ELECTRIC POWER RESEARCH INSTITUTE

Materials Reliability Program: Topical Report for Primary Water Stress Corrosion Cracking Mitigation by Surface Stress Improvement (MRP-335, Revision 1)

2013 TECHNICAL REPORT

Materials Reliability Program: Topical Report for Primary Water Stress Corrosion Cracking Mitigation by Surface Stress Improvement (MRP-335)

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Abstract

The objective of this report is to define appropriate inspection requirements and intervals for certain components—Alloy 600 reactor pressure vessel head penetration nozzles and Alloy 82/182 dissimilar metal welds in primary system piping—that have been treated by surface stress improvement (SSI) methods (that is, peening) for the purpose of mitigating primary water stress corrosion cracking.

Given the demonstrated effectiveness of the candidate SSI techniques of laser and water jet peening, relaxation of the inspection requirements for these components is appropriate after SSI treatment. The specific inspection requirements are supported by detailed deterministic and probabilistic modeling that is supported by extensive testing. Because the inspection requirements for these components are prescribed by Nuclear Regulatory Commission (NRC) regulations (based on American Society of Mechanical Engineers Boiler & Pressure Vessel Code Cases), NRC approval is required for relaxation of these inspection requirements following peening mitigation. Licensees may reference this report in support of site-specific relief requests.

Keywords
Alloy 600
Laser peening
Primary water stress corrosion cracking
Relief requests
Surface stress improvement
Water jet peening

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Section 1 Introduction

1.1 Objective

The objective of this report is to define appropriate inspection requirements and intervals for Alloy 600 reactor pressure vessel head penetration nozzles (RPVHPNs) and for Alloy 82/182 dissimilar metal welds (DMWs) in primary system piping that have been treated by surface stress improvement (SSI) methods (i.e., peening) for the purpose of mitigating primary water stress corrosion cracking (PWSCC). The specific inspection requirements are supported by detailed deterministic and probabilistic modeling supported by extensive testing. Because the inspection requirements for these components are prescribed by NRC regulations (based on ASME Boiler & Pressure Vessel Code Cases), NRC approval is required for relaxation of these inspection requirements following peening mitigation. Licensees may reference this report in support of site-specific relief requests.

1.2 Background

PWSCC has occurred at PWR reactor coolant system DMW piping butt welds made with Alloys 182 and 82 and Alloy 600 RPVHPNs attached to the reactor vessel top head using Alloy 82/182 J-groove welds. In response to this cracking, Code Cases N-770-1 [1] and N-729-1 [2] have been issued by the American Society of Mechanical Engineers (ASME) that establish in-service inspection requirements for these components. These versions of the Code Cases have been accepted with conditions and made mandatory by the Nuclear Regulatory Commission (NRC) through 10 CFR 50.55a.[1] Later versions of these Code Cases have been prepared but have not as yet been accepted by the NRC. The later version of the DMW code case (N 770-2 [4]) covers the situation where PWSCC has been mitigated by application of a global stress relief method, but does not as yet specifically cover surface stress improvement (SSI) by peening. None of the versions of the RPVHPN code case (N-729, -1, or -2) cover situations where PWSCC has been mitigated by stress relief methods.

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[1] Code Case N-722-1 [3], which provides requirements for direct visual examinations for evidence of leakage at Alloy 600/82/182 PWR pressure boundary components, has also been made mandatory by NRC with conditions. N-722-1 explicitly does not address RPVHPNs, and the visual examination intervals under N-722-1 are identical to those of N-770-1 for unmitigated Alloy 82/182 piping butt welds. Code Case N-722-2, which was approved by ASME on September 8, 2011, excludes the primary piping Alloy 82/182 butt welds covered by N-770-1, but N-722-1 is the version made mandatory by NRC regulations as of the date of publication of this report.

The inspection intervals specified in ASME Section XI and Code Cases N-770-1 and N-729-1 vary depending on the resistance to PWSCC of the specific component being considered. The intervals for components made with Alloys 600, 182, and/or 82 are the shortest, while intervals for components made with PWSCC resistant materials are longer. Intervals for components made with Alloys 600, 182, and/or 82 that have had mitigation measures applied are also relaxed as compared to those for unmitigated components. It is expected that the ASME Code may use this topical report and MRP-267 R1 [5] as the technical basis for revising N-729 and N-770 to include inspection requirements specific to Alloy 600 RPVHPNs and Alloy 82/182 DMWs mitigated by peening. Prior to these code cases and the relevant NRC regulations (10 CFR 50.55a) being revised, it is intended that this topical report may be used on a site-specific basis to request inspection relief from current requirements.

1.3 Approach

The basic approach taken in this report is to determine, through the use of deterministic and probabilistic safety analyses, the inspection requirements and intervals that are appropriate for Alloy 600/82/182 components that have had SSI applied by use of peening. Because of the demonstrated effectiveness of these methods to prevent PWSCC crack initiation and stop growth of shallow flaws, it is appropriate that longer inspection intervals be used for Alloy 600 RPVHPNs and Alloy 82/182 DMWs mitigated by peening in comparison to the current inspection intervals for unmitigated components. A probabilistic approach was taken to address the chance that flaws too deep to be arrested by the peening application are not detected prior to the peening being performed.

1.4 Locations and Peening Methods Addressed

This report addresses the use of SSI at the following locations and using laser peening (LP) or water jet peening (WJP) methods:

- The inner diameter (ID) surfaces of DMWs in reactor coolant system piping butt welds.
- The nozzle ID surfaces of RPVHPNs in the area with high weld residual stresses due to the presence of the J-groove attachment weld. It is noted that a water environment is relatively easily established for nozzle IDs, and thus peening methods that are typically performed underwater may be readily applied to this surface.
- The nozzle OD surfaces of RPVHPNs in the area with high weld residual stresses due to the presence of the J-groove attachment weld.
- The J-groove weld surfaces of RPVHPNs, including the surfaces of the Alloy 82/182 weld filler metal and Alloy 82/182 weld butter metal that are normally wetted during operation.

1.5 Peening Requirements

The requirements for peening mitigation of Alloy 600/82/182 components in PWRs are listed below in Table 1-1. The table includes the page number and section of the report where each requirement is located.

Table 1-1
Requirements for Peening Mitigation of Alloy 600/82/182 Components in PWRs

Page Number	Report Section	Requirement
2-2	Basis for no unacceptable side effects	Based on this experience, this document requires evaluations to identify susceptibility to FIV, and if susceptible, requires post-peening inspections to verify that problems did not occur.
2-3	Benefit of Pre-Peening Inspections	Detected flaws shall be removed prior to peening if no other evaluation, repair, or mitigation action is used to address the detected flaws. If the flaws will be addressed by another repair or mitigation action, peening may be performed over the flaws either prior to or after the other repair or mitigation action.
3-2	Mitigation basis for peening	The potential for growth by fatigue of shallow flaws located in the peening compressive residual stress zone shall be considered on an application-specific basis.
3-2	Mitigation basis for peening	The fatigue assessment shall consider the stress cycles that occur at the specific location.
3-4	Verification of No Unacceptable Side Effects	Based on this experience, this document requires evaluations of adjacent areas prior to water jet peening to identify susceptibility to FIV, and if susceptible,, requires post-peening inspections to verify problems did not occur.
3-5	Growth of PWSCC Cracks	It is required that performance demonstrated UT methods will be applied to RPVHPN tube base metal and to DMWs in conjunction with peening applications. It is also required that the ID surfaces of RPVHPNs and DMWs be examined by ET or PT methods, and that detected flaws be removed, e.g., by polishing and grinding before peening is performed. It is also required that the ID surfaces of RPVHPNs and DMWs be examined by ET or PT methods, and that detected flaws shall be removed, e.g., by polishing and grinding before peening is performed if no other evaluation, repair, or mitigation action is used to address the detected flaws. If the flaws will be addressed by another repair or mitigation action, peening may be performed over the flaws either prior to or after the other repair or mitigation action.

Table 1-1 (continued)
Requirements for Peening Mitigation of Alloy 600/82/182 Components in PWRs

Page Number	Report Section	Requirement
3-6	Plant/application-specific factors	As discussed in Section 3.1, the potential for growth by fatigue of shallow flaws located in the peening compressive residual stress zone shall be considered on an application-specific basis.
3-6	Plant/application-specific factors	The fatigue assessment shall consider the applied stress cycles that occur at the specific location, in combination with the levels of compressive stress expected from the selected peening method (adjusted for temperature and load cycling induced relaxation).
3-6	Quality assurance considerations	Since surface stress improvement by peening affects the performance of nuclear safety related systems and components, it shall be performed in accordance with a quality assurance program meeting the requirements of Appendix B to 10 CFR 50 and the utility's plant specific commitments.
3-6	Quality assurance considerations	Further, since peening is a special process, it shall be controlled in a manner consistent with Criterion IX, "Control of Special Processes," of Appendix B and any applicable plant specific commitments. As stated in that criterion, this requires that the personnel and procedures involved need to be appropriately qualified.
3-6	Quality assurance considerations	Since there are no industry standards that apply to peening, these qualifications shall be done to vendor requirements developed and documented per their 10 CFR 50 Appendix B quality assurance program and to utility requirements and commitments applicable at the plant site.
4-3	Examination requirements developed for Alloy 600/82/182 components mitigated by peening	Table 4-1 contains a summary of the current inspection requirements for RPVHPNs and DMWs with unmitigated Alloy 600/82/182 materials that are in Code Cases N-729-1 and N-770-1. In addition, the table defines appropriate requirements for inspections to be performed on these components before and after application of peening, as well as the required minimum nominal depth of the compressive residual stress produced by the peening treatment.

Table 1-1 (continued)
Requirements for Peening Mitigation of Alloy 600/82/182 Components in PWRs

Page Number	Report Section	Requirement
4-4	Examination requirements developed for Alloy 600/82/182 components mitigated by peening	The extent of the required surface to be peened in the case of RPVHPNs is defined by the examination volume/area of Figure 2 of ASME Code Case N-729-1 [2]. This includes the entire wetted surface of the Alloy 82/182 J groove weld and butter material, as well as the surface of the Alloy 600 tube material in the region of high weld residual stress that is susceptible to PWSCC.
4-4	Examination requirements developed for Alloy 600/82/182 components mitigated by peening	An evaluation shall be performed prior to water jet peening to identify susceptibility of adjacent areas to flow induced vibration. A post-mitigation visual examination (VT-1 or VT-3) shall be performed if the evaluation shows susceptibility to damage from the peening process. Such evaluations need to consider the experience of the extensive peening performed in Japan, the specific peening process performed, and whether there is any potential for inadvertent damage to components adjacent to the target peening area.
4-5	Examination requirements developed for Alloy 600/82/182 components mitigated by peening	It is not necessary that volumetric or surface examinations be performed post-peening as the peening process does not introduce any significant geometrical changes of the treated component, and because flaws detected prior to peening shall be removed or repaired prior to peening.
4-5	Dissimilar metal welds (DMWs) in primary system piping	The inspection requirements in Table 4-1 that shall be used with peened Alloy 82/182 DMWs are as follows: Prior to Peening • An ultrasonic examination shall be performed of the weld using a technique that has been qualified to the performance demonstration requirements of Appendix VIII of Section XI of the ASME Code. • An eddy current (ET) or liquid penetrant (PT) inspection shall also be performed of the weld ID. The ET or PT technique need not be qualified using formal performance demonstration techniques, but shall have been demonstrated by the inspection vendor per current practices (e.g., per ASME Section V).

