PWROG) to develop flaw tolerance evaluations for the reactor coolant pump (RCP) weld locations in the Combustion Engineering plants along with flaw tolerance evaluations of the reactor vessel (RV) inlet nozzles was also used. The technical basis for the extension of the re-examination interval is based on the information discussed above. This approach required no new information or new analyses. Instead, the existing information is compiled and documented in one clear and concise technical basis document demonstrating that a 10-year interval provides an acceptable level of safety and a burden reduction for licensees.

1.2 Results

The analyses summarized in this report show that the flaw tolerance is very good for the large-diameter (≥ 14 NPS) cold leg butt weld locations. The time for through-wall crack growth due to PWSCC is close to 10 years even for large assumed initial flaws. Furthermore, the time to grow from a flaw size capable of providing a detectable leak to the critical flaw size is in excess of 10 years and can be longer than 40 years.

Probabilistic analyses, based on probabilistic fracture mechanics (PFM) and statistical methods, have shown that the probability of initiation and/or through-wall growth in cold leg piping is significantly lower than that for piping operating at higher temperatures. These analyses have also shown that the length of the inspection interval has very little effect on the probability of through-wall crack propagation.

Based on these results, it is reasonable to conclude that the inspection intervals in MRP-139 and ASME Code Case N-770 [2] for uncracked cold leg Alloy 82/182 welds can be extended to 10 years while maintaining an acceptable level of safety.

1.3 Suggested Revisions

It is suggested, based on the results discussed above, that the inspection intervals of 6 and 7 years required by MRP-139 and Code Case N-770, respectively, for uncracked and unmitigated large-diameter cold leg Alloy 82/182 butt welds be revised to 10 years, consistent with the interval specified by ASME Section XI [3].

Section 2: Introduction

2.1 Background

Section XI of the ASME Boiler and Pressure Vessel Code [3] specifies a 10-year interval for inservice inspection of pressure-retaining welds. MRP-139 [1] and ASME Code Case N-770 [2] both require a more proactive periodic volumetric re-examination of cold leg Alloy 82/182 dissimilar metal (DM) butt welds, essentially every six or seven years. This population includes various branch connections, RCP inlet and outlet nozzles, SG outlet nozzles, and the RV cold leg nozzles. The branch nozzles are typical of the Babcock & Wilcox (B&W) and Combustion Engineering (CE) designs, are generally inspected from the outside diameter (OD), and have varying accessibility and personnel radiation exposure issues depending on plant design and environmental conditions. Only a limited number of US plants (one) have DM welds in the SG nozzles that are directly exposed to the primary water environment and thus fall within the scope of MRP-139 and Code Case N-770. However, it should be noted that there are a large number of SG nozzles with Alloy 182 as a portion of the weld, though not exposed to the primary water environment and these welds may be required to be inspected as a result of an NRC condition on Code Case N-770. These SG nozzle welds will also typically be examined from the OD with plant-specific access and radiation exposure implications.

The RV cold leg nozzles are typically inspected from the inside diameter (ID) which requires that the core barrel be removed for access (See Figure 2-1). This exam, under ASME Section XI inspection requirements, occurs once per interval (10 years typically) which coincides with the inspection of the RV shell welds, thus minimizing core barrel removal evolutions. Inspection of these nozzles on a six- or seven-year interval requires removal of the core barrel solely for the purpose of performing these nozzle inspections. Removal of the core barrel should be minimized for a variety of reasons. As with any heavy lift operation, there are inherent risks to the personnel involved in the lift activities. Experience has shown that there are also risks associated with equipment damage including damage to the lift rig, guide studs, or the lower internals and reactor vessel itself. Damage to these items has the potential to put plant personnel in further adverse situations along with significantly increasing outage time and radiation exposure.

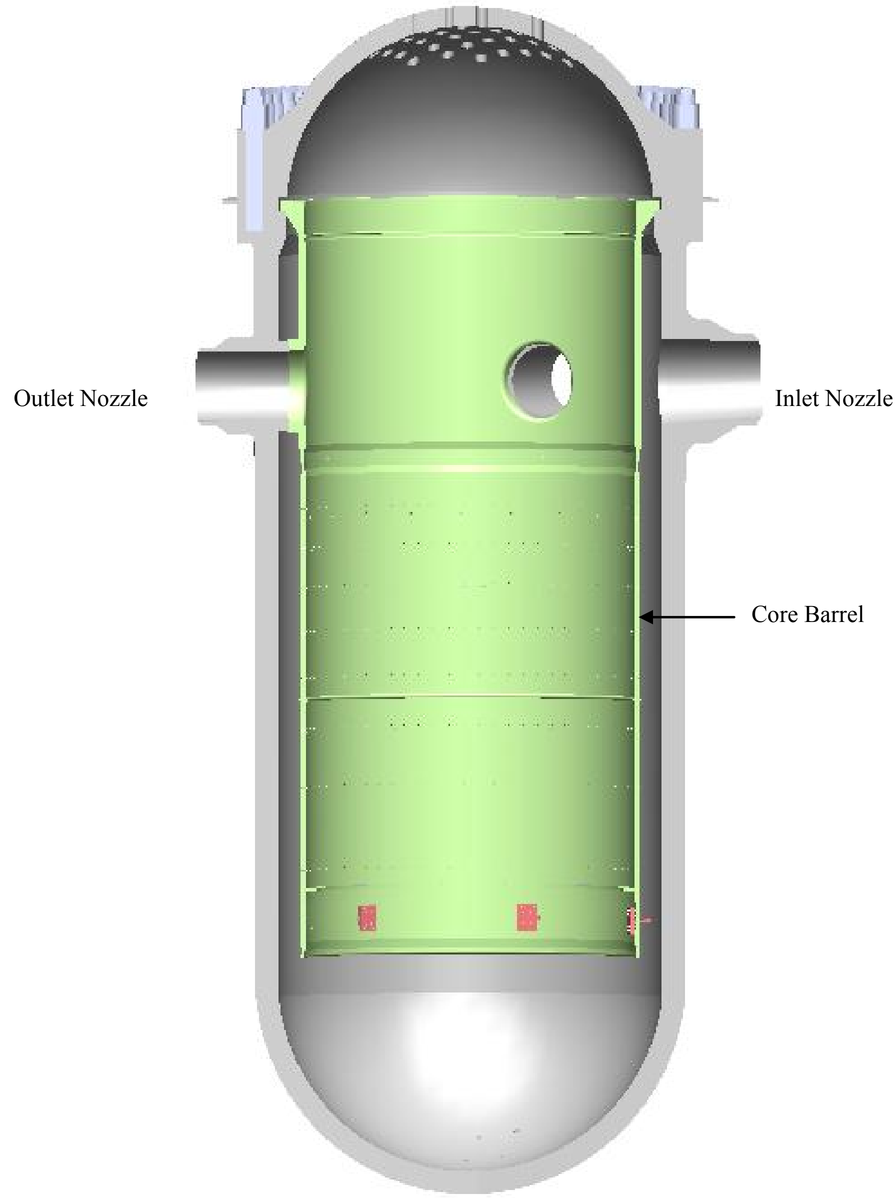


Figure 2-1
Relationship of Core Barrel to Reactor Vessel and Inlet and Outlet Nozzles

2.2 Hardships Associated with Removing the Core Barrel

The removal of the reactor vessel lower internals assembly (core barrel) is considered to be a critical lift due to the weight of the component, the tight clearances involved, and the radiation emitted by the assembly. For these reasons, only the personnel directly involved with the movement of the internals are typically allowed in containment during the evolution. (Although site-specific procedures will vary, most will have much in common with the following description.) Remote cameras are utilized to allow most of the personnel involved with the lift to be outside of the refueling cavity area to minimize personnel radiation exposure. Most lower internals lifts are performed solely by viewing cameras. The Polar Crane operator(s) is instructed to sit on the floor of the cab or behind shielding and not to raise his head above the cab area of the crane to maintain his radiation dose as low as reasonably achievable (ALARA). Communications are via portable radios. Prior to lifting the lower internals, a "dry run" is typically performed where the crane is attached to the lifting rig and placed onto the guide studs in the reactor cavity. Temporary markings are then made to provide alignment references for the reactor vessel. These markings are used by the crane operator and the crew to align the crane to the vessel. The lifting rig is then moved to the storage location and a second set of markings made. Following completion of the "dry run," the lifting rig is installed onto the guide studs and the lower internals are latched onto the rig. The internals are then lifted until full load is achieved. This position is maintained for 10 minutes. Following the 10-minute hold, the internals are lifted out of the reactor vessel and moved onto their storage stand in the refueling cavity.

For many plants, removing the core barrel requires that it be raised well above the refueling cavity water level during transfer from the reactor vessel to the storage stand location. As can be expected, the radiation exposure levels for this activity are very high and necessitate unrelated work to stop for evacuation of personnel from containment and installation of shielding for the polar crane operator(s). Additionally some plants are configured such that the core barrel upper portion remains exposed above the refueling cavity water level during storage, often requiring installation of temporary shielding walls. These walls severely limit the ability to perform other outage cavity maintenance activities and involve significant time and dose for their handling.