Table 1-1 (continued)
Requirements for Peening Mitigation of Alloy 600/82/182 Components in PWRs

Page Number	Report Section	Requirement
4-5	Dissimilar metal welds (DMWs) in primary system piping	It is emphasized that the surface (ET or PT) examinations that are required in this report for use prior to peening are not relied upon in the safety analyses described in Section 5 and Appendix A. Instead they are a secondary method intended to provide additional assurance of flaw detection and removal. Subsequent to Operation The relaxed schedule for performance of volumetric and visual examinations of peened welds is shown on Table 4-1 as a function of the operating temperature of the weld.
4-5	Reactor pressure vessel head penetration nozzles (RPVHPNs)	The inspection requirements in Table 4-1 that shall be used with peened RPVHPNs are as follows: Prior to Peening • An ultrasonic examination of the nozzle tube shall be performed from the nozzle ID using a technique that has been qualified to the performance demonstration requirements of Appendix VIII of Section XI of the ASME Code (as required by the conditions of 10 CFR 50.55a(g)(6)(ii)(D)(4)). Alternatively, consistent with 10 CFR 50.55a(g)(6)(ii)(D)(3), surface examination of equivalent surfaces of the nozzle tube, as identified by Figure 2 of ASME Code Case N-729-1, shall be performed. • An eddy current (ET) or liquid penetrant (PT) inspection shall also be performed of the nozzle ID. The ET or PT technique need not be qualified using formal performance demonstration techniques, but shall have been demonstrated by the inspection vendor per current practices (e.g., per ASME Section V). It is emphasized that the surface (ET or PT) examinations that are required in this report for use prior to peening are not relied upon in the safety analyses described in Section 5 and Appendix B. Instead they are a secondary method intended to provide additional assurance of flaw detection and removal.

Table 1-1 (continued)
Requirements for Peening Mitigation of Alloy 600/82/182 Components in PWRs

Page Number	Report Section	Requirement
4-6	Reactor pressure vessel head penetration nozzles (RPVHPNs)	<u>Subsequent to Operation</u> • The relaxed schedule for performance of volumetric and visual examinations of peened penetrations is shown on Table 4-1 as a function of EDY. <u>Leak Path Examination</u> • Consistent with 10 CFR 50.55a(g)(6)(ii)(D)(3), a demonstrated volumetric or surface leak path assessment through all J-groove welds shall be performed each time the periodic volumetric/surface examination is performed.
6-2	Bases for no unacceptable side effects	Based on this experience, this document requires evaluations to identify susceptibility to FIV, and if susceptible, requires post-peening inspections to verify that problems did not occur.
6-3	Application-specific information supporting inspection relief	The following technical information shall be developed by the licensee to support inspection relief based on surface stress improvement achieved by the peening processes discussed in this report: • Identification of the components to be given surface stress improvement peening treatments, together with identification of the specific areas to be treated. • Identification of the specific processes that will be used for each area of each component. • Discussion of how the specific processes that will be used have been demonstrated to be effective with no unacceptable side effects per the criteria discussed in this report. It is assumed that this discussion will rely heavily on MRP-267R1 [5] and on this MRP-335 report, i.e., will indicate that the processes to be used are within the ranges of the parameters shown to be effective and to not result in undesirable side effects in MRP-267R1 and MRP-335. If any process parameters are outside the ranges qualified per these reports, they shall be identified and justified.

Table 1-1 (continued)
Requirements for Peening Mitigation of Alloy 600/82/182 Components in PWRs

Page Number	Report Section	Requirement
6-3	Application-specific information supporting inspection relief	• Plant- and application-specific assessment of the potential for fatigue crack growth of shallow flaws located in the peening compressive residual stress zone. As discussed in Section 3.1, fatigue effects due to cyclic stresses could possibly act to cause growth of cracks that are too shallow to grow by PWSCC. The fatigue assessment shall consider the applied stress cycles that occur at the specific location, in combination with the levels of compressive stress expected from the selected peening method (adjusted for temperature and load cycling induced relaxation). If the compressive stresses from peening are sufficient to always keep the stress intensity factor at the crack tip negative, then no fatigue-induced crack growth will occur. However, if the stress intensity factor becomes positive for some part of the stress cycle, then some crack growth could occur, but less than would occur in the absence of peening. The purpose of the fatigue assessment is to show that the relaxed schedule of in-service inspections following peening is sufficient to address this potential concern. Finally, note that fatigue growth of shallow flaws is not expected to be a concern for RPVHPNs because of the relatively low cyclic stresses at these nozzles. • Identification of the specific changes in inspection requirements that are requested based on application of surface stress improvement by peening.

1.6 Report Organization

This report is organized as follows:

- This first section describes the purpose of the report, the approach used, and how it is organized. It also includes a list identifying the specific requirements for peening mitigation of Alloy 600/82/182 components in PWRs.

- Section 2 describes the peening processes that are available for use to mitigate PWSCC. It also discusses inspection issues and possible limitations imposed by geometric considerations.
- Section 3 describes how the effectiveness of peening as a PWSCC mitigation measure has been demonstrated on a generic basis. It also discusses those plant-specific features that need to be addressed to ensure the effectiveness of the peening application at a specific-plant application.
- Section 4 defines appropriate inspection requirements and intervals for use with peening mitigation of Alloy 82/182 DM butt welds in PWR primary system piping and Alloy 600 RPVHPNs. Section 4 also covers the technical basis and current requirements for in-service examinations of unmitigated DMWs and RPVHPNs.
- Section 5 presents the deterministic and probabilistic analyses that were used to establish appropriate inspection requirements and intervals for Alloy 82/182 DMWs and Alloy 600 RPVHPNs mitigated by peening. The deterministic analyses are based on PWSCC crack growth calculations, and the probabilistic analyses include the key aspects of the PWSCC degradation process including crack initiation, crack growth, and crack detection via NDE.
- Section 6 contains the main conclusions developed by this report. In this regard, this section summarizes the bases for concluding that peening will be effective as a PWSCC mitigation measure and that the peening has no unacceptable side effects. It then summarizes the bases that support appropriate relaxation of inspection requirements for components that have been peened.
- Section 7 lists the references that are cited in the body of this report.
- Appendix A and Appendix B describe detailed probabilistic safety assessments for DMWs and for RPVHPNs, respectively. These assessments show that the risks of leakage and nozzle ejection are reduced or similar for mitigated components inspected at certain relaxed intervals in comparison to them for unmitigated components inspected at the currently required intervals for unmitigated components.

Section 2 Process Requirements and Information

This section briefly describes the peening processes that are available for use to mitigate PWSCC in PWRs. It also discusses inspection issues and possible limitations imposed by geometric considerations.

2.1 Process overview and description

There are three peening methods addressed in this report:

- Underwater laser peening (ULP).[2]
- Water jet peening (WJP), also known as cavitation peening.
- Air laser peening (ALP).

The laser peening (LP) processes operate by the same physical principles, but are referred to as ULP and ALP for the purposes of this report given the differences in energy level, spot size, and beam delivery method for the processes historically applied by the participating LP vendors. ULP has historically been applied underwater, and ALP has historically been applied in air with a tampering layer of water sprayed over the treated surface. However, both processes could be delivered either in air or at an underwater location depending on the tooling design.

Detailed descriptions of these peening methods are contained in MRP-267R1 [5]. The specific peening applications of the methods that are covered in this report are the following:

- Peening of the ID surfaces of reactor coolant system DMW butt welds. The welds involved include those at reactor vessel outlet and inlet nozzles, reactor vessel safety injection and core flood nozzles, and reactor coolant pump nozzles.
- Peening of ID surfaces of nozzles in RPVHPNs.

[2] The process used by Toshiba for laser peening in its initial applications in Japan involved the use of fiber optical cables, and was called fiber laser peening. Starting in about 1998 Toshiba introduced a portable laser system that, in some applications, does not include any fiber optics, i.e., it uses other optical transmission methods. At about this time, Toshiba changed the name used for its process to "laser peening" from "fiber laser peening." The term "underwater laser peening (ULP)" is used specifically in this report for laser peening by Toshiba whether or not the process involves use of fiber optical cables.

- Peening of J-groove weld surfaces and adjacent base material and butter layers at the OD of RPVHPNs.

2.2 Process field experiences

The many locations in numerous plants that have been peened in Japanese BWRs and PWRs using ULP and WJP are described in detail in MRP-267R1 [5]. The main locations in Japanese PWRs that have been peened using these techniques are as follows:

- Reactor vessel outlet nozzle DMWs: WJP at 17 PWRs
- Reactor vessel inlet nozzle DMWs: WJP at 18 PWRs, and ULP at 2 PWRs
- Reactor vessel safety injection nozzle DMWs: WJP at 6 PWRs, and ULP at 2 PWRs
- Bottom mounted instrument nozzle ID surfaces: WJP at 20 PWRs, and ULP at 2 PWRs.
- Bottom mounted instrument J-groove weld and adjacent nozzle OD base material: WJP at 21 PWRs, and ULP at 2 PWRs.

Peening in Japanese PWRs for PWSCC mitigation started in 2001. There have been no reports of problems or PWSCC detected subsequent to peening in the PWRs. However, there have been no reports of subsequent in-service volumetric or surface inspections of the peened parts in PWRs to date. In-service inspections have been performed on peened BWR components, including enhanced visual examinations. To date, no service-related cracking has been reported in the peened components.

2.3 Basis for no unacceptable side effects

The bases for concluding that there will not be unacceptable side effects in U.S. PWRs associated with peening for PWSCC mitigation include the following:

- WJP and ULP have been used extensively in Japanese PWRs and BWRs for over 10 years with no reported unacceptable side effects to the peened parts. However, in Japanese BWRs, there have been flow induced vibration (FIV) induced failures of nozzles and instrument lines located close to the peened areas, as noted in MRP-267R1. In response to the FIV problems, the Japanese have instituted pre-peening evaluations to ensure that such problems do not occur and have also instituted post-peening inspections to verify that problems did not occur. Based on this experience, this document requires evaluations to identify susceptibility to FIV, and if susceptible, requires post-peening inspections to verify that problems did not occur.
- Extensive qualification testing, including examination of many peened samples and mockups, has been performed of the WJP and ULP processes as described in MRP-267R1 [5]. No unacceptable side effects have been identified in this testing. For example, testing showed that peening did not affect the structural integrity of the treated component by introducing flaws into the component, or by causing growth of pre-existing cracks.

- Shot peening has been widely used as a PWSCC mitigation method in steam generator tubes since the mid-1980s, and has not resulted in any unacceptable side effects. The peened surfaces have not experienced unusual corrosion nor have they interfered with normal eddy current test inspections and occasional ultrasonic inspections.

Testing of the ALP process for application in nuclear power plants is not as developed as for the water jet peening and underwater laser peening processes, and there has not been any experience with using this method in PWR or BWR reactor coolant applications. Thus, conclusive statements about its possible side effects in PWR applications cannot be made at this time. However, the facts that it is widely and successfully used in the aerospace industry in critical applications and that it operates by the same physical principles as ULP as discussed in MRP-267R1 [5] indicate that unacceptable side effects are unlikely.

2.4 Stress improvement depth attained

Data for the three peening processes considered in this report regarding the compressive stress fields developed by peening in Alloy 600 and its weld metals are summarized below for the applications being considered in this report.

- WJP: WJP develops compressive stress fields with depths of roughly 1 mm on surfaces where the jet impinges the surface at angles close to perpendicular. In areas with limited access where the jet approaches the surface at a shallow angle (e.g., nozzle tube ID surfaces), the depth of the stress field is about 0.5 mm [5].
- ULP: ULP develops compressive stress fields with depths of more than 1 mm [5].
- ALP: The ALP process is capable of producing a compressive residual stress field that is several millimeters deep depending on the selected process parameters [5]. It is expected that the process parameters that will be used for peening the J-groove welds of RPVHPNs and adjacent base metal surfaces will be selected to achieve depths of the compressive stress field of 3 mm or more.

2.5 Inspectability (before and after treatment)

2.5.1 Before Peening

2.5.1.1 Benefit of Pre-Peening Inspections

A pre-peening non-destructive examination has the benefit of reducing the probability of any flaws being left in service that are too deep to be arrested by the compressive residual stress zone produced by the peening process. Detected flaws shall be removed prior to peening if no other evaluation, repair, or mitigation action is used to address the detected flaws. If the flaws will be addressed by another repair or mitigation action, peening may be performed over the flaws either prior to or after the other repair or mitigation action.. The depths of the compressive stress fields developed by the types of peening covered in this

report are discussed above in Section 2.4. Available information regarding the inspectability and probability of detection (POD) for the applications considered in this report is discussed below.

The probabilistic safety analyses presented in Appendix A and Appendix B and summarized in Section 5.3 show that surface stress improvement using peening coupled with examinations using performance demonstrated UT at certain relaxed schedules results in a similar or reduced effect on nuclear safety compared to the corresponding case for unmitigated components inspected according to standard inspection requirements and intervals (i.e., risk neutral approach). This implies that ET (or PT) examinations are not required, i.e., that the detection of flaws using UT is sufficiently good to result in sufficiently low risks of crack growth. Nevertheless, practice in Japan has been to perform ET before peening of nozzle ID surfaces and DMW ID surfaces in order to provide additional assurance of flaw detection and removal, and it is considered prudent to follow this practice for domestic plants. On the other hand, ET has not normally been applied to nozzle J-groove welds and adjacent material surfaces in Japan, and it is not planned for use at this location in the USA.

The reasons for not using ET at the J-groove welds are (1) flaws that are located exclusively in the J-groove weld are not a direct concern for the structural integrity of the head (i.e., do not credibly pose a direct concern for pressure boundary rupture), (2) the requirement for a deep compressive stress field (at least 3 mm) to be produced at the wetted surface of the J-groove weld reduces the possibility of subsequent growth of a flaw in the weld material, and (3) ET of irregular weld surfaces at RPVHPNs is more difficult than for nozzle and DMW ID surfaces. Furthermore, surface examinations of the wetted surface of the J-groove weld of RPVHPNs are not required as part of the current inspection requirements for unmitigated RPVHPNs. The direct safety concerns for RPVHPNs are nozzle ejection due to a very large circumferential flaw in the nozzle tube located at or above the top of the J-groove weld and structurally significant boric acid corrosion of the low-alloy steel head material due to significant pressure boundary leakage. The probabilistic calculations in Appendix B for RPVHPNs demonstrate that the examinations developed for use with peening, including direct visual examinations for evidence of pressure boundary leakage, are sufficient to address these concerns, resulting in a sufficiently small effect on nuclear safety.

It is emphasized that the surface (ET or PT) examinations that are required in this report for use prior to peening are not relied upon in the safety analyses described in Section 5 and Appendix A and Appendix B. Instead they are a secondary method intended to provide additional assurance of flaw detection and removal. Thus, it is not necessary that the ET or PT examination be performed using a technique that has been qualified in accordance with the requirements of a Performance Demonstration program similar to that defined in Appendix VIII of ASME Section XI for UT. Rather, current practices for demonstrating surface examinations (e.g., per ASME Section V) are acceptable.

2.5.1.2 Available Information Regarding Inspection Sensitivity

The sensitivity of UT and ET inspection methods as applied to DMWs in primary system piping and RPVHPNs is discussed in Section 5.2.2. Probability of detection (POD) curves for UT developed on the basis of statistically rigorous analyses of Performance Demonstration data are available for DMWs for the circumferential flaw orientation in MRP-262R1 [19]. This report shows median POD values of at least about 95% for circumferential flaw depths of 10% of the wall thickness or deeper. In the absence of similarly rigorous data for axial flaws in DMWs and circumferential and axial flaws in RPVHPN tubes, UT POD curves were developed for use in the probabilistic analyses of Appendix A and Appendix B on the basis of current Performance Demonstration requirements and engineering judgment as conservatively low POD estimates.

As indicated in MRP-267R1 [5], MHI indicates that a representative detectability depth of flaws by eddy current methods for nozzle ID and DMW butt weld surfaces is 0.5 mm. This level of inspectability is consistent with steam generator tube experience, where a POD is reported for PWSCC when examinations are performed using cross coil (e.g., plus point), array, or rotating pancake coil (RPC) eddy current probes (e.g., references ([6], [7], [8]). For all three types of probes, 100% of samples with flaws of 40% of wall or more deep, i.e. with depth over about 0.4 mm, were detected.

2.5.2 After Peening

Based on the appearance and microstructure of peened samples of Alloy 600 and its weld metals as discussed in MRP-267R1 [5], it is expected that the types of peening covered in this report will have only minor impacts on the inspectability of the peened parts by either ultrasonic or eddy current methods. In addition, data collected by Hitachi-GE and documented in Section A.4.1 of MRP-267R1 [5] showed no adverse effect on UT examinations performed on specimens treated by WJP compared to the UT signals obtained prior to peening. This expectation is also supported by steam generator experience, as discussed below.

Many thousands of steam generator tubes have been successfully inspected by eddy current methods before and after shot peening. Many of these tubes have also been successfully inspected using ultrasonic methods. While water jet peening, underwater laser peening, and air laser peening are not the same as the shot peening performed of steam generator tubes, the level of cold work and surface effects appear to be roughly similar, or less severe in the case of WJP, ULP , and ALP, as shown by microscopic examination of test samples [5]. Thus, the steam generator experience indicates that it is unlikely that peening of Alloy 600/182/82 surfaces will have a deleterious effect on the ability to inspect peened areas using eddy current or ultrasonic methods.

2.6 Assessment of potential crack growth during operation after peening

Tests have been performed by MHI, Hitachi-GE, and Toshiba to determine if flaws that are present at the time of peening will grow after peening. The tests performed, and the results, are covered in Appendix A of MRP-267R1 [5]. These tests involved developing cracks in stressed specimens of sensitized Alloy 600 using tetrathionate or polythionic acid or in specimens of stainless steel using boiling magnesium chloride, peening some of the specimens, and subjecting them to further exposures in the cracking environment. These tests showed that flaws with depths less than the depth of the compressive stress field did not grow in the peened specimens, while those in non-peened specimens did grow. Flaws with depths that significantly exceeded the depth of the compressive stress field grew during the post-peening exposure, indicating that peening cannot be relied upon to prevent growth of flaws with depths significantly greater than that of the compressive stress field.

2.7 Geometric application limitations

This topic is addressed separately for the three methods of peening being considered in this report since they have different limitations.

- The only identified geometric limitation for WJP is that the low angle of approach inside nozzles results in a lower depth of the compressive stress field, about 0.5 mm, vs. that developed in locations where the water jet approaches the surface at a high angle, where it is about 1 mm.
- No geometric limitations have been identified for ULP, for which a compressive stress field of at least about 1 mm is developed in all of the locations considered in this report (DMW butt weld ID surfaces and J-groove nozzle ID and weld/OD surfaces).
- No geometric limitations are expected for application of ALP to the wetted OD and weld surfaces of RPVHPNs, or to the ID of main RCS loop welds. The applicability of the ALP process described in MRP-267R1 [5] to the ID surface of RPVHPNs is yet to be confirmed.

2.8 Surface condition limitations (if any)

There are no known limitations imposed by surface conditions on the peening applications being considered in this report. The successful use of the WJP and ULP methods for many BWR and PWR applications confirms that the surface conditions of the Alloy 600/182/82, stainless steel, and low-alloy steel materials present at the peening locations are compatible with the peening processes.

While there are no known limitations imposed by surface conditions, conceptually there are conditions that one could conceive of as limiting the effectiveness of peening in the applications being considered in this report:

- Areas with unusually high levels of local cold work (e.g., due to aggressive grinding) could conceivably reduce the effectiveness of the peening process. Toshiba successfully applied underwater laser peening to a 20% cold worked

stainless steel, which indicates that the levels of cold work present on plant parts are unlikely to interfere with peening (Appendix A of MRP-267R1 [5]). In addition, as also discussed in Appendix A of MRP-267R1, water jet peening, underwater laser peening, and air laser peening of heavily ground U-bends of Alloy 182 successfully inhibited initiation of PWSCC, while non-peened specimens cracked when exposed to aggressive PWSCC conditions. It is also noted that the ASM Handbook volume on surface engineering [9] notes that surface condition and surface hardness are generally not limitations for shot peening. The laser and water jet peening methods being considered to mitigate PWSCC produce a much deeper compressive stress field in comparison to that for conventional shot peening, and as such are expected not to be subject to surface condition or surface hardness limitations.

- One could envision surface oxides as possibly limiting peening effectiveness by providing a hard shell that prevents plastic deformation of the underlying metal. However, this effect has not been noted in either laboratory tests or service applications. Further, oxide thicknesses on plant materials are in the neighborhood of 1 μm thick, and thus are much too thin and too structurally weak to interfere with peening, which involves dimensions on the order of 1 mm, i.e., 1000 times larger.

2.9 Coverage verification

The approaches taken to ensure 100% coverage of the areas being peened for WJP, ULP, and ALP are described in Sections 5.3.2, 3.1.3.1, and 5.4.2, respectively, of MRP-267R1 [5]. In summary, they are as follows:

- WJP: Complete coverage of the areas designated for WJP are assured by use of overlapping passes and by extending the peening out to about one inch beyond the edge of the designated area (or to the nozzle end as applicable). Process controls are used to ensure that the desired area is peened and that it is peened for desired length of time. After the peening is completed, the records are given a QA/QC or an independent review to ensure that 100% coverage was achieved.
- ULP: Complete coverage of the areas designated for ULP are assured by use of overlapping passes and by extending the peening out to beyond the edge of the designated area. Process controls are used to ensure that the desired area is peened for the desired number of pulses per unit area. After the peening is completed, the records are given a QA/QC or an independent review to ensure that 100% coverage was achieved. In addition, a visual inspection is performed to ensure that all of the desired surface shows visible signs of peening (ULP changes the surface enough to make obvious the difference between peened and unpeened areas).
- ALP: Complete coverage of the areas designated for ALP are assured by use of overlapping passes and by extending the peening out to beyond the edge of the designated area. Process controls are used to ensure that the desired area is peened for the desired number of pulses per unit area. Verification of complete coverage is performed automatically by use of a 3D computer model with as-built dimensions, in which the laser spot location, energy, and pulse duration are recorded for each successful laser firing. In addition, a

visual inspection may be performed to ensure that all of the desired surface shows visible signs of peening (ALP changes the surface enough to make obvious the difference between peened and unpeened areas).

2.10 ASME Code Considerations Regarding Limitations on Peening and Need for Post-Peening Stress Relief

Section III of the ASME Code has some limitations on application of peening to welds during the welding process and on the need for stress relief heat treatments after cold forming. As discussed in the following paragraphs, these limitations and requirements are not considered applicable to the peening processes covered in this report.

Paragraph NB-4422, Peening, in Section III, Subsection NB, of the ASME Code reads: "Controlled peening may be performed to minimize distortion. Peening shall not be used on the initial layer, root of the weld metal, or on the final layer unless the weld is postweld heat treated." This limitation in the Code is clearly directed at control of the heavy type of peening (e.g., hammer peening) that is sometimes used to control distortion during the welding process (while the weld is cooling) [10], and is not applicable to the superficial type of peening being considered here that will be applied on finished parts. This conclusion has been confirmed by the ASME Section III Standards Committee in an inquiry response letter dated August 22, 2012 [21]:

> "Question (1): Does NB-4422 apply when peening is performed for the purpose of introducing compressive stress on a weld or base metal surface after all welding, heat treating, and examinations have been completed?
>
> Reply (1): No."

Paragraph NB-4652 in Section III of the ASME Code indicates that heat treatment of formed carbon steel or austenitic stainless steel parts may be required following bending or forming. This paragraph is not considered applicable to the type of peening considered here since the proposed peening is so superficial that it causes negligible distortions of the heavy wall parts involved and thus does not constitute bending or forming.