The design of the internals lift rig is also susceptible to operational and alignment problems. Human performance (HP) contributes to most of the reported operational events and is considered preventable. The following is a list of HP impediments:

- Applicable operational experience (OE) was not discussed during the pre-job briefing,
- Clear visual determination of alignment affected by several factors, and
- Communications between all personnel were not established.

Multiple events involving issues such as crane misalignment or only having two of the three lifting legs engaged/disengaged during polar crane lift have resulted in significant damage to the lifting rig and reactor components. These events occurred after all fuel was removed from the core and thus, the events did not pose a threat to nuclear, industrial, or environmental safety. However, ALARA principles under radiological safety were challenged. Additional worker dose was accumulated during the recovery operations.

Infrequently Performed Test or Evolution (IPTE) process implementation additional enhancements are also identified to minimize the risk for lower internals handling events. These include: investigating remote crane operation, use of laser/photogrammetry alignments, providing a load cell readout in the crane cab, using load cells with alarms, providing OE, and covering these events in continuing training.

Inspection of the reactor vessel nozzle welds from the ID is done remotely. While OD exams may be possible at some plants, additional accessibility issues resulting in personnel safety and ALARA concerns arise for those plants where OD access is only through the floor of the refueling cavity, significantly limiting any benefits to this alternative.

2.3 Scope and Objectives

The objective of this project is to develop a robust technical basis for extending the large-diameter (≥ 14 NPS) Alloy 82/182 RV cold leg, RCP, and SG cold leg butt weld volumetric exam re-inspection interval to ten years. This will enable the RV cold leg exams to be performed on an interval that is consistent with the interval for the removal of the core internals.

Section 3: Current Inservice Inspection Requirements

Inspection requirements for Alloy 82/182 weld locations were first specified in Section XI of the ASME Boiler and Pressure Vessel Code. These requirements, for Examination Category B-F and B-J welds, were not specific to Alloy 82/182 weld materials but applied to all dissimilar metal or similar metal welds. More recently, requirements specific to Alloy 82/182 weld materials were developed and published in MRP-139 [1] and most recently in ASME Section XI Code Case N-770 [2]. A discussion of the cold leg butt weld re-examination frequency requirements is provided in the following sections.

3.1 ASME Section XI

ASME Section XI [3], Table IWB-2500-1, requires volumetric and/or surface examination of 100% of dissimilar metal vessel nozzle-to-safe-end welds (Examination Category B-F) and dissimilar metal piping welds (Examination Category B-J). Section XI requires that these examinations be performed on a 10-year interval. Prior to the 2007 Edition, this requirement was specified in IWB-2412, "Inspection Program B." IWB-2412, "Inspection Program A," provided a set of requirements for inspection on a higher frequency earlier in plant life. However, Inspection Program A was not used by any plants operating in the United States and was removed from Section XI beginning in the 2007 Edition. The requirements for inspection on a 10-year interval are now specified in IWB-2411.

It should be noted that most plants in the U.S. have implemented a risk-informed inservice inspection (RI-ISI) program for piping welds. These RI-ISI programs reduce the number of welds selected for examination and may change the examination method. In some cases, the reduction in the number of welds examined included the elimination of examinations of Alloy 82/182 DM welds because these welds were, at the time, not known to have an active degradation mechanism. However, the RI-ISI program does not alter the Section XI 10-year inspection interval for those welds that are examined.

3.2 MRP-139

MRP-139, Revision 1, "Primary System Piping Butt Weld Inspection and Evaluation Guideline," [1] was published in December 2008. This report defines categories of weldments for welds fabricated with Alloy 82/182 weld materials. Categories E and I are applicable to welds at cold-leg temperatures. Category E weldments are defined as “those not made with resistant materials, have not been given an SI (stress improvement) treatment, are greater than or equal to 4″ NPS or serve an ECCS function (i.e., B&W non-Makeup HPI nozzles), and are exposed to cold leg temperatures.” Category I weldments are defined as “those that are not made of resistant materials and cannot be volumetrically inspected…and are exposed to temperatures equivalent to cold leg temperatures.” Resistant materials are those considered to not be susceptible to PWSCC. Table 6-1 of MRP-139 specifies that the examinations of these weld categories be performed once every six years.

The requirements of MRP-139 have been identified as “mandatory” in NEI-03-08, “Guideline for the Management of Materials Issues.” Based on this “mandatory” classification, these guidelines have been implemented by all plants operating in the United States.

3.3 ASME Code Case N-770

ASME Code Case N-770, Revision 1, “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 Application of Listed Mitigation Activities,” [2] was approved by ASME in January 2009. This Code Case defines Inspection Item B as an “unmitigated butt weld at cold leg operating temperature $\geq$ 525°F (274°C) and $<$ 580°F (304°C).” Code Case N-770 specifies that these items receive a visual examination once each 10-year interval and a volumetric examination every second examination period not to exceed seven years.

This extension of the MRP-139 requirement of six years to seven years was made to be more compatible with ASME Section XI Code Periods which are typically one third of the 10-year interval and two sequential periods can be at most seven years in duration. Furthermore, the technical basis document for Code Case N-770 [4] cited that the time for unmitigated cold leg welds to crack through wall ranges from 20 to 40 years Revision 1 to this Code Case was approved by ASME in December 2009 and a Revision 2 is in progress. Neither of these revisions has changed the requirements for frequency of inspection of the cold leg weld locations although Revision 2 of the Code Case will make provisions for large-diameter cold leg piping with restricted access. Relaxed coverage requirements may be justified by an integrity analysis, but the inspection frequency is unchanged.

On June 21, 2011 the NRC issued a revision to 10 CFR 50.55a which makes the requirements of N-770, Revision 1, mandatory for plants operating in the United States. Following the effective date of July 21, 2011, every plant in the U.S. will be required to implement the requirements of N-770 in accordance with the schedule details provided in the final rule. Upon site-specific implementation of the Code Case per 10 CFR 50.55a, the MRP-139-1 Mandatory requirements are then rescinded [18].

Section 4: Service Experience for Cold Leg Alloy 82/182 Butt Welds

4.1 Overview

Alloy 82/182 butt welds in domestic PWR plants have received a volumetric and surface inspection as required by Section XI of the ASME Code as well as visual inspections for boric acid leakage. These inspections have been required since the inception of piping inspection requirements of Section XI around 1980. As discussed in Section 3, a more aggressive volumetric examination schedule has been self-imposed in the U.S. since 2005 through the requirements of MRP-139 for Alloy 82/182 DM welds. All such welds have now been examined at least once employing examination methods qualified in accordance with ASME Section XI, Appendix 8.

Similar accelerated inspections have been performed at PWR plants worldwide. The majority of incidents of cracking in Alloy 82/182 weld materials or Alloy 600 base metal have occurred in the reactor vessel head penetrations, head penetration welds, or the pressurizer nozzle butt welds. These locations operate at hot leg temperatures or higher. A summary of service experience for other reactor coolant piping welds is provided in the following sections.

4.2 Cold Leg Butt Weld Locations

The location of large-diameter ($\geq$ 14 NPS) Alloy 82/182 welds operating at cold leg temperatures in the Westinghouse, Combustion Engineering, and Babcock and Wilcox plant designs are discussed in Section 3 of MRP-113 [5] and are summarized in Table 4-1.

Table 4-1
Typical Large-diameter Alloy 82/182 Cold Leg Butt Weld Locations

Application	Typical Temperature (°F)	Typical ID (inches)	Typical Number
Westinghouse Plants[1] • Steam Generator Outlet Nozzles[2] • Reactor Vessel Inlet Nozzles[3]	550-560	27.5	3
Combustion Engineering Plants • Reactor Coolant Pump Inlet Nozzles[4] • Reactor Coolant Pump Outlet Nozzles[4]	549-560	30 30	4 4
Babcock and Wilcox Plants • Reactor Coolant Pump Inlet Nozzles • Reactor Coolant Pump Outlet Nozzles • Reactor Vessel Core Flood Nozzles • Core Flood Tank Nozzle	557	28 28 14 14	4 4 2 2

1. Data is for a Westinghouse 3-loop plant. Number of typical locations is dependent on number of loops.
2. One Westinghouse plant has Alloy 82/182 butt welds between the reactor coolant piping and steam generator nozzles that are directly exposed to the reactor coolant.
3. There are no Alloy 82/182 RPV nozzle welds in Westinghouse 2-loop plants and some early Westinghouse 3-loop and 4-loop plants.
4. Some CE plants do not have Alloy 82/182 RCP suction and discharge nozzle welds.