2.11 Summary of key process application variables

The key process application variables for WJP and ULP are described in Section 3 of MRP-267R1 [5]. In summary, they are as follows:

- Water Jet Peening (WJP)
  - Nozzle diameter
  - Jet stand-off distance and nozzle offset in ID applications
  - Water flow rate
  - Application time

  - Impingement angle
  - Stationary nozzle time
  - Water level and water temperature
- Underwater Laser Peening (ULP)
  - Laser type (wavelength)
  - Pulse energy (mJ/pulse)
  - Pulse repetition rate (pulses/sec)
  - Pulse duration (ns)
  - Laser spot footprint dimensions (mm)
  - Pulse number density (pulses/mm^2)
  - Temperature of water

The process controls that will be used with ALP of RPVHPNs have not as yet been fully defined. The process involved and the general methods used to control it are described in Section 2 of MRP-267R1 [5]. It is expected that the process parameters will be similar to those described above for the underwater laser peening process since both rely on laser generated plasma pulses, with the main difference being spot size and power.

Section 3 Verification of Peening Effectiveness

This section describes how the effectiveness of peening as a PWSCC mitigation measure has been demonstrated on a generic basis. It also discusses those plant-specific features that need be addressed to ensure the effectiveness of specific peening applications at plants.

3.1 Mitigation basis for peening

In order to prevent the initiation of new PWSCC the application of peening has to result in the peak tensile stresses at the wetted surface of PWSCC material being less than the "threshold" stress for initiation of PWSCC. While it is considered that there is no firm "threshold" below which PWSCC will never occur, from a practical experience perspective it appears that a tensile stress of about 20 ksi (138 MPa) is a conservative lower bound estimate of a stress level below which PWSCC initiation will not occur during plant lifetimes [11].[3] This applies to steady-state stresses during normal operation since SCC initiation is a long-term process, and does not apply to transient stresses that occur only for short periods of time.

With regard to inhibiting crack growth due to PWSCC, the important parameter is the stress intensity factor at the tip of any cracks that are present in the surface. If this stress intensity factor is less than the critical stress intensity factor for SCC, K_{ISCC}, then crack growth will not occur. The critical stress intensity factor for growth of PWSCC is generally thought to be about 5 to 9 MPa√m (5 to 8 ksi√in) but is not well known. For simplicity and to be conservative, it is taken as zero in this report. Thus, crack growth due to PWSCC will not occur if the stress intensity factor at the tip of the deepest crack present in the peened location is shown to be zero or less, when calculated considering peening induced residual stresses plus the applied stresses that occur during normal full power operation, including the effects of any stress concentration factors that act at the location being considered. If the steady-state stress intensity factor becomes positive at any location on the crack, then some PWSCC-driven growth could occur.

[3] The 20 ksi (138 MPa) threshold stress corresponds to about 80% of the lower bound yield strength for Alloy 600 materials at operating temperatures.

In addition to PWSCC caused crack initiation and growth, crack initiation and growth can also occur due to fatigue. This is further discussed below:

- The locations for which peening is being considered are required by the ASME Code to have calculated fatigue usage factors less than 1.0, such that initiation of fatigue cracks is expected to be unlikely. The addition of compressive stresses by peening will further reduce susceptibility to fatigue crack initiation, and eliminate the possibility of fatigue crack initiation if the stress at the surface remains compressive through all transient loads.
- If small cracks are present (due to fatigue crack initiation, previous PWSCC initiation, or otherwise), fatigue effects due to cyclic stresses could possibly act to cause crack growth. This is a potential concern that needs to be evaluated given that a shallow flaw could potentially grow by fatigue to a depth significantly beyond the peening compressive residual stress zone. If this were to occur, more rapid growth by PWSCC during steady-state operation might subsequently occur. If the compressive stresses from peening are sufficient to always keep the stress intensity factor at the crack tip negative, then no fatigue-induced crack growth will occur. However, if the stress intensity factor becomes positive for some part of the stress cycle, then some crack growth could occur, but less than would occur in the absence of peening.

The potential for growth by fatigue of shallow flaws located in the peening compressive residual stress zone shall be considered on an application-specific basis. The fatigue assessment shall consider the stress cycles that occur at the specific location. The need for an application-specific fatigue assessment is included in the discussion of Section 6.4, "Application-specific information supporting inspection relief."

3.2 Performance of peening methods

3.2.1 Magnitude and Depth of Compressive Stresses

The magnitude and depth of the compressive stresses generated by the peening processes covered in this report are described in detail in the appendices of MRP-267R1 [5]. For any specific plant application, the most applicable values from MRP-267R1 may be applied as needed. Alternatively, values supplied by the vendors for the specific material-geometry application being considered can be used. For reference purposes, typical values from MRP-267R1 are discussed below. The values for the ALP process are for applications that did not use an ablative layer, for reasons discussed in MRP-267R1.

- Alloy 600 base material with good access (large radius or flat surface)
  - ULP (Toshiba): Surface stress -450 to -900 MPa (-65 to -130 ksi), compressive to depths of more than 1.0 mm.

- WJP (MHI): Surface stress ranging from -267 to –411 MPa (-39 to -60 ksi), compressive to depths of more than 1.0 mm.

- ALP (MIC): Shallow surface layer with tensile stress of about +400 MPa, dropping to zero at a depth of about 20 µm, and decreasing to -400 to -660 MPa (-58 to -96 ksi) at depths of about 35 to 70 µm. The stress remains compressive to depths of more than 1.5 mm. In this regard, it is expected that the ALP process parameters selected for use at RPVHPN J-groove welds will result in compressive stress fields to depths of more than 3 mm.

- Alloy 82/182 weld metal with good access

  - ULP (Toshiba): Surface stress ranging from -500 to –1000 MPa (-73 to -145 ksi), compressive to > 1.0 mm.

  - WJP (MHI): Surface stress ranging from -293 to –414 MPa (-42 to -60 ksi), compressive to > 1.0 mm.

  - ALP (MIC): No data available for the stress depth profile for Alloy 82/182 welds; assumed to be similar to data for Alloy 600 given above. This assumption is justified by the capability of ALP to produce compressive residual stress depth as great as 8 mm depending on the treated material and chosen process parameters.

- Alloy 600 base material at ID of small diameter tube

  - ULP (Toshiba): Surface stress ranging from -300 to -500 MPa (-44 to -73 ksi), compressive to > 1.0 mm (after peening both ID and OD).

  - WJP (MHI): Surface stress of -210 to -470 MPa (-30 to -68 ksi), compressive to ~0.5 mm.

  - WJP (Hitachi-GE): Surface stress of -500 to -670 MPa (-73 to -97 ksi), compressive to ~0.5 mm.

3.2.2 Maintenance of Compressive Stresses for Plant Lifetime

A detailed evaluation is contained in Section 4 of MRP-267R1 [5] that describes the experimental and analytical evaluations that show that sufficiently high compressive stress fields will be present for the extended lives of plants to keep the compressive stresses effective for the mitigation of PWSCC. The experiments involve measurement of residual stresses in samples after exposure to periods of high temperature and to numerous stress cycles, and show that the stresses decrease moderately during the first few cycles, but then remain relatively constant with time and cycles. An analytical evaluation was performed using an activation energy approach that concludes that the results of these experiments indicate that the peening will remain effective for more than 60 years of operation.

As discussed in Section 3 of MRP-267R1 [5], plant experience with shot peened steam generator tubes also indicates that compressive stresses remain high after long periods of operation.

3.2.3 Verification of No Unacceptable Side Effects

As discussed in MRP-267R1 [5], neither plant experience nor laboratory tests have identified any unacceptable side effects to parts that have been peened with the peening methods being considered in this report. However, as noted in MRP-267R1, flow induced vibration problems have occurred to adjacent nozzles and instrument lines. Based on this experience, this document requires evaluations of adjacent areas prior to water jet peening to identify susceptibility to FIV, and if susceptible, requires post-peening inspections to verify that problems did not occur.

3.3 Effectiveness of peening methods

3.3.1 Initiation of PWSCC

As discussed above in Section 3.1, initiation of PWSCC will not occur during plant lifetimes if the peak stress at the wetted surface during normal operation is below the practical "threshold" tensile stress of about 20 ksi (138 MPa). The application of peening puts the surface into a known state with high residual compressive stresses. The only additional stresses that need to be considered are applied stresses during operation, including effects of any stress concentrations acting at the location being considered. As discussed in the following, the compressive stresses produced by peening are sufficient to preclude the possibility of PWSCC crack initiation subsequent to peening for long-term operation.

- The peak applied stresses will rarely be more than 30 ksi (207 MPa) at DMW butt weld surfaces, and in the extreme are very likely to be limited to 50 ksi (345 MPa), which is approximately equal to 3 times the Code allowable stress parameter S_m for stainless steel pipe material at a design temperature of 650°F (based on Equation 10 of ASME Section III Division 1 NB-3600). The expected initial surface compressive stresses generated by peening are at least about 300 MPa (44 ksi), but can decrease to about 200 MPa (29 ksi) as a result of temperature and load cycle effects. The total stress at the surface thus will likely be less than zero (i.e., compressive), and very likely less than the effective "threshold" stress of 20 ksi (138 MPa). Thus, crack initiation is prevented.
- Based on extensive previous weld residual stress FEA work performed by the authors for CRDM/CEDM nozzles in many PWRs (see, e.g. [12]), the peak applied stresses at the ID surfaces of RPVHPNs are relatively low, between 15 and 25 ksi (103-172 MPa) or less. The expected initial surface compressive stresses generated by peening are at least about 300 MPa (44 ksi), but can decrease to about 200 MPa (29 ksi) as a result of temperature and load cycle effects. The total stress at the surface thus will be below zero. Thus, crack initiation is prevented.
- Based on extensive previous weld residual stress FEA work performed by the authors for CRDM/CEDM nozzles in many PWRs (see, e.g. [12]), the peak

applied stresses at the OD surfaces of RPVHPNs, at either the weld or base material, are relatively low, less than 5 ksi (35 MPa) or less. The expected initial surface stresses generated by ALP (without an ablative layer) are about +450 MPa (65 ksi), but with compressive stresses developing just below the surface at about -450 MPa (-65 ksi), i.e. zero stress at 15 μm and -450 MPa at 35 μm. The high tensile surface stresses could result in local initiation of very shallow cracks but the high subsurface compressive stresses limit their growth to less than about 20 or 30 μm according to a stress-intensity-factor-based crack growth calculation. Thus, the initiation of cracks with depths that are of engineering significance is prevented. Similarly, the use of ULP or WJP on the OD surfaces of RPVHPNs would preclude future PWSCC initiation at this location.

3.3.2 Growth of PWSCC Cracks

It is required that performance demonstrated UT methods will be applied to RPVHPN tube base metal and to DMWs in conjunction with peening applications. It is also required that the ID surfaces of RPVHPNs and DMWs be examined by ET or PT methods, and that detected flaws shall be removed, e.g., by polishing and grinding before peening is performed if no other evaluation, repair, or mitigation action is used to address the detected flaws. If the flaws will be addressed by another repair or mitigation action, peening may be performed over the flaws either prior to or after the other repair or mitigation action. Nevertheless, some undetected flaws may remain. Growth of these cracks is expected to be controlled by the stress intensity factor at the crack tip, as discussed above in Section 3.1. The stress intensity factor at the crack tip is a function of the depth and shape of the crack, the compressive stresses generated by peening that remain after thermal and load cycle reductions have occurred, and applied stresses and stress concentration factors. Probabilistic analyses using appropriate uncertainty distributions for all key modeling inputs have been performed to address this concern for growth of pre-existing flaws, as described in Section 5.3 and in Appendix A and Appendix B. As indicated in those locations, the safety risks associated with growth of cracks in mitigated components inspected at the suggested relaxed schedules discussed in Section 4 are less or similar than those for unmitigated components inspected at currently required schedules.