4.3 Summary of Service Experience

All dissimilar metal (DM) welds in pipes 4" NPS and greater, including those containing Alloy 82/182, in categories B-F and B-J, have been subject to volumetric examination every 10 years, following the requirements of ASME Section XI. In some cases, these examinations were eliminated as part of a risk-informed ISI program while in other cases they were supplemented by visual inspections for boric acid leakage. A summary of service experience [6] for Alloy 82/182 butt welds is provided in the following sections. Though there have been numerous incidents of PWSCC identified in the pressurizer nozzle welds, this service experience is not included since these events have occurred at temperatures significantly higher (~653°F) than typical cold leg temperatures.

Reactor Vessel Inlet and Outlet Nozzles

The only known incidents of PWSCC in the reactor vessel inlet and outlet nozzles have occurred in the Alloy 82/182 nozzle-to-safe-end weld region of the outlet nozzle. These nozzles typically operate at 608°F - 621°F. The first incidents occurred in the outlet nozzles of Ringhals 3 and 4, and Virgil C. Summer in the year 2000. Since that time, over 100 automated UT examinations of these welds in operating plants in the U.S. and internationally have been completed, typically coincident with the inspection of the reactor vessel shell welds. No additional surface indications were found until 2008, when indications were identified in the outlet nozzles of two different reactor vessels. The first was at OHI-3 in Japan. This indication was detected prior to the application of water-jet peening to mitigate PWSCC. The indication was measured by UT as being 10 mm in length and 5 mm in depth. When the indication was actually removed by progressive grinding, it was measured to have a length of 13.5mm and a depth of 20.3 mm. The cavity has been left in place. The second indication was detected at Salem Unit 1 as a result of UT inspection, prior to the application of the mechanical stress improvement process (MSIP). This indication was determined to have a depth of ~15 mm. Finally, in 2009, an indication was found in the Seabrook reactor vessel outlet nozzle. This indication was axially oriented with a depth of ~15.6mm and a length of ~24.4mm. A summary of the incidents of PWSCC found in the reactor vessel outlet nozzles is provided in Table 4-2

Table 4-2
Summary of Cracking in Reactor Vessel Outlet Nozzles

Plant	Temperature (F)	EFPY[1]
VC Summer	621	15.6
Seabrook	621	16.3
OHI 3	617	14.0
Ringhals 3	613	12.8
Ringhals 4	613	12.3
Salem 1	608	19.7

1. Effective Full Power Years of Operation at the time the indication was found.

Steam Generator Primary Nozzles

Cracking in the steam generator nozzles has only been observed in the Alloy 82/132 inlet nozzle-to-safe-end weld region of steam generators in Japan. For plants in the U.S. that have stainless steel reactor coolant system main loop piping, steam generators were originally fabricated with stainless steel nozzle-to-safe-end welds. Many plants have replaced their steam generators and in doing so have installed steam generators with either stainless steel welds, or welds fabricated with Alloys 52 and 152, which are considered to be relatively unsusceptible to PWSCC. One plant in the U.S. does have Alloy 82/182 welds in the steam generator nozzle-to-safe-end welds. This plant recently (spring 2012) mitigated the inlet (hot leg) welds and identified cracking, presumed to be PWSCC, in one nozzle. In some cases Alloy 82/182 welds were used with a layer of Alloy 52/152 to seal the Alloy 82/182 material from the primary coolant water. As a result of a condition imposed by the NRC on Code Case N-770 in

10 CFR 50.55a, owners are required to have NRC approval before such welds can be considered as mitigated and not in the scope of Code Case N-770.

In Japan, most steam generators were originally fabricated with Alloy 132 nozzle-to-safe-end welds. Alloy 132 is similar to Alloy 182 and is equally susceptible to PWSCC. Therefore, the Japanese PWRs with susceptible welds are implementing peening as mitigation for these welds. In preparation for peening, the inside surface of the welds must be inspected. While these inspections (and subsequent peening) had been successfully applied at five plants, during the inspections of Mihama 2 and Tsuruga 2 in the fall of 2007, indications were detected. In November of 2007, NISA, the Japanese regulatory authority, issued a guideline for each susceptible unit to inspect the nozzle-to-safe-end weld region at their earliest convenience. As a result, five additional plants have detected cracking in this region. All indications have been detected in the inlet nozzle-to-safe-end weld region, which is the hottest location, typically operating at 608°F - 621°F. Note that no indications have been found in the outlet nozzles, which operate at cold leg temperatures. A summary of this experience is provided in Table 4-3.

Table 4-3
Summary of Cracking in Japanese Steam Generator Inlet Nozzle-to-Safe-End Welds

Plant	Date	Number of Indications, Max. L, Max D		
		A Loop	B Loop	C Loop
Mihama Unit 2 500 MWe	September 2007	13 indications L=17mm D=13mm	0 indications	N/A
Tsuruga Unit 2 1110 MWe	November 2007	1 indications L=N/A D=N/A	5 indications L=21mm D=12mm	23 indications L=14mm D=13mm
Takahama Unit 2 780 MWe	December 2007	3 indications L=7mm D=N/A	2 indications L=7mm D=6mm	4 indications L=11mm D=8mm
Genkai Unit 1 529 MWe	January 2008	3 indications L=5mm D=N/A	0 indications	N/A
Takahama Unit 3 870 MWe	February 2008	7 indications L=28mm D=9mm	16 indications L=38mm D=15mm	9 indications L=14mm D=9mm
Tomari Unit 2 579 MWe	April 2008	3 indications L=13mm D=7mm	10 indications L=10mm D=5mm	N/A
Takahama Unit 4 870 MWe	October 2008	7 indications L=14mm D=12mm	8 indications L=30mm D=13mm	21 indications L=33mm D=16mm
D = Depth, L = Length, N/A = Not Applicable				

Other Piping Weld Locations

In Combustion Engineering (CE) and Babcock and Wilcox (B&W) plants, there are a number of Alloy 182 or Alloy 82 butt welds used to join stainless steel lines (instrumentation lines, drain lines, surge lines, etc.) to the main loop piping, which is carbon steel. There have been numerous incidents of cracking in these locations. Again, the cracking has been found predominantly in the high temperature lines, with very few incidents of cracking in the colder locations [7]. However, these few incidents in the colder locations have occurred in welds with diameters of less than 14 NPS which do not have the flaw tolerance of the welds that are 14 NPS and greater, as will be discussed later in this report. Therefore, these welds have not been included in the proposed change in inspection requirements discussed in this report.

4.4 Observations and Conclusions

The following conclusions can be drawn from the above experience:

- It can be concluded that all known incidents of cracking in large bore Alloy 82/182 piping welds have occurred in locations operating at hot leg temperatures or higher.
- No safety or structural integrity concern has resulted from cold leg butt weld PWSCC to date.

Section 5: Deterministic Analyses: Flaw Tolerance of Cold Leg Weld Regions

5.1 Overview

In response to the early cracking incidents discussed in Section 4, a number of analyses were performed to assess the stability of piping with PWSCC flaws and determine the predicted extent of through-wall crack propagation. These analyses were documented in the reports discussed below and served as the basis for the inspection and evaluation guidelines identified in MRP-139.

5.2 Previous Analyses

5.2.1 MRP-44 – Interim Alloy 600 Safety Assessments for US PWR Plants

MRP-44 [8], published in April 2001, provided interim safety assessments for the most susceptible Alloy 82/182 weld locations in US PWR plants. These locations included the reactor vessel outlet nozzle to hot leg weld for Westinghouse designs, the pressurizer surge line welds for Combustion engineering plants, and the CRDM nozzle-to-reactor-vessel-head J-groove welds for the Babcock and Wilcox plants. Calculations were performed to demonstrate that there is a large tolerance for axially oriented flaws and circumferentially oriented cracks that propagate through-wall over a relatively short arc length and then propagate circumferentially around the pipe, provided that leakage is detected. This report concluded the following:

- If cracks develop in welds, they are expected to be predominantly axial.
- Axial cracks in pipe welds bounded by low-alloy steel or stainless steel materials at either end of the weld are limited to the width of the weld. The critical flaw size for rupture is several times greater than the width of the welds.
- Through-wall circumferential cracks that propagate around the pipe will produce leaks that can be detected in service before exceeding available structural margins.

The NRC performed a review of this report and concluded that it provided a basis for continued safe operation while additional analyses and inspections are performed. It should be noted that these conclusions were reached for the evaluation of locations that operate at or above hot leg temperatures.