3.4 Plant/application-specific factors

The plant/application-specific factors that need to be considered for a specific application include the following:

- The likelihood of flaws being present in the application based on industry and plant-specific experience. If it seems likely that shallow flaws could be present, preparations may be made to remove them if they are detected, e.g., by grinding and polishing. If there is a high likelihood of flaws being present that are too deep to be removed by grinding and polishing, then other mitigation measures may be considered or preparations may be made for local removal and repair of such flaws (e.g., by grinding and welding).

- As discussed in Section 3.1, the potential for growth by fatigue of shallow flaws located in the peening compressive residual stress zone shall be considered on an application-specific basis. The fatigue assessment shall consider the applied stress cycles that occur at the specific location, in combination with the levels of compressive stress expected from the selected peening method (adjusted for temperature and load cycling induced relaxation). The need for an application-specific fatigue assessment is included in the discussion of Section 6.4, "Application-specific information supporting inspection relief."

3.5 Quality assurance considerations

Since surface stress improvement by peening affects the performance of nuclear safety related systems and components, it shall be performed in accordance with a quality assurance program meeting the requirements of Appendix B to 10 CFR 50 and the utility's plant specific commitments. Further, since peening is a special process, it shall be controlled in a manner consistent with Criterion IX, "Control of Special Processes," of Appendix B and any applicable plant specific commitments. As stated in that criterion, this requires that the personnel and procedures involved need to be appropriately qualified. Since there are no industry standards that apply to peening, these qualifications shall be done to vendor requirements developed and documented per their 10 CFR 50 Appendix B quality assurance program and to utility requirements and commitments applicable at the plant site.

Section 4 Examination Requirements

Section XI of the ASME Boiler & Pressure Vessel Code specifies periodic in-service inspections of safety-significant LWR components including primary system pressure boundary components. Because of the concern for PWSCC of Alloy 600/82/182 pressure boundary components in PWRs, augmented inspection requirements have been developed for such locations. These augmented inspection requirements are currently defined in ASME Code Cases that are made mandatory with conditions by US NRC regulations, specifically in 10 CFR 50.55a. The inspection requirements identify the nondestructive examination (NDE) inspection method, inspection frequency, inspection coverage, and flaw acceptance standards. In general, these items are based on the location, configuration, and historical condition of the component.

In the context of the current inspection requirements for key Alloy 600/82/182 locations in PWRs, this section defines appropriate inspection requirements for Alloy 82/182 piping DMWs and Alloy 600 RPVHPNs mitigated by SSI (i.e., peening) mitigation. Given the demonstrated effectiveness of the SSI techniques, relaxation of the inspection requirements for these components is appropriate after SSI treatment. As discussed in Section 5, the specific inspection requirements developed for use with peening are supported by detailed deterministic and probabilistic modeling. Because the inspection requirements for these components are prescribed by NRC regulations, NRC approval is required for relaxation of current inspection requirements following peening mitigation.

4.1 Summary of technical basis and current requirements for in-service examinations for unmitigated Alloy 600/82/182 components

The basic inspection regimes currently required for the Alloy 600/82/182 components that are the focus of this report are described below.

4.1.1 Dissimilar metal welds (DMWs) in primary system piping

ASME Code Case N-770-1 [1] (dated December 25, 2009) provides inspection requirements for visual, volumetric, and surface inspections of piping butt welds in the primary system that are made of Alloys 82 and/or 182, which are considered to be susceptible to PWSCC. This code case has been made mandatory by the US NRC through regulation 10 CFR 50.55a(g)(6)(ii)(F),

subject to the conditions detailed in this regulation. The conditions applied by the NRC cover topics such as how to treat welds that have had PWSCC mitigation measures applied. Note that the inspection requirements including inspection frequencies for Alloy 82/182 piping and nozzle butt welds were previously defined in Revision 1 of MRP-139 [13].

The volumetric re-inspection interval per N-770-1 for components not treated by a qualified mitigation method depends on the operating temperature of the component in consideration of the strong dependence of PWSCC susceptibility to temperature. The volumetric inspection frequency for unmitigated Alloy 82/182 DMWs operating at hot-leg temperature (Category A-2) is every 5 years. The volumetric inspection frequency for unmitigated Alloy 82/182 DMWs operating at cold-leg temperature (Category B) is every second inspection period (as defined in ASME Section XI), not to exceed 7 years.

Code Case N-770-1 includes specific categories to address inspection methods and frequencies for piping DMW locations mitigated against PWSCC. These requirements are currently not directly applicable to SSI treatments. The SSI treatment methods described in this report are not clearly defined in Code Case N-770-1 although SSI treatment is similar to stress improvement without welding, which is addressed in N-770-1. For stress improvement methods for which the N-770-1 requirements are currently clearly applicable, the volumetric inspection requirement following mitigation of an uncracked DMW (Category D) is a single examination within 10 years following mitigation, followed by a program of periodic inspections in which the component is placed into a population to be examined on a sample basis, provided that no indications of cracking are found.

An update of N-770-1 (Code Case N-770-2, June 9, 2011 [4]) has been prepared and issued by ASME, but the version that is currently made mandatory by the NRC regulations is still N 770-1 as of summer 2012. N-770-2 includes a modest change in the inspection requirements for components mitigated by a qualified stress improvement process.

4.1.2 Reactor pressure vessel head penetration nozzles (RPVHPNs)

ASME Code Case N-729-1 [2] (dated March 28, 2006) provides the current inspection requirements for RPVHPNs attached using partial-penetration (i.e., J groove) welds, including CRDM/CEDM nozzles. It bases the frequency of inspection in part on calculated parameters called the Effective Degradation Years (EDY) and the Reinspection Years (RIY) of the head, each of which is a function of the time and temperature history of the head. The code case provides detailed instructions regarding how to evaluate and follow up visual inspections that detect evidence of reactor coolant leakage or boric acid wastage, and also on how to follow up on flaws detected by volumetric or surface examinations. The technical bases for the requirements of N-729-1 are documented in MRP-117 [14], the top-level safety assessment report MRP-110 [15], and lower-level safety assessment reports MRP-103 [16], MRP-104 [17], and MRP-105 [18]. This code case has been made mandatory by the US NRC through regulation 10 CFR

50.55a(g)(6)(ii)(D), subject to the conditions detailed in this regulation. The conditions applied by the NRC generally cover issues related to performance of ultrasonic inspections and required re-inspection intervals.

For heads with Alloy 600 nozzles, the volumetric inspection intervals (between examinations of all nozzles) per N-729-1 are based on the Reinspection Years (RIY) parameter, which is a measure of operating time normalized to a head temperature of 600°F using the consensus temperature dependence of the PWSCC crack growth rate. The required interval is every 8 calendar years or before RIY = 2.25, whichever is less.

As of summer 2012, there are heads with Alloy 600 nozzles in service at 28 U.S. PWRs. The heads at 41 U.S. PWRs have been replaced with heads using PWSCC-resistant nozzles made of Alloy 690. Of the 28 Alloy 600 heads remaining in service, 20 heads operate at the reactor cold-leg temperature and are typically referred to as "cold" heads. The others generally operate at temperatures closer to the reactor hot-leg temperature.

The effect of the inspection regime per N 729-1 is that the non-cold heads with Alloy 600 nozzles remaining in service must generally perform volumetric examinations for indications of PWSCC every one or two refueling outages. The corresponding interval for the cold heads with Alloy 600 nozzles is typically every four or five 18-month fuel cycles, or three or four 24-month fuel cycles. More frequent volumetric/surface examinations may be required if PWSCC has previously been detected in the subject head.

An update of N-729-1 (Code Case N-729-2, April 9, 2010) has been prepared and issued by ASME, but the version that is currently made mandatory by the NRC regulations is still N-729-1 as of summer 2012. There are no substantive changes in the inspection requirements between N-729-1 and N-729-2.

4.2 Examination requirements developed for Alloy 600/82/182 components mitigated by peening

Table 4-1 contains a summary of the current inspection requirements for RPVHPNs and DMWs with unmitigated Alloy 600/82/182 materials that are in Code Cases N-729-1 and N-770-1. In addition, the table defines appropriate requirements for inspections to be performed on these components before and after application of peening, as well as the required minimum nominal depth of the compressive residual stress produced by the peening treatment.

In the case of peening, three different categories of inspection requirements are defined. The pre-mitigation inspection is typically performed in the same outage during which peening is applied.[4] A follow-up examination is a one-time inspection to be performed a certain number of cycles after the peening

[4] The pre-mitigation examination may be delayed to after the mitigation outage provided that the inspection requirements for unmitigated component apply until the examination is performed and PWSCC must not be detected during the delayed examination for the relaxed inspection requirements to apply. This restrictive option provides flexibility for the timing of outage activities.

application for addressing the possibility of flaws that were not either detected in the pre-peening examination or sufficiently shallow to have been arrested by the peening process. The required timing of the follow-up inspections was established on the basis of the detailed probabilistic calculations. Finally, there are two types of in-service inspections (ISIs) that are required to be performed regularly at the intervals prescribed in Table 4-1. In addition, a post-mitigation inspection (a.k.a. pre-service inspection) may be performed just after the application of peening before the unit begins to operate.

The technical bases for these pre- and post-peening inspections are discussed in Section 5 and are further detailed in Appendix A and Appendix B. The probabilistic analyses in Section 5 show that the application of peening coupled with the required post-peening in-service inspection schedules results in reduced or similar safety risks as compared to those associated with unpeened components inspected at the currently required schedules. The benefit of peening in the deterministic and probabilistic analyses was modeled on the basis of the compressive residual stress field assumed to be induced at the treated surface by peening. These stress assumptions were made consistent with the minimum nominal depth of the compressive residual stress entries in Table 4-1. Note that the nominal depth of the compressive residual stress was assumed to be at least 3 mm (0.12 inch) for the outer surfaces of RPVHPNs. This requirement is consistent with the detectability of flaws located on the RPVHPN tube OD using the standard UT performed from the tube ID. The requirement for a relatively large nominal compressive residual stress depth of 3 mm for the outer surfaces of RPVHPNs also has the benefit of reducing the possibility of a PWSCC flaw being located in the J-groove weld that is too deep to be arrested by the peening treatment.

The extent of the required surface to be peened in the case of RPVHPNs is defined by the examination volume/area of Figure 2 of ASME Code Case N-729-1 [2]. This includes the entire wetted surface of the Alloy 82/182 J-groove weld and butter material, as well as the surface of the Alloy 600 tube material in the region of high weld residual stress that is susceptible to PWSCC. The technical basis for this susceptible region is provided in MRP-95R1 [11] using FEA stress calculations and the locations of flaws detected in RPVHPNs in U.S. plants.

An evaluation shall be performed prior to water jet peening to identify susceptibility of adjacent areas to flow induced vibration. A post-mitigation visual examination (VT-1 or VT-3) shall be performed if the evaluation shows susceptibility to damage from the peening process. Such evaluations need to consider the experience of the extensive peening performed in Japan, the specific peening process performed, and whether there is any potential for inadvertent damage to components adjacent to the target peening area. It is not necessary that volumetric or surface examinations be performed post-peening as the peening process does not introduce any significant geometrical changes of the treated component, and because flaws detected prior to peening shall be removed, repaired, or mitigated prior to or after peening. Furthermore, experimental work detailed in MRP-267 Revision 1 [5] has demonstrated that the peening

processes do not affect the structural integrity of the components or the inspectability of the components by UT.

4.2.1 Dissimilar metal welds (DMWs) in primary system piping

The inspection requirements in Table 4-1 that shall be used with peened Alloy 82/182 DMWs are as follows:

Prior to Peening

- An ultrasonic examination shall be performed of the weld using a technique that has been qualified to the performance demonstration requirements of Appendix VIII of Section XI of the ASME Code.
- An eddy current (ET) or liquid penetrant (PT) inspection shall also be performed of the weld ID. The ET or PT technique need not be qualified using formal performance demonstration techniques, but shall have been demonstrated by the inspection vendor per current practices (e.g., per ASME Section V).