5.2.2 MRP-113 – Alloy 82/182 Pipe Butt Weld Safety Assessment for U.S. PWR Plant Designs

MRP-113 [5] provides the final safety assessment addressing PWSCC of Alloy 82/182 butt welds in PWR plant primary systems. It is a continuation of the work documented in MRP-44. The conclusions of this report are supported by the analysis and conclusions contained in a host of supporting MRP reports including but not limited to MRP-109 [9], MRP-112 [10], and MRP-116 [11]. MRP-109 provides the results of deterministic analyses performed to assess butt weld PWSCC in Westinghouse and Combustion Engineering plants while MRP-112 provides the results of deterministic analyses for Babcock and Wilcox plants. MRP-116 provides the results of probabilistic fracture mechanics analyses performed to assess the probability of leaks, the probability of rupture due to crack growth, and the change in core damage frequency (CDF) resulting from PWSCC of Alloy 82/182 butt welds. Though the results of MRP-116 are summarized in MRP-113, the results of MRP-116 will be discussed in Section 6.0

Initiation and Growth Rate Comparison

There are several factors that influence the initiation and growth of cracks in Alloy 82/182 weld materials. The most significant of these factors include the susceptible material, the tensile stress, and the environment. As discussed in MRP-113, the general experience is that, for materials of equal PWSCC susceptibility with equal applied tensile stress, the time to crack initiation is a function of the operating temperature. Locations that operate at higher temperatures, such as the pressurizers, typically exhibit cracking sooner than locations that operate at lower temperatures, such as in the RCS cold legs. For typical PWR plant pressurizer (653°F), hot leg (600°F), and cold leg (550°F) temperatures, and a thermal activation energy of 50 kcal/mole for crack initiation, the multipliers on time to initiation of PWSCC for hot leg and cold leg locations relative to pressurizer locations are 7.7 and 63.7, respectively. If predictions are based on crack growth rate data, the activation energy can be taken as 31 kcal/mole and the corresponding multipliers on time are 3.5 and 13.1, respectively. In other words, under typical conditions, cracks in cold leg locations take 63.7 times as long to initiate and grow at a rate 13.1 times slower than cracks in pressurizer locations.

Critical Crack Size Assessment

Westinghouse (MRP-109) and AREVA (MRP-112) have performed analyses to determine the critical flaw sizes for a range of Alloy 82/182 butt welds in plants from all three US nuclear steam supply system (NSSS) suppliers. These critical crack size calculations were based on ASME Code Section XI methodology. Critical crack sizes were calculated for both the circumferential and axial orientations, recognizing that experience indicates that axial flaws are limited to grow by PWSCC to the width of the weld. These analyses were performed to determine the most limiting conditions for the plants in the domestic fleet. The results of the limiting crack sizes are shown in Table 6-1 of MRP-113 while the results pertaining to cold leg locations are summarized in Table 5-1 of this report. The data in Table 5-1 shows that Alloy 82/182 cold leg butt welds in domestic PWR plants can tolerate axial and circumferential flaws of a significant size while maintaining structural integrity.

Table 5-1
Critical Flaw Size Assessment Summary – Cold Leg Welds

Location	NSSS	Limiting Plant	Burst Pressure for 2.5″ Long Through-Wall Axial Flaw (ksi)	Critical Through-Wall Axial Flaw Length (in)[1]	Critical Through-Wall Circ Flaw Length (deg)	Critical 360° Part Depth a/t Ratio
RPV Inlet	W	B	8.2	28.1	115	.66
	W	C	7.7	25.9	130	.70
RPV Core Flood	B&W	A	–	22.3	194	.75
SG Outlet	W	D	8.8	30.0	155	.77
RCP Suction	CE	J	9.4	38.2	115	.62
RCP Discharge	CE	J	9.4	38.2	104	.56

1. These critical axial flaw lengths are much greater that the width of the Alloy 82/182 butt welds.

Crack Growth Analysis

No calculations were performed for the growth rate of axial flaws since the analysis results demonstrated that the maximum lengths of through-wall axial cracks, which are limited to the width of the Alloy 82/182 weld, are significantly less than the calculated critical crack sizes. Westinghouse and AREVA performed crack growth analyses for circumferentially oriented cracks. These analyses were originally performed using the weld crack growth rate model in MRP-21 [12]. After the final crack growth model was published in MRP-115 [13], check calculations were then performed for the limiting cases. These cases confirmed that the results obtained from the analyses using the MRP-21 crack growth rate model were conservative. While there are differences in the approaches taken by Westinghouse and AREVA, the results from both approaches show that the flaw tolerance in cold leg weld locations is very high.

The results of the analyses performed by Westinghouse and AREVA for the Alloy 82/182 butt weld cold leg locations are summarized in Tables 5-2 and 5-3 respectively.

Table 5-2
Crack Growth Analysis of Part-Circumferential Through-Wall Flaws in Cold Leg Butt Welds: Westinghouse and CE Design Plants: Based on MRP-21 Crack Growth Rates

Location	NSSS	Limiting Plant	Time to Through-Wall 6:1 Aspect Ratio[1] (years)	Time to Through-Wall 2:1 Aspect Ratio[1] (years)	Time from 1 GPM[2] to Critical Flaw Size (years)	Time from 10 GPM[2] to Critical Flaw Size (years)
RPV Inlet	W	B	22.3	> 40	> 40	> 40
SG Outlet	W	D	> 40	> 40	> 40	> 40
RCP Suction	CE	J	27.0	> 40	> 40	> 40
RCP Discharge	CE	J	19.7	> 40	> 40	38.5

1. Aspect ratio defined as: Flaw length:Flaw depth.
2. Through-wall crack producing either 1 GPM or 10 GPM leak.3.

Table 5-3
Crack Growth Analysis of Part-Circumferential Through-Wall Flaws in Cold Leg Butt Welds: Babcock & Wilcox Design Plants: Based on MRP-21 Crack Growth Rates

Location	NSSS	Limiting Plant	Time from Initiation to 75% Through-Wall (years)	Time from 1 GPM to Critical Flaw Size (years)
RPV Core Flood	B&W	A	> 40	> 70

As can be seen by the results in Tables 5-2 and 5-3, the times for growth of postulated flaws to limiting size in cold leg butt weld locations are very long. In most cases the results show that more than 40 years is required to reach 75-100% through-wall. These long times result from the crack tip stress intensity factor dropping below the MRP-21 threshold of 9 MPa$\sqrt{m}$ for PWSCC crack growth. The only growth predicted under these conditions would be by fatigue.

Westinghouse and AREVA performed additional crack growth assessments using the MRP-115 crack growth rate model without the stress intensity factor threshold. The data show that the times for cracks to grow through-wall are reduced. However, the times for cracks to grow from a 1 GPM or 10 GPM leak to critical length are increased. This increase results from the fact that the new crack growth rates are lower than the original model rates at higher K levels. In both cases, the calculations were performed using the same assumed initial flaw sizes as the earlier analyses.

5.3 Recent Analyses

5.3.1 Flaw Evaluation of CE Design RCP Suction and Discharge Nozzle DM Welds

An extensive series of evaluations have been performed on the Alloy 82/182 dissimilar metal butt welds located at the safe-end regions of the CE designed reactor coolant pump suction and discharge nozzles. These nozzles present inspection coverage challenges, which hinder the likelihood of obtaining the required inspection coverage (i.e. > 90%). These evaluations are documented in WCAP-17128-NP, Revision 1 [14]. The evaluations were divided into 3 steps: 1) Defense-in-Depth, 2) ASME Flaw Tolerance, and 3) Advanced FEA Flaw Tolerance.

Defense-in-Depth

To provide a measure of the flaw tolerance which exists in the RCP nozzle region, calculations were performed to quantify the margin between leakage detection and the time required for a flaw to reach a critical length. Initial through-wall circumferential flaws were postulated based on leakage calculations that were consistent with the NRC-approved leak-before-break methodology. Flaw sizes were postulated that resulted in leakage rates that are within typical nuclear power plant leak detection capabilities. The growth of the postulated flaws due to PWSCC and fatigue crack growth (FCG) was then calculated until the flaws reached a critical size. This critical size is based on a limit load methodology: the critical flaw size calculated is the circumferential flaw length required to cause pipe failure due to plastic collapse. The results of these evaluations are shown in Figure 5-1. The results shown in Figure 5-1 are conservative, as residual stress was not included in this analysis. Inclusion of residual stress was determined to slow the growth of cracks oriented in the circumferential direction. Considering that the leak detection capability required by plant technical specifications for most plants in the U.S. is better than 1 GPM, even if a flaw grew through-wall, the shortest time in which it can be expected to grow to a critical length is 10 years. Since the actual leak rate sensitivity is closer to 0.1 GPM, the time to grow to a critical length exceeds 15 years.

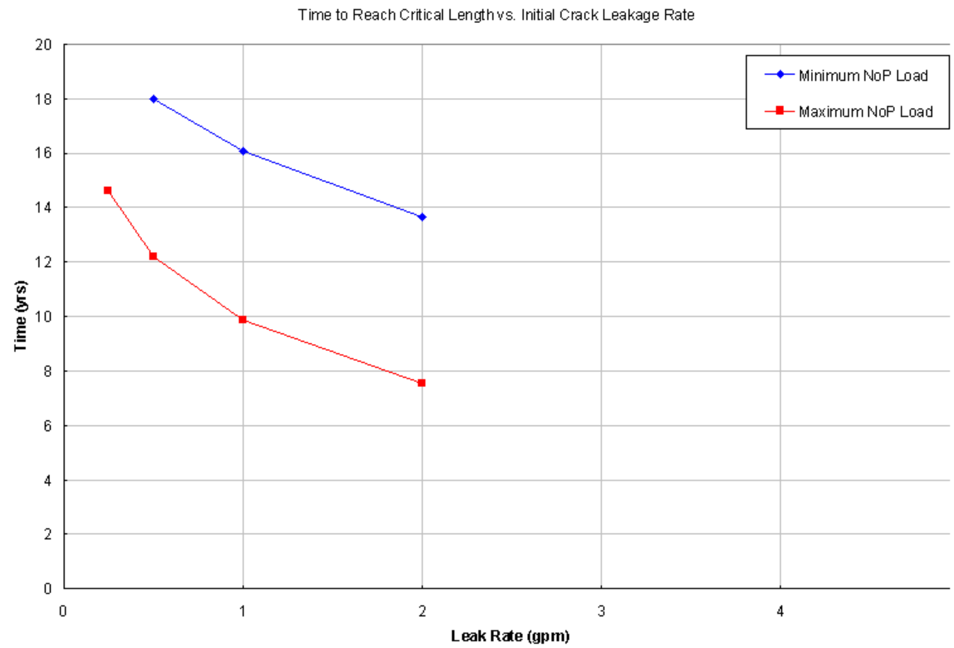


Figure 5-1
Time from Leakage to Critical Circumferential Flaw Length (No Residual Stress Case) for a Through-wall Flaw

ASME Section XI Flaw Tolerance

A series of flaw tolerance calculations were carried out in WCAP-17128-NP, Revision 1 [14] to determine the time required for a postulated surface flaw to reach the ASME Section XI allowable flaw size. Both fatigue crack growth and stress corrosion cracking were considered, and the results were presented in terms of the allowable service time for a range of flaw sizes and shapes. The calculations determined the range of flaws which are acceptable for service periods from two to four years. These calculations include the required Section XI flaw evaluation margins and were presented for both axial and circumferentially oriented flaws. Residual stresses were calculated using finite element analysis techniques [5] assuming cases of no weld repairs and weld repairs of different through-wall depths up to 50% from the ID. The results for the circumferential flaws show that very large flaws can be tolerated in this region as the residual stress effects were found to retard flaw growth for circumferential flaws (i.e., the results for the cases without weld repairs are more limiting). While the results for the axial flaws do not exhibit as much tolerance as for circumferential flaws, the limited length of the flaw causes the aspect ratios to also be limited. Though not included in WCAP-17128-NP, additional analyses consistent with those described above were performed for circumferential flaws for a service period of 10 years. The results of these evaluations, with and without residual stresses due to weld repairs, are shown in Figures 5-2 and 5-3, respectively. These results show that flaws with an aspect ratio as large as 10 and a through-wall depth of 20% will be acceptable for at least 10 years.

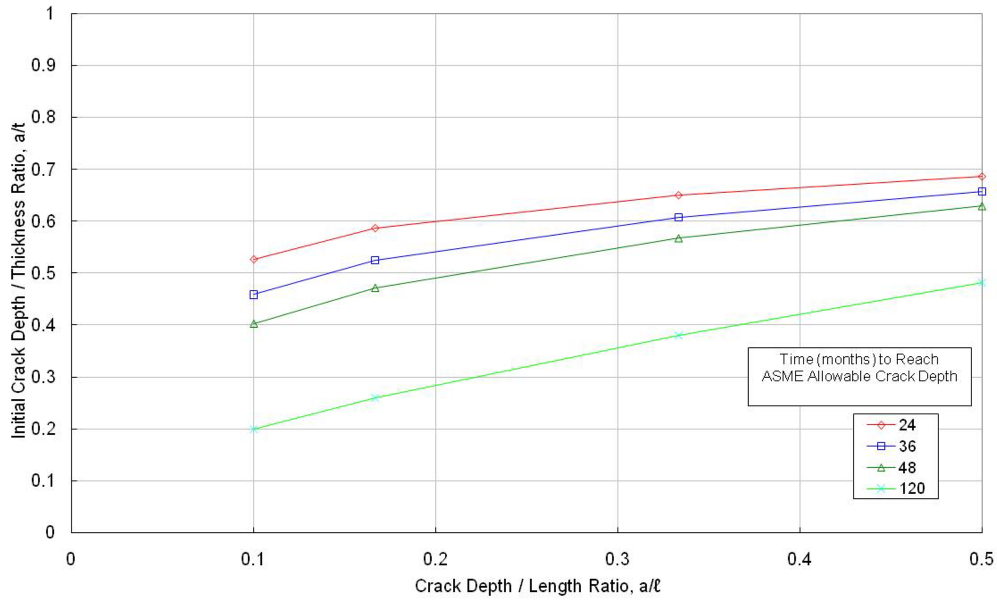


Figure 5-2
Maximum Acceptable Initial Circumferential Flaws, Accounting for PWSCC and FCG, without Residual Stresses

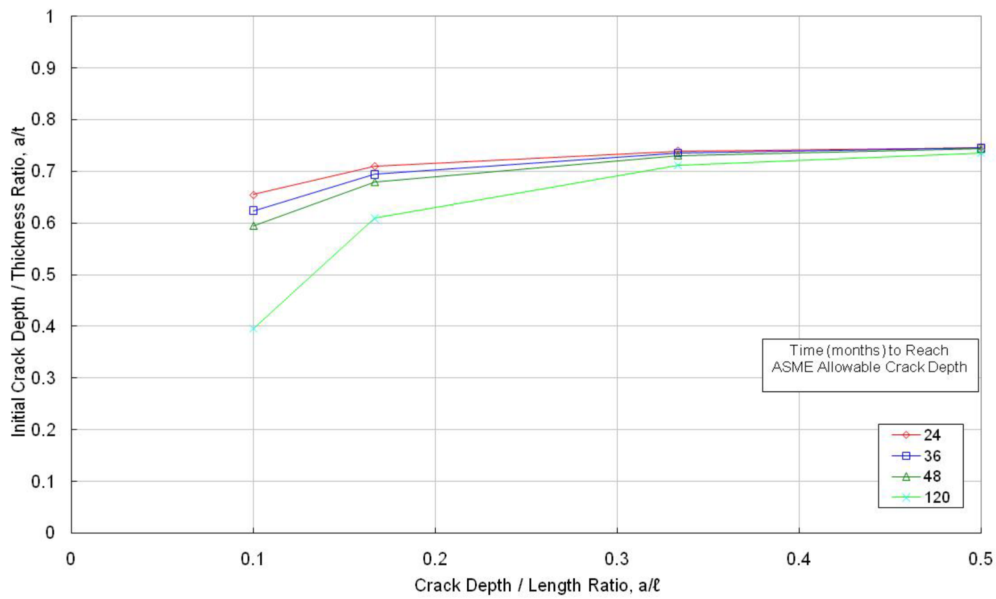


Figure 5-3
Maximum Acceptable Initial Circumferential Flaws, Accounting for PWSCC and FCG, with Fabrication Residual Stresses and an Inner Surface Weld Repair

Advanced Flaw Tolerance Analysis

The ASME flaw tolerance work was supplemented with advanced finite element analyses, wherein the postulated flaw was allowed to grow due to PWSCC in a natural shape, dictated by the stresses present. The results of these analyses are shown in Table 5-4 and are based on a postulated surface flaw in the region which cannot be inspected, with length equal to 14% of the circumference. The depth of the flaw was varied from 20% to 30% of the wall, to bracket the range of uninspectable materials. These depths were chosen based on very conservative aspect ratios of 0.04 and 0.03, respectively. These are significantly larger than the aspect ratio of 0.1667 typically observed in service, and it is highly likely that any flaws deeper than this would have tails which would be detected in the inspected region. Results show that the postulated flaw will remain within the ASME Code acceptable depth for 7.5 to over 11 years, depending on its initial depth, and requires between 9.3 and 13 years to reach a through-wall condition. These results do not account for the beneficial impact of the stainless steel field weld that is made to join the cold leg or crossover leg safe-end to the stainless steel RCP casing. This weld induces a region of compressive stress in the mid wall region of the pipe, which would further retard the crack growth.