It is emphasized that the surface (ET or PT) examinations that are required in this report for use prior to peening are not relied upon in the safety analyses described in Section 5 and Appendix A. Instead they are a secondary method intended to provide additional assurance of flaw detection and removal.

Subsequent to Operation

The relaxed schedule for performance of volumetric and visual examinations of peened welds is shown on Table 4-1 as a function of the operating temperature of the weld.

4.2.2 Reactor pressure vessel head penetration nozzles (RPVHPNs)

The inspection requirements in Table 4-1 that shall be used with peened RPVHPNs are as follows:

Prior to Peening

- An ultrasonic examination of the nozzle tube shall be performed from the nozzle ID using a technique that has been qualified to the performance demonstration requirements of Appendix VIII of Section XI of the ASME Code (as required by the conditions of 10 CFR 50.55a(g)(6)(ii)(D)(4)). Alternatively, consistent with 10 CFR 50.55a(g)(6)(ii)(D)(3), surface examination of equivalent surfaces of the nozzle tube, as identified by Figure 2 of ASME Code Case N-729-1, shall be performed.
- An eddy current (ET) or liquid penetrant (PT) inspection shall also be performed of the nozzle ID. The ET or PT technique need not be qualified using formal performance demonstration techniques, but shall have been

demonstrated by the inspection vendor per current practices (e.g., per ASME Section V).

It is emphasized that the surface (ET or PT) examinations that are required in this report for use prior to peening are not relied upon in the safety analyses described in Section 5 and Appendix B. Instead they are a secondary method intended to provide additional assurance of flaw detection and removal.

Subsequent to Operation

- The relaxed schedule for performance of volumetric and visual examinations of peened penetrations is shown on Table 4-1 as a function of EDY.

Leak Path Examination

- Consistent with 10 CFR 50.55a(g)(6)(ii)(D)(3), a demonstrated volumetric or surface leak path assessment through all J-groove welds shall be performed each time the periodic volumetric/surface examination is performed.

The leak path examination detects through-wall cracking by checking for areas at the interface between the nozzle tube and low-alloy steel head material where leakage has caused a loss of interference fit. The leak path examination is a second method for detection of through-wall cracking in addition to direct visual examinations (VE) of the outer surface of the head for evidence of pressure boundary leakage. As such, the leak path examination addresses the fact that there is no qualified volumetric examination for the J-groove weld material. The probabilistic model of Appendix B conservatively does not take credit for the leak path examination as a second method for detection of through-wall cracking in addition to the simulated visual examinations.

Table 4-1
Inspection Requirements Developed for Alloy 600 RPVHPNs and Alloy 82/182 DMWs in Primary System Piping Mitigated by Peening

Code Case		Nominal Peen Depth (Note 1)	Pre-Mitigation (Note 2)	Follow-up Exams	ISI Volumetric Exam	ISI Direct Visual Exam of Metal Surface (VE)
N-729	Alloy 600 Reactor Vessel Head (EDY ≥ 8)	N/A	N/A	N/A	All nozzles every 8 Yr prior to RIY = 2.25	Each RFO
N-729	Alloy 600 Reactor Vessel Head (EDY < 8)	N/A	N/A	N/A	All nozzles every 8 Yr prior to RIY = 2.25	Every 3rd RFO or 5 Yr, whichever is less (Note 4)
	Peened Alloy 600 Reactor Vessel Head (EDY ≥ 8)	Note 3	Volumetric and ET or PT from nozzle ID only (Note 5)	Volumetric and VE at 1st RFO	Each Interval (Note 6)	Each RFO
	Peened Alloy 600 Reactor Vessel Head (EDY < 8)	Note 3	Volumetric and ET or PT from nozzle ID only (Note 5)	Volumetric and VE at 2nd or 3rd RFO (but within 5 Yr)	Every 2nd Interval (Note 6)	Every 3rd RFO or 5 Yr, whichever is less (Note 6)
N-770	Unmitigated Alloy 82/182 Piping Butt Weld HL Operating Temperature ≤ 625°F (Item A-2)	N/A	N/A	N/A	Every 5 Yr (if not cracked)	Each RFO
N-770	Unmitigated Alloy 82/182 Piping Butt Weld CL Operating Temperature ≥ 525°F and < 580°F (Item B)	N/A	N/A	N/A	Every 2nd Inspection Period, not to exceed 7 Yr (if not cracked)	Each Interval
	Peened Alloy 82/182 Piping Butt Weld HL Operating Temperature ≤ 625°F	ID surface of 82/182 at least 0.04 in. (1 mm)	Volumetric and ET or PT of ID (Note 5)	Volumetric at 1st or 2nd RFO; VE at 1st and 3rd RFOs	Each Interval (Note 6)	Each Interval (Note 6)
	Peened Alloy 82/182 Piping Butt Weld CL Operating Temperature ≥ 525°F and < 580°F	ID surface of 82/182 at least 0.04 in. (1 mm)	Volumetric and ET or PT of ID (Note 5)	Volumetric and VE at 2nd or 3rd RFO	Every 2nd Interval (Note 6)	Each Interval (Note 6)

Notes: (1) The nominal peening depth refers to the depth of the compressive stress produced by the peening treatment.
(2) The pre-mitigation exam may be delayed to after the mitigation outage provided that the inspection requirements for unmitigated component apply until exam is performed and PWSCC must not be detected during the delayed exam for the relaxed inspection requirements to apply.
(3) The nominal peening depth for the Alloy 600 nozzle ID surface is at least 0.02 in. (0.5 mm), and the nominal peening depth for the Alloy 600 nozzle OD surface inboard of the weld and the wetted surface of the Alloy 82/182 J-groove weld is at least 0.12 in. (3 mm). The extent of the required treated surface is defined by the examination volume/area of Figure 2 of N-729-1.
(4) Note 4 of Table 1 of N-729-1 requires that no flaws unacceptable for continued service under -3130 or -3140 have been detected, or else the VE is performed each RFO.
(5) It is not required that the pre-mitigation ET or PT exam meet the requirements of a Performance Demonstration qualification similar to Appendix VIII of Section XI.
(6) Consistent with treatment of other PWSCC mitigation techniques in ASME Code Case N-770-1, detection of planar flaws connected to the wetted surface or leakage shall trigger appropriate additional actions such as flaw disposition and more frequent examinations.

Section 5 Supporting Analyses

5.1 Approach

To demonstrate the impact of peening on PWSCC of Alloy 600/82/182 components, this section presents deterministic and probabilistic analyses that factor in surface stress improvement and its effects on various processes involved in PWSCC including component loading (and the resultant stress states), crack initiation, crack growth, and crack detection.

The deterministic analyses specifically investigate the impact of the surface stress improvement on PWSCC crack growth versus time. These analyses predict crack growth versus time, at various assumed crack locations, from various initial crack sizes. In order to demonstrate the efficacy of compressive surface stress to slow or stop crack growth, calculations are made for cracks that are subject to stress profiles representative of those present in components before peening, or stress profiles representative of those present in components after peening.

The probabilistic analyses take a more comprehensive approach to predicting the effect of surface stress improvement on PWSCC, incorporating detailed probabilistic models for component loading, crack initiation, crack growth, and crack detection. The integrated probabilistic model, which unites the various models into a probabilistic simulation framework, allows the prediction of PWSCC throughout the operating lifetime of the PWR.

5.2 Deterministic Analysis of Peening Effects

This section focuses on deterministic growth calculations for cracks in unmitigated and peened components.

For reference, Section 5.2.1 describes the assumed compressive layer depths imparted by peening; cracks shallower than this compressive layer depth are unable to grow because they are not acted on by a tensile force. Section 5.2.2 describes the assumed probabilities of detection for UT and ET inspections as a function of crack depth. The PODs for cracks with depths greater than the compressive layer depth are informative of the likelihood of cracks remaining active after an outage in which inspection and peening occur.

Section 5.2.3 gives deterministic growth calculations for cracks that do exist after an outage in which inspection and peening occur. This section also includes a validation study demonstrating correspondence between stress intensity factors

calculated with an analytical weight function method and a high fidelity finite element approach.

5.2.1 Effect of Peening on Stress Profile

The modeled post-peening stress profile is characterized by a thin compressive region near the peened surface followed by a rapid transition to the pre-peening stresses. This profile is assumed to be the same in orthogonal directions. The key attributes of this stress profile are the compressive stress magnitude at the surface[5] and the penetration depth – the depth to which peening imparts compressive stresses. An example post-peening stress profile is shown in Figure 5-1 (the details of which are given in Appendix A).

Data and other information from peening vendors suggest that a compressive surface stress magnitude between 400 and 1000 MPa (58.0 to 145 ksi) can be achieved by peening. Thermal and load cycling is anticipated to reduce this by up to 50-80% over the lifetime of the plant (with a large majority of relaxation occurring during the first operational cycle after peening). The compressive stress magnitude is assumed to be 400 MPa (58.0 ksi) for the deterministic crack growth analyses in Section 5.2.3.

The penetration depth of peening is expected to vary depending on the component and location being peened. For the ID of a DMW component, WJP or ULP are expected to impart a compressive residual stress depth of at least approximately 1 to 1.5 mm. For the ID of a RPVHPN, it is conservatively assumed that the nominal compressive residual stress depth is only 0.5 mm. This value is conservatively based on stress measurement data reported in MRP-267 Revision 1 [5] for the reactor vessel bottom mounted nozzle (BMN) geometry indicating a compressive residual stress depth as small as about 0.5 mm for the WJP method due to the inability to direct the peening jet normal to the ID surface. Even though the ID of CRDM and CEDM nozzles is much greater than that for BMNs, the compressive stress depth for peening of the ID surfaces of RPVHPNs was conservatively based on the residual stress data for BMN mockups treated by WJP.

For the outer surface locations of a RPVHP, where ALP is currently being considered for peening application, the compressive residual stress depth is assumed to be approximately 3 mm based on the capability of ALP to produce compressive residual stresses as deep as 8 mm depending on the treated material and chosen ALP parameters. The quantities given above are assumed for the deterministic crack growth analyses in Section 5.2.3.

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[5] It is noted that ALP without a sacrificial ablative layer results in a very thin (~15 μm) layer of high tension at the component surface. As discussed in MRP-267R1, these stresses rapidly decrease to highly compressive values within about 35 μm. The stresses then remain compressive until at least a depth of 1.5 mm. This very thin region of tensile stress is not reflected in the detailed probabilistic model in this study but is not expected to have any significant effect since the high compressive stresses just below this thin layer will dominate the stress intensity factor at the tips of any cracks and thus also control crack growth behavior.

Finally, it is noted that after the superposition of operational loads (e.g., pressure loads) with the residual stresses, the depth of the compressive layer becomes different from the peening penetration depth. For locations where the operational loads result in tensile stresses, the compressive layer depth shifts nearer to the peened surface – this is predicted to reduce the penetration depth by between 10-30% at key ID locations, namely those locations subjected to tensile bending stresses. A 30% reduction is applied to all ID penetration depths given above to get the operational compressive layer depth.