Table 5-4
Results of Advanced Finite Element Crack Growth Analyses for Circumferential Flaws

Initial Depth/Thickness (a/t)	Initial Length/ Circumference	Time to a/t = .75	Time to a/t = 1.0
0.20	0.14	10.68 years	12.52 years
0.20	0.23	9.6 years	11.1 years
0.30	0.14	7.44 years	9.34 years
0.30	0.23	6.45 years	7.85 years

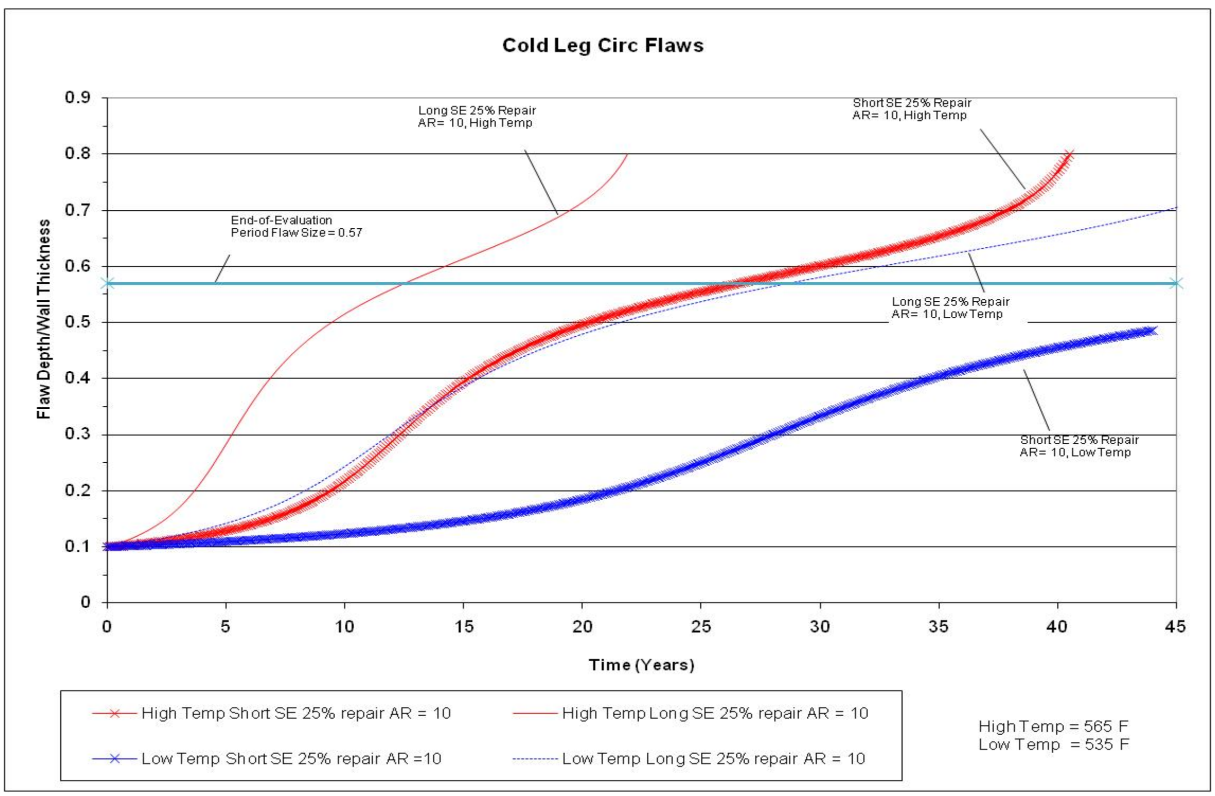
Summary

This work documented in WCAP-17128-NP, Revision 1 [14] has demonstrated that the pump safe-end to nozzle weld regions have significant margins, and therefore do not require the accelerated inspection frequency specified in MRP-139 [1] and Code Case N-770 [2]. The three approaches used to support this conclusion have been consistent in their findings.

5.3.2 Reactor Vessel Inlet Nozzle Flaw Tolerance Evaluations

Westinghouse has performed a generic flaw tolerance evaluation to determine the maximum flaw sizes in the reactor vessel inlet dissimilar metal welds that would support continued operation for a period of 10 years. This evaluation was performed consistent with the ASME Section XI flaw tolerance evaluations performed for the RCP nozzles as discussed in Section 5.3.1. Along with the normal operating steady state piping loads, the impact of welding residual stresses under different safe end lengths and the various extent of inside surface weld repairs during the initial weld fabrication process were considered in the evaluation. These residual stresses were also calculated using finite element analysis techniques that are consistent with recent industry guidance [15]. A parametric study was performed to evaluate the residual stresses for the different weld and safe-end configurations present in the Westinghouse fleet. Based on a comparison of the various residual stress distributions from the parametric study, it was concluded that a long (Length > 4.5″) safe end with either a 25% or 50% inside surface weld repair would produce limiting PWSCC crack growth results. A high and a low cold leg operating temperature were also considered in the evaluation to represent the range of operating temperatures in the fleet [16].

Based on the circumferential crack growth results shown in Figure 5-4, even for the most conservative case (high temperature with a 25% weld repair) a flaw with a depth of 15% of the wall thickness would not grow to the maximum allowable ASME flaw size in less than 10 years of continued operation. It should be noted that the results presented in Figure 5-4 are not representative of a single plant. These results are based on the limiting thickness in the Westinghouse PWR fleet combined with the limiting piping loads from another plant in the Westinghouse PWR fleet and therefore, these results are conservative.



Note: AR = Aspect Ratio, SE = Safe-End

Figure 5-4
Circumferential Flaw PWSCC Crack Growth at the RV Inlet nozzle DM Welds

5.3.3 Steam Generator Nozzle Flaw Tolerance Evaluations

As indicated in Section 4.3, cracking has recently been identified in one steam generator inlet nozzle in the U.S. and but flaw tolerance evaluations have not been performed. Results for the steam generator outlet nozzles could be expected to be similar to those reported above for the reactor coolant pump and reactor vessel cold leg locations.

5.4 Conclusions for Deterministic Analyses

All of the flaw tolerance analyses performed to date have shown that the critical crack sizes in large-diameter butt welds operating at cold leg temperatures are very large. Assuming that a flaw initiates, the time required to grow to through-wall is in excess of 20 years in most cases analyzed. The time to grow from a through-wall leak to a crack equal to the critical crack size can be in excess of 40 years.

More recent analyses have been performed for the RV nozzles using through-wall residual stress distributions that were developed based on the most recent guidance. These analyses have shown that the flaw tolerance of these locations is high and postulated circumferential flaws will not reach the maximum ASME allowable depth in less than 10 years. Supplemental advanced finite element analyses performed for the CE RCP suction and discharge nozzles shows that even if a large flaw is assumed to exist, the time to grow through-wall is a minimum of approximately 8 years. Furthermore, this flaw would be expected to take at least 10 years to grow to a critical length.

Section 6: Probabilistic Analyses

6.1 Overview

All of the analyses discussed to this point have been deterministic in nature. These deterministic analyses have assumed the existence of an initiated flaw and have used conservative inputs to determine the rate of crack growth. Probabilistic analyses can be used to determine the likelihood of a flaw initiating and growing through-wall. These analyses can be performed using probabilistic fracture mechanics and also using statistical methods. These two approaches are discussed in the following sections.

6.2 Probabilistic Fracture Mechanics Approach – MRP-116

As part of the original effort to develop the MRP-139 requirements, a probabilistic safety assessment was performed by Westinghouse for domestic Westinghouse, Combustion Engineering and Babcock & Wilcox design PWR plants using probabilistic fracture mechanics (PFM) methods. This work is summarized in MRP-113 and detailed results are provided in MRP-116 [11]. Though this assessment was performed in 2004, it is the most recent probabilistic assessment of PWSCC susceptible welds of different sizes and operating conditions. While there have been advancements in the understanding of variables that effect PWSCC, the assessment still provides valuable insights into the likelihood of piping weld failure due to PWSCC.

The probabilistic safety assessment builds on the deterministic work and addresses the probability that a flaw could grow through the wall and could eventually lead to rupture and a resultant increase in core damage frequency. The evaluations documented in the report were intended to cover all the Alloy 82/182 butt weld locations in operating PWRs in the USA. The probabilistic safety assessment brings together the deterministic results, as well as complementary work to provide input on the effects of repairs and crack growth modeling.

Probabilistic fracture mechanics evaluations were performed to address the identified degradation mechanisms of PWSCC and FCG on Alloy 82/182 dissimilar metal butt welds. The evaluations performed considered the limiting butt welds in large-diameter pipes and smaller diameter pipes based on the deterministic evaluations for the Westinghouse, CE, and B&W NSSS designs. The RV inlet nozzle and RCP welds were not specifically evaluated because they were not determined to be limiting locations in the deterministic evaluations. Evaluations for each of the limiting locations considered the small axial leak and small circumferential leak failure modes, and can be conservatively used to represent the results for cold leg locations. The results of the PFM evaluation for the circumferential leak probabilities, which represent a direct safety concern, are summarized in Table 6-1.

Table 6-1
Summary of 40-Year Leak Probabilities

Nozzle	Design	Circumferential 40-Year Small Leak Probability With ISI
Decay Heat	B&W	5.00E-05
RV Outlet Nozzle	W	2.00E-04
Safety/Relief	CE/W	9.81E-06
SDC	CE	2.70E-08
SG Inlet	CE	3.38E-06
Spray	CE/W	1.25E-04
Surge HL	CE	3.38E-06
Surge PZR	CE/W	2.00E-04
	B&W	2.00E-04

As shown in Table 6-1, the circumferential leak probabilities at 40 years are small. It must be noted that all of these probabilities are for cases evaluated at hot leg or pressurizer operating temperatures. Though not explicitly evaluated, based on the differences in crack initiation and growth times discussed in Section 5.2.2, the probabilities for locations at cold leg temperatures would be expected to be at least an order of magnitude less than those for the welds at hot leg temperatures, and higher.

As part of the MRP-116 probabilistic fracture mechanics evaluations, a sensitivity study was performed to determine the effects of ISI accuracy and frequency. This sensitivity study was performed for a weld that was considered to be representative of the welds included in the study. The results of the study are shown in Table 6-2. Though the weld considered in this study was not a cold leg weld, the results of the study would be expected to envelope the results for cold leg weld locations.

Table 6-2
Inservice Inspection Sensitivity Study

Description[1]	40-Year Circumferential Small Leak Probability	Risk[4] (Core Damage Frequency)
No ISI[2]	6.06E-05	4.55E-09
10 Year ISI[2]	5.92E-05	4.44E-09
1 Year ISI[2]	3.67E-05	2.75E-09
1 Yr ISI and Improved Quality[3] of Inspection	1.18E-05	8.82E-10

1. Residual stress input unchanged
2. Standard inspection quality for 50% detection of a flaw 25% through the wall
3. Standard inspection quality for 50% detection of a flaw increased to detect a flaw 10% through the wall
4. For conditional core damage probability (CCDP) = 3.0E-03

Based on the results of the probabilistic fracture mechanics analyses, it was concluded in MRP-116 that:

- Changes in inspection frequency or improvements in capability or accuracy have only a small benefit for the locations with the highest leak probabilities.
- Risk results do not justify shortening the current 10-year ASME Code Section XI inspection interval, as long as all Alloy 182/82 locations are included.

NRC Regulatory Guide 1.174 [17] provides An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Current Licensing Basis. Regulatory Guide 1.174 defines an acceptably small change-in-risk as one that meets the following criteria:

- Change in Core Damage Frequency (CDF) $< 1 \times 10^{-6}$ per reactor year
- Change in Large Early Release Frequency (LERF) $< 1 \times 10^{-7}$ per reactor year

Based on the results shown in Table 6-2, the change in risk (CDF) in moving from a hypothetical 1 year ISI interval to the ASME Section XI 10 year ISI interval would be 1.69×10^{-9} per reactor year. This change is more than 2 orders of magnitude below the regulatory criteria for an acceptably small increase in risk. It is reasonable to conclude that the increase in risk in moving from a 6 or 7 year interval as required by MRP-139 or Code Case N-770, respectively, to a 10 year interval would be even less than 1.69×10^{-9} per reactor year and further acceptable per Regulatory Guide 1.174. Furthermore, it would also be expected that the change would be less for cold leg weld locations. In other words, the shorter intervals specified in MRP-139 and Code Case N-770 are not needed for the cold leg locations to satisfy risk objectives.

6.3 Statistical Approach

A probabilistic analysis was performed in WCAP-17128-NP, Revision 1 to assess the susceptibility of cold leg welds to PWSCC. The analysis considered available industry experience data for the locations of Alloy 82/182 DM welds. More specifically, the data analyzed included Alloy 82/182 DM welds that were nominally 28 inches in diameter or larger at the:

1. Reactor vessel inlet and outlet nozzles,
2. Steam generator inlet and outlet nozzles, and
3. Reactor coolant pump suction and discharge nozzles.

In addition to the service experience data for the above large nozzles, service experience for the pressurizer surge nozzle was also analyzed in one case.

The collected service experience data was fit to a Weibull distribution which was then used to calculate the probability of cracking as a function of EFPY. This was done for three different temperatures with the intent of covering the range of temperatures on the cold nozzle DM weld locations (548°F to 556°F), as well as a representative hot nozzle DM weld location (615°F). Three different cases were evaluated based on the data to which the Weibull distribution was fit. Case 1 is based on all the available inspection results, for reactor vessel nozzles, steam generator nozzles, pump nozzles, and pressurizer surge nozzles. Case 2 includes all the nozzles except the pressurizer nozzles, and Case 3 includes only the reactor vessel and RCP nozzles. The results of these cases at the three temperatures are shown in Table 6-3. The cumulative probability of cracking with respect to effective full power years of operation was also determined for each of the three cases and is shown in Figures 6-1 to 6-3.

Table 6-3
Summary of Probability of Cracking Results for Hot and Cold Leg Welds

At EFPY	Case 1	Case 2	Case 3
Temperature 548°F			
20	0.25%	0.00%	0.01%
40	0.57%	0.03%	0.05%
60	0.93%	0.12%	0.15%
Temperature 556°F			
20	0.38%	0.01%	0.02%
40	0.88%	0.10%	0.13%
60	1.42%	0.35%	0.35%
Temperature 615°F			
20	6.98%	20.92%	9.84%
40	15.32%	86.63%	44.34%
60	23.71%	99.92%	80.10%

The results in Table 6-3 show that there is no discernable difference between the cases at the cold leg temperatures. Furthermore, the predicted probability of cracking for DM welds operating at cold leg temperatures is extremely low, even at 60 effective full power years (EFPY). The results of the Weibull curve fitting for the three cases indicate that even though DM welds have had many flaws at hot temperature locations, none have been found at cold temperature butt weld locations, and this gives a very low probability of flaws existing in cold temperature locations. Results in Table 6-3 show that the highest probability of an indication at cold leg temperatures was only 1.42%, at 60 EFPY (Case 1 at 556°F). A 60 EFPY value is beyond a plant's licensed life, even with a 20-year life extension.

The cumulative probability of cracking with respect to effective full power years of operation was also determined for each of the three cases and is shown in Figures 6-1 to 6-3.

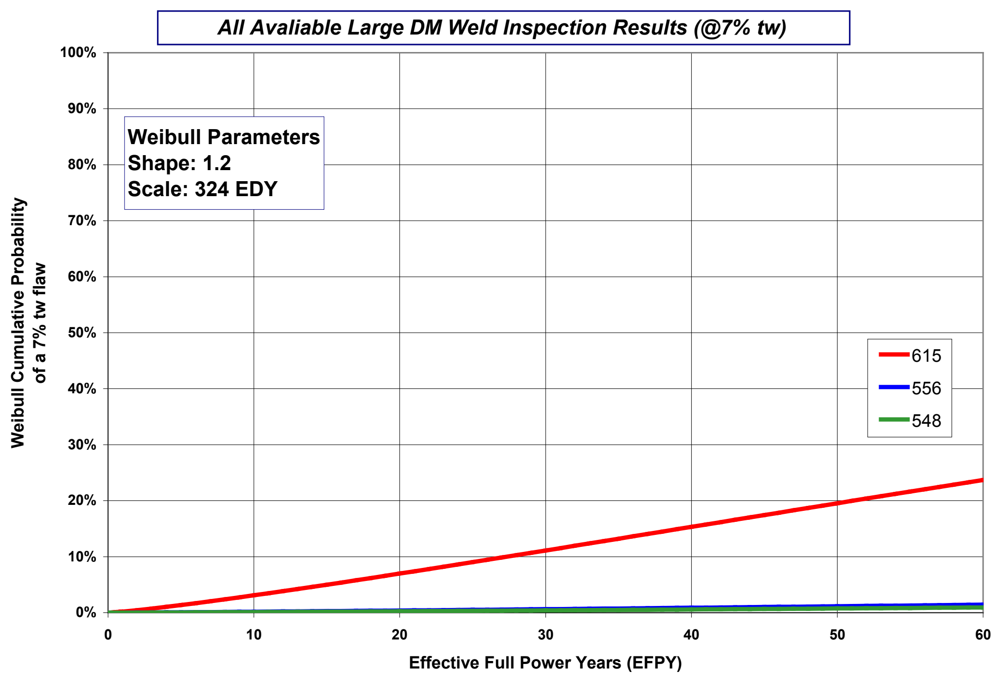


Figure 6-1
All Available Large DM Weld Inspection Results (7% Through-wall) – Case 1