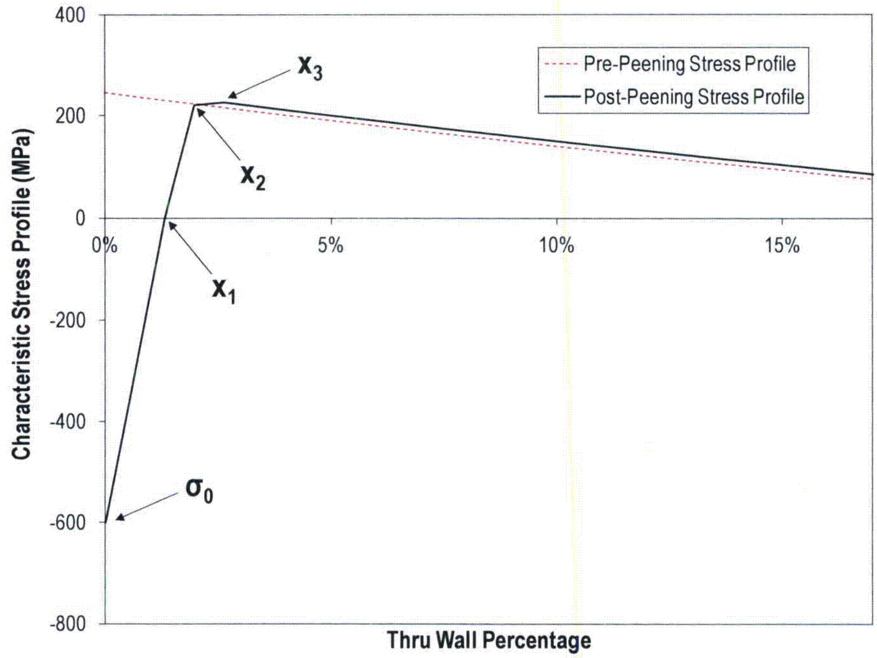

Figure 5-1
Characteristic Stress Profile near Peened Surface

5.2.2 Inspection and Detection

Similar to past studies of PWSCC, crack inspection is modeled with POD curves that are functions of crack geometry (e.g., deeper cracks lead to a higher likelihood of detection).

The median UT inspection POD curve used for cracking on DMW component IDs is from MRP-262R1 [19]. This curve is shown in Figure 5-2. Because the MRP-262 curve was developed using only circumferential cracks, and a review of examination data suggests a generally lower POD for axial cracks, the POD predicted by the MRP-262 curve is reduced by 20% for axial cracks.

The median UT inspection POD curve used for cracking on RPVHPN ID and OD Locations is shown in Figure 5-3. In the absence of rigorous experimental investigation, this curve was derived based on the lowest qualification criteria specified in 10 CFR 50.55a as detailed in appendix Section B.8.4.2. UT

inspection is not modeled as being used for detection of cracking at in weld locations.

The median ET inspection POD curve used for cracking on DMW and RPVHPN ID Locations is shown in Figure 5-4. In the absence of a rigorous experimental investigation, this curve was derived based on a review of ET POD for various probe types and locations, as detailed in appendix Section A.8.4.3. ET inspection is not modeled as being used for detection of cracking at the outer surface locations of penetrations.

These POD curves, together with the compressive layer depths discussed in the previous section (including the depth reduction for tensile operating stresses), allow the following conclusions to be drawn:

- At DM weld ID locations, cracks between 0.7 mm and 7 mm at the time of the pre-peening inspection are the most likely to remain active (undetected but outside of the peening compressive layer depth) after the outage during which inspection and peening occur. If ET is performed, this range becomes 0.7 mm to approximately 1.5 mm.
- At the RPVHPN ID locations, cracks between 0.35 mm and 9 mm at the time of the pre-peening inspection are the most likely to remain active after the outage during which inspection and peening occur. If ET is performed, this range becomes 0.35 mm to approximately 1.5 mm.
- At the RPVHPN OD locations, cracks between 2 mm and 9 mm at the time of the pre-peening inspection are the most likely to remain active after the outage during which inspection and peening occur.

The following section explores the growth of cracks that remain active after peening.

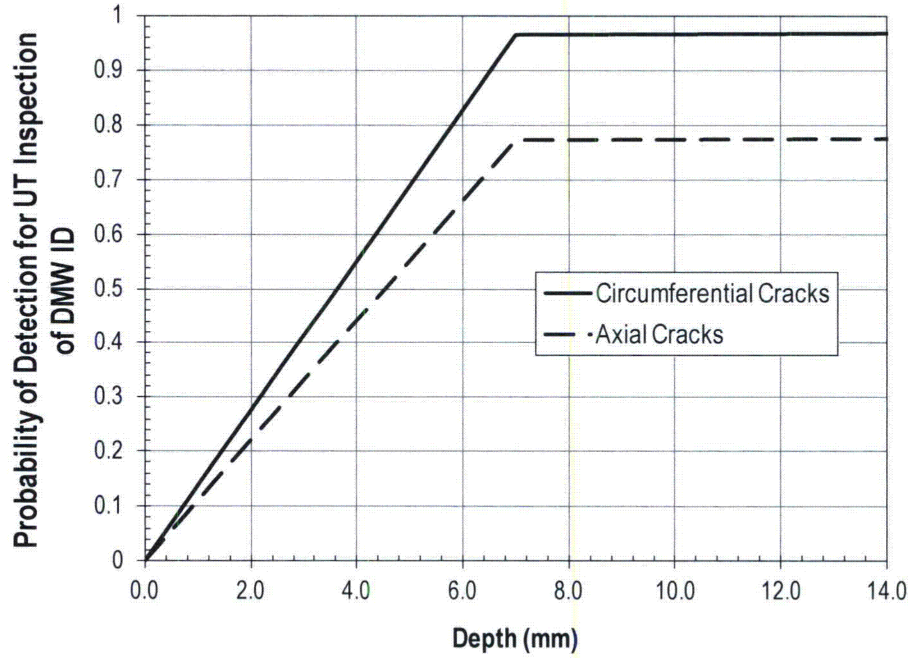

Figure 5-2
Median Assumed UT Inspection POD Curve for DMW ID Cracking

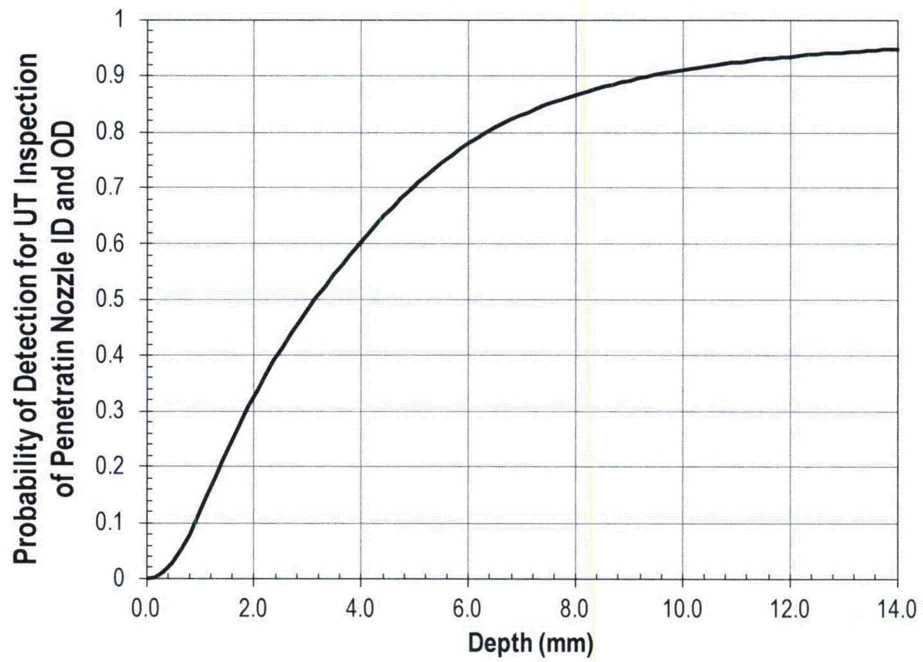

Figure 5-3
Median Assumed UT Inspection POD Curve for RPVHPN ID and OD Cracking

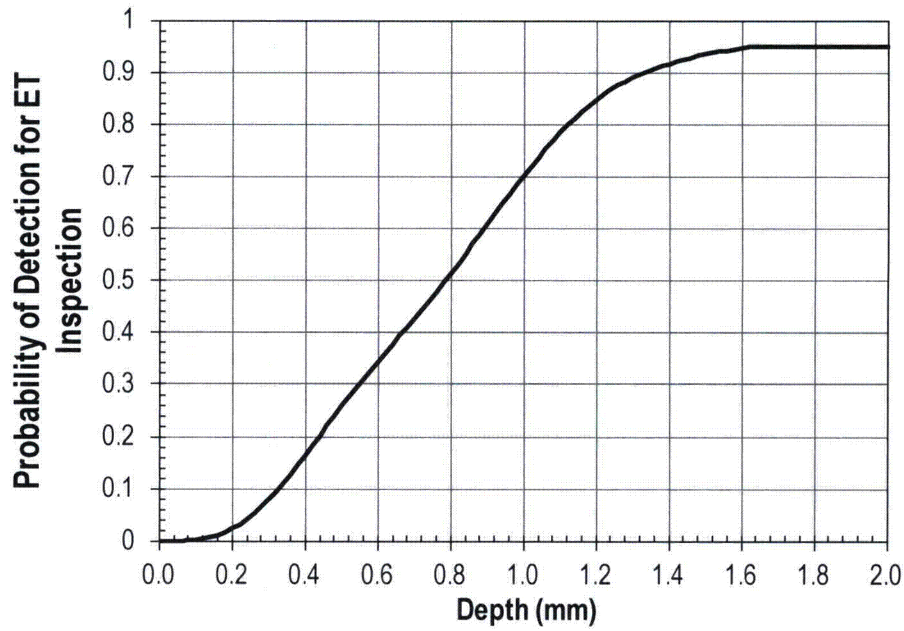

Figure 5-4
Median Assumed ET Inspection POD Curve for DMW ID and RPVHPN ID and OD Cracking

5.2.3 Crack Growth

This section presents predictions for crack growth in unmitigated and peened components so as to demonstrate the benefit of peening. Growth predictions are given for cracks on the inner diameter of DM weld components (Section 5.2.3.1) and at various locations on reactor head penetrations (Section 5.2.3.2). For growth in peened components (i.e., components with a thin compressive stress layer near the surface), three prediction types are presented:

- The first uses the more classical weight function method (detailed in appendix section A.5.2) to predict the stress intensity factors at the crack surface and deepest point locations.
- The second disregards the effect of peening on the growth of the crack surface point locations. This convention, which is further explained in appendix section A.5.5, is used to approximate the realistic "balloon"-type growth of the crack front below the peening compressive layer. Figure 5-5 demonstrates the crack front shapes predicted with FEA, the classical approach, and the "balloon" growth approximation, when the crack has reached the same depth. Numerical studies have demonstrated that the depth growth of a realistic crack is generally bounded by the classical approach and balloon growth approximation.
- The third accounts for the effects of partial crack closure. When partial crack closure occurs, membrane stresses are produced over the area of closure and are assumed to act equal and opposite to the compressive stresses over the same area. This results in a balancing of some of the compressive load. So, if

partial crack closure is not accounted for, a larger benefit to peening may be predicted. This effect is further detailed in appendix section A.5.5.

The component loading models that are used to determine the stresses on the crack in each analysis are detailed in appendix sections A.3 and B.3 for DMWs and RPVHPNs, respectively. The crack growth models (including the stress intensity factor calculations) are detailed in appendix sections A.5 and B.5.

In general, the inputs used for the deterministic calculations in this section are taken to be the median of the respective distributed inputs for the analogous, hot component, probabilistic analyses in the following section. For the reader's benefit, these deterministic inputs are given in Table 5-1 (for the DMW calculations) and Table 5-2 (for the RPVHPN calculations), and are bolded in these tables for instances in which they do not match the median of their analogous distributed input. The selection and/or derivation of the distributed inputs, and effectively the deterministic inputs, are detailed in appendix sections A.8 and B.8.

Finally, Section 5.2.3.3 provides a validation study demonstrating correspondence between stress intensity factors calculated with an analytical weight function method and a high fidelity finite element approach.

5.2.3.1 Dissimilar Metal Welds (DMWs)

Two distinct DMW cracks were studied deterministically: a circumferential crack located at the point of maximum tensile bending and an axial crack (of arbitrary location). The average growth rates of other crack locations/orientations are bounded by these predictions.

The weld-to-weld growth variation factor was set to its 75th percentile value (1.39) to generate these results. The temperature of the component was set to 600°F for the deterministic crack growth calculations.