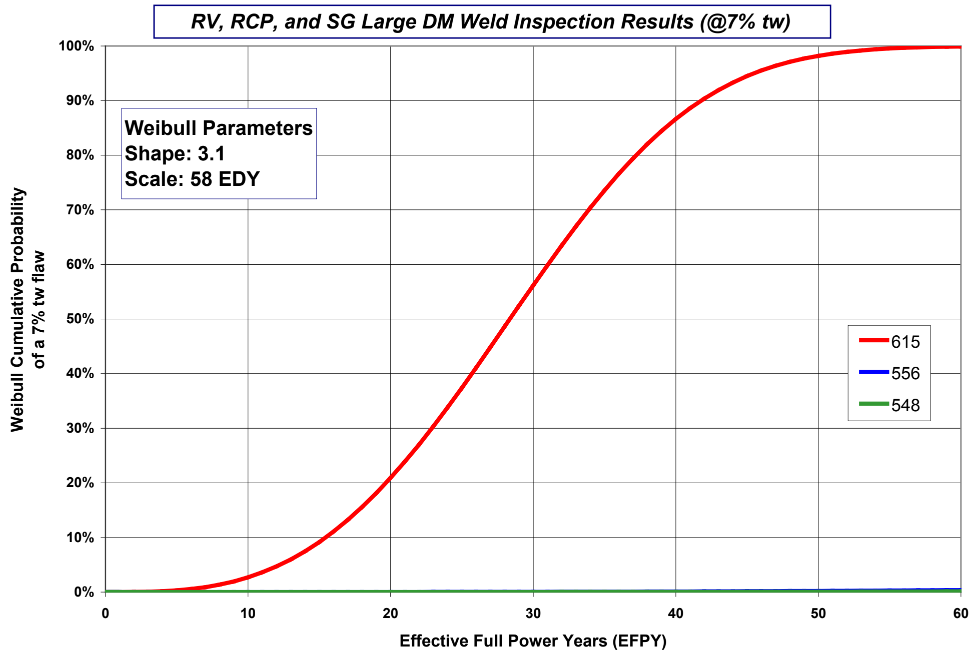


Figure 6-2
All Available Large DM Weld Inspection Results (7% Through-wall) – Case 2

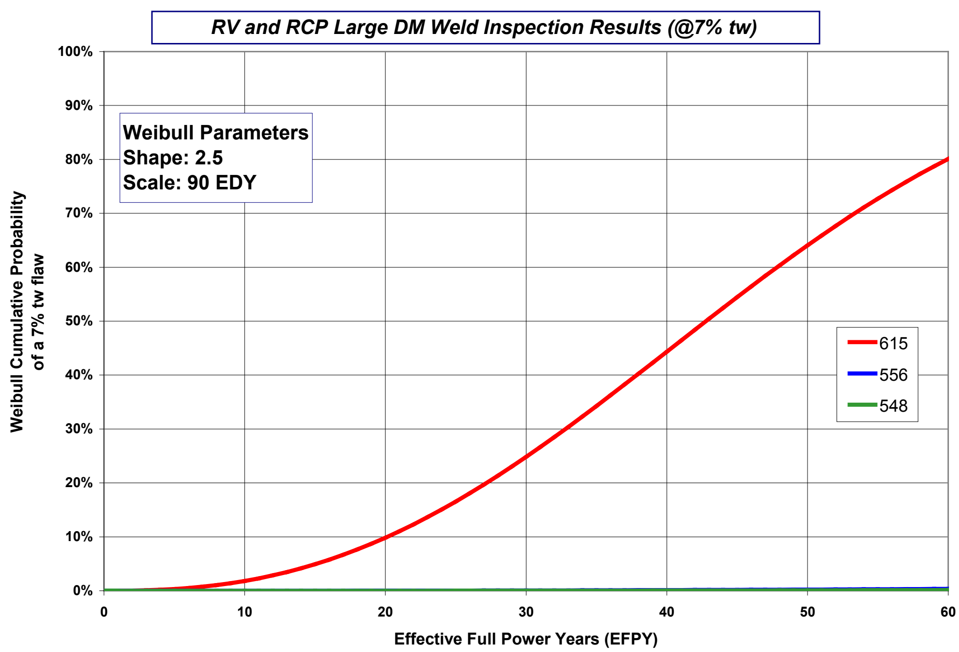


Figure 6-3
All Available Large DM Weld Inspection Results (7% Through-wall) – Case 3

6.4 Conclusions for Probabilistic Analyses

Analyses have been performed to calculate the probability of failure for Alloy 82/182 welds using both probabilistic fracture mechanics and statistical methods. Both approaches have shown that the likelihood of cracking or through-wall leaks, in large-diameter cold leg welds is very small. Furthermore, sensitivity studies performed using probabilistic fracture mechanics have shown that even for the more limiting high temperature locations, more frequent inspections than required by Section XI, such as that in MRP-139 or Code Case N-770, has only a small benefit in terms of risk.

Though past service experience may not be an absolute indicator of the likelihood of future cracking, the experience does give an indication of the relative likelihood of cracking in cold leg temperature locations versus hot leg temperature locations. While there is a significant amount of PWSCC service experience in hot leg locations, the number of indications in large-bore buttwelds is still small relative to the number of potential locations. Also, all indications have been detected before they were a safety concern. Therefore, if hot leg PWSCC is a leading indicator for cold leg PWSCC, and the higher frequency of inspections will be maintained for the hot leg locations, it is reasonable to conclude that a moderately less rigorous inspection schedule would be capable of detecting any cold leg indications before they became large enough to be a concern.

Section 7: Conclusions

While there has been a large amount of service experience with primary water stress corrosion cracking of Alloy 82/182 buttwelds, this experience has been limited to those welds operating at hot leg temperatures or higher (608°F - 621°F), with few exceptions. There have been no incidents of cracking in large diameter butt welds operating at cold leg temperatures (< 575°F) that can be attributed to PWSCC. The MRP-139 and Code Case N-770 requirements for more frequent inspection were taken as a proactive measure. However, the accumulation of more positive service experience indicates that while this increased inspection frequency is needed for the more susceptible hot leg locations, it is not necessary to maintain an acceptable level of safety and quality for cold leg welds. Furthermore, it has been realized that accessing these cold leg weld locations for inspection presents a hardship to utilities and may present an increase in plant risk due to the complications associated with removal of the reactor vessel core barrel.

There have been numerous evaluations performed of the likelihood of through-wall cracking and flaw tolerance in cold leg Alloy 82/182 welds. The analyses performed as the original basis for MRP-139 showed that the large-diameter cold leg welds had high flaw tolerance and a very low probability of failure. More recent analyses, which considered design specific residual stress distributions, have confirmed the original conclusions that flaw tolerance is high. Furthermore, the more recent analyses have shown that even large circumferential flaws, with a high likelihood of being detected during inservice inspection, will not grow to the maximum depth allowed by ASME Section XI in 10 years. These analyses have been performed based on the assumption that a flaw has initiated, which as shown by more recent probabilistic analyses based on service data is unlikely at the present time.

It is therefore concluded, that an interval of 10 years for re-examination of large-diameter cold leg Alloy 82/182 locations will provide a more than adequate level of safety and quality. Furthermore, this interval will reduce hardship on utilities and minimize the overall plant risk associated with movement of the reactor vessel core barrel. Proposed revisions to MRP-139 and Code Case N-770 to incorporate a 10-year re-examination interval for large-diameter cold leg butt welds are shown in Section 8.

Section 8: Proposed Revisions to MRP-139 and Code Case N-770

The inspection of Alloy 182/82 DM welds since 2005 have been performed to the requirements of report MRP-139, Revision 1 (Reference 1). These inspection requirements have now been replaced by those of Code Case N-770 (Reference 2).

The proposed revisions to Code Case N-770 and MRP-139 to require an inspection interval of 10 years are discussed in the following sections.

8.1 Proposed Revision to Code Case N-770 for Cold Leg Locations

It is proposed that Inspection Item B of Table 1 of Code Case N-770 be revised as follows:

Existing Table 1 Requirements for Inspection Item B:

Inspec-tion Item	Parts Examined	Examination Requirements /Fig. No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination	Deferral of Examination to End of Interval
B	Unmitigated butt weld at Cold Leg operating temperature (-2410) ≥ 525°F (274°C) and < 580°F (304°C)	Weld Surface Fig. 1	Visual (2), (3) Volumetric (4)	-3140 -3130	Once per interval Every second inspection period not to exceed 7 yr (5)	Not Permissible

Proposed Table 1 Requirements for Inspection Item B:

Inspec-tion Item	Parts Examined	Examination Requirements / Fig. No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination	Deferral of Examination to End of Interval
B-1	Unmitigated butt weld at Cold Leg operating temperature (-2410) ≥ 525°F (274°C) and < 580°F (304°C), Less than NPS 14 (DN 350)	Weld Surface Fig. 1	Visual (2), (3) Volumetric (4)	-3140 -3130	Once per interval Every second inspection period not to exceed 7 yr (5)	Not Permissible
B-2	Unmitigated butt weld at Cold Leg operating temperature (-2410) ≥ 525°F (274°C) and < 580°F (304°C), NPS 14 or Larger (DN 350)	Weld Surface Fig. 1	Visual (2), (3) Volumetric (4)	-3140 -3130	Once per interval Once per interval	Permissible

8.2 Proposed Revision to MRP-139 for Cold Leg Locations

Section 6.5.2 should be revised to read "PWSCC Category E welds less than 14 NPS shall be volumetrically inspected 100% every six years. PWSCC Category E welds 14 NPS or greater shall be volumetrically inspected 100% every ten years."

Table 6-1, "Examination Extent and Schedule" for PWSCC Category E shall be revised from "100% every six years" to "100% every six years for less than 14 NPS. 100% every ten years for 14 NPS or greater."

Section 9: References

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Programs:

Nuclear Power

Pressurized Water Reactor Materials Reliability Program

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