For reference in converting between through-wall fraction and absolute depth, the component thickness in these studies is 69.9 mm. This is representative of a Westinghouse reactor vessel nozzle geometry.

Figure 5-6 and Figure 5-7 show the growth vs. time calculations for a circumferential and axial crack, respectively, with an initial through-wall fraction of 5% (3.5 mm). This initial through-wall fraction is the median depth at the time of initiation in the DMW probabilistic base case model[6]. At this initial

[6] Since the PWSCC initiation model is based on the results of in-service inspections, the distribution of initial flaw through-wall fraction is defined using the expected sensitivity of the UT inspection technique. As shown in Figure 5-2, the median initial depth of 3.5 mm corresponds with a UT POD of 50%. This convention allows crack growth to not be simulated from actual initiation when growth rate estimates would be unreliable due to the very small crack sizes. While this convention is conservative due to larger cracks sizes and less chance of early detection, it may be non-conservative in the case of peening because cracks may be predicted to be larger, and thus more detectable, at the time of the pre-peening and follow-up inspections, (i.e., before entering the relieved inspection schedule). Sensitivity studies are presented in Appendix A to assess this possibility.

through-wall fraction, the effect of peening is predicted to be modest, delaying through-wall growth by approximately 18 months for the circumferential crack and by 2-3 months for the axial crack. Figure 5-8 shows the stress intensity factor at the deepest crack point vs. through-wall fraction for the circumferential crack as it goes through-wall. Generally speaking, peening biases the stress intensity factor down and this acts to slow, or sometimes stop, growth.

Figure 5-9 shows the drastic effect peening can have on cracks with depths similar to the depth of the peening penetration depth. For a crack with an initial through-wall fraction of 1% (0.7 mm), the peening stresses are predicted to arrest growth entirely.

Figure 5-10 shows the growth vs. time calculations for a circumferential crack with an initial through-wall fraction of 2% (1.4 mm), approximately twice the depth of the compressive layer. This figure includes the growth predictions on the peened component when the balloon crack growth approximation is allowed and when partial crack closure is accounted for. As expected, approximating balloon growth reduces the benefit of the peening because the crack continues to growth in length, which increases the stress intensity factor at the deepest point on the crack (as demonstrated in Figure 5-11). Accounting for partial crack closure only effects growth when the crack depth is similar to the peening penetration depth so its effect is minor for this particular initial condition.

Figure 5-12 through Figure 5-14 give time to through-wall growth vs. initial crack through-wall fraction. Figure 5-13 and Figure 5-14 provide a log-scale presentation to better detail the initial through-wall fractions for which peening is more effective. The median UT POD vs. crack depth curve is included on the log-scale plots to illustrate the likelihood of each crack depth (and its corresponding time to through-wall growth) existing after the pre-peening inspection.

In line with experimental data and other information provided by vendors, peening is predicted to arrest growth for cracks less than or somewhat (~10-100%) deeper than the compressive layer depth. Peening can be beneficial for slowing the growth of cracks significantly (~100%-1000%) deeper than the compressive layer depth, but the effectiveness depends on the nature of the pre-peening stresses.

Approximating balloon crack growth compromises the predicted effectiveness of the peening for cracks significantly (>100%) deeper than the compressive layer depth. As mentioned earlier, the actual crack growth is expected to fall somewhere between the results of the classical and balloon approximation approaches. Conservatively, for all base case probabilistic analyses, the balloon growth approximation is used.

Accounting for crack closure impacts growth predictions for cracks slightly (~10-100%) deeper than the compressive layer depth. As demonstrated in Figure 5-13, accounting for partial crack closure can be the difference between predicting the total arrestment of a crack rather than the continuation of slow growth. Because accounting for partial crack closure requires a substantial computational effort, it

is not applied for base case probabilistic analyses, but is included for a sensitivity case.

Using the UT POD curve, it can be ascertained that there is a range of crack depths that are likely to be missed by UT at the pre-peening inspection, but could still grow through-wall rapidly despite the surface stress improvement. Using the ET POD curve, it can be ascertained that most (not all) cracks undetected by ET are expected to be shallow enough that their through-wall growth would be slowed or arrested by the surface stress improvement. The probabilistic analyses, described in the next section, address the combination of inspection and growth (and initiation) in a more robust manner to build a bridge between these deterministic analyses and actual leakage statistics for characteristic DMW components.

As is discussed in appendix section A.3.3, residual stress after peening is modeled under the assumption that any tensile stresses removed near the surface of application are redistributed such that total axial and hoop forces remain unchanged, before and after peening. By convention, this force balance is achieved by distributing tensile stresses removed near the surface uniformly over the remaining thickness of the component. To test this convention, a set of deterministic calculations were redone with force balanced over the first 4 mm of the component, which results in a short region of high (>800 MPa) tensile stress located directly below the peening compressive layer, instead of the entire through-wall thickness, which results in a slight additional stress over the entire component thickness (as demonstrated in Figure 5-15). Results for these calculations are compared in Figure 5-16 and Figure 5-17. As expected, the tensile stress concentration fosters the growth for short cracks, which in turn accelerates through-wall growth rates. This result is non-conservative, but the modeling convention is considered reasonable given that: i) there is no known evidence to support a tensile stress concentration under the peening compressive layer of this magnitude, ii) in experiments applying the concentrated force balance to various component and crack geometries, the through-wall growth time was reduced by less than 20% (and this reduction was even smaller when using the balloon growth approximation for predicting crack growth), and iii) the convention can be conservative for deep cracks that exist after peening because of the more deeply distributed tensile stresses.

Finally, Figure 5-18 gives the predictions of time to through-wall growth vs. initial through-wall fraction for cracks of two different initial aspect ratios. In this particular case, the longer crack, with the same initial depth, is predicted to grow through-wall 0-40% faster than the shorter crack. Both types of crack can be completely arrested if they are shallow enough compared to the compressive layer depth.

Table 5-1
Inputs for DMW Deterministic Calculations

Symbol	Description	Units	Value
	General Component Inputs		
t	Component wall thickness	m	0.0699
D_o	Component outer diameter	m	0.9017
w	DM weld width	m	0.0445
$\mathbf{T}$	**Operating temperature**	**°F**	**600.0**
P_{op}	Normal operating pressure	MPa	15.5
F_{DWx}	Deadweight loads	kN	0
M_{DWx}		kN-m	0
M_{DWy}		kN-m	0
M_{DWz}		kN-m	0
F_{NTEx}	Thermal expansion loads	kN	0
M_{NTEx}		kN-m	0
M_{NTEy}		kN-m	4519.4
M_{NTEz}		kN-m	0
	Growth Rate Inputs		
Q_g	Thermal activation energy for PWSCC flaw propagation	kJ/mole	130.0
$\mathbf{f_{ww}}$	**Weld factor**	**Nondim**	**1.39**
$\mathbf{f_{weld}}$	**Within weld factor**	**Nondim**	**1.00**
α	Flaw propagation rate equation power law constant	$(m/s)/(MPa\text{-}m^{0.5})^{1.6}$	2.01E-12
b	Flaw propagation rate equation power law exponent	Nondim	1.6
K_{Ith}	K_I Stress intensity factor threshold	$MPa\text{-}m^{0.5}$	0.0
$T_{ref,g}$	Absolute reference temperature to normalize PWSCC flaw propagation data	°F	617.0
$\mathbf{\Delta t}$	**Time step size for crack increment**	**yr**	**1/20**
	Residual Stress Inputs		
σ_{0WRSa}	Weld residual axial stress on ID surface	MPa	300.3
X_c	Fractional through-thickness at which weld residual axial stress profile crosses zero	Nondim	0.25
f_{WRSa}	Random scaling factor for weld residual axial stress on OD surface	Nondim	0.75
σ_{0WRSh}	Weld residual hoop stress on ID surface	MPa	300.3
X_{min}	Fractional through-thickness at which weld residual hoop stress is minimum	Nondim	0.5
f_{WRSh1}	Random scaling factor for minimum weld residual hoop stress	Nondim	0.5
f_{WRSh2}	Random scaling factor for weld residual hoop stress on OD surface	Nondim	1.0
$\sigma_{0,PPRS}$	Initial peening stress on applied surface	MPa	-406.0
$x_{1,PPRS}$	Penetration depth	mm	1.0
$f_{1,PPRS}$	See Appendix Section C.3.3 for definition	Nondim	2.0
$f_{2,PPRS}$	See Appendix Section C.3.3 for definition	Nondim	0.7

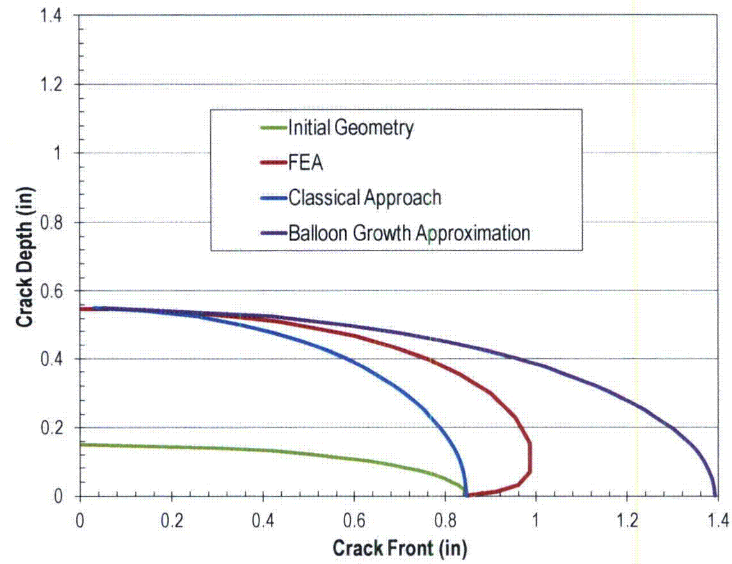

Figure 5-5
Example of Crack Front Shapes Predicted in a Peened Component with: a) FEA, b) classical analytical methods, or c) the balloon growth approximation

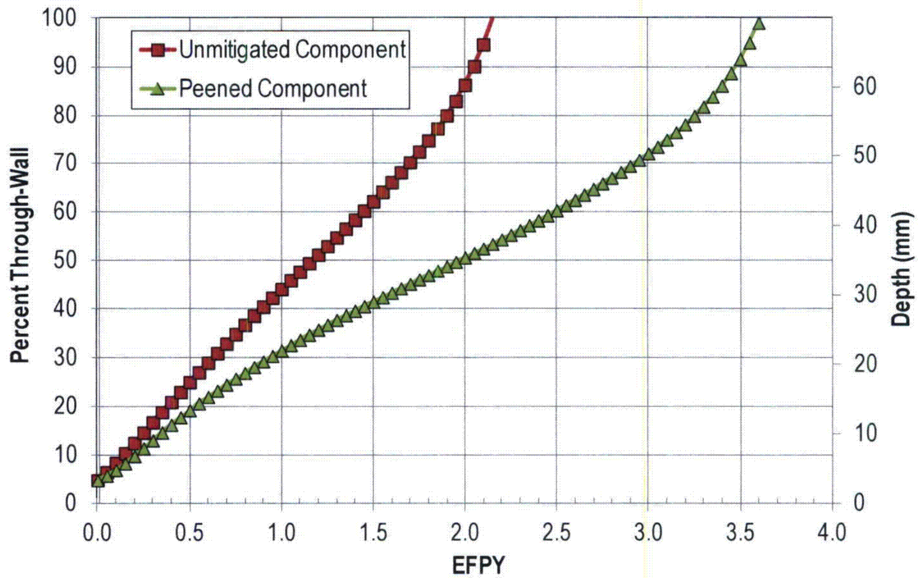

Figure 5-6
Through-Wall Fraction vs. Time for Circumferential Crack on Unmitigated and Peened Component (a_0/t=5% (3.5 mm) and $2c_0/a_0$=8.5)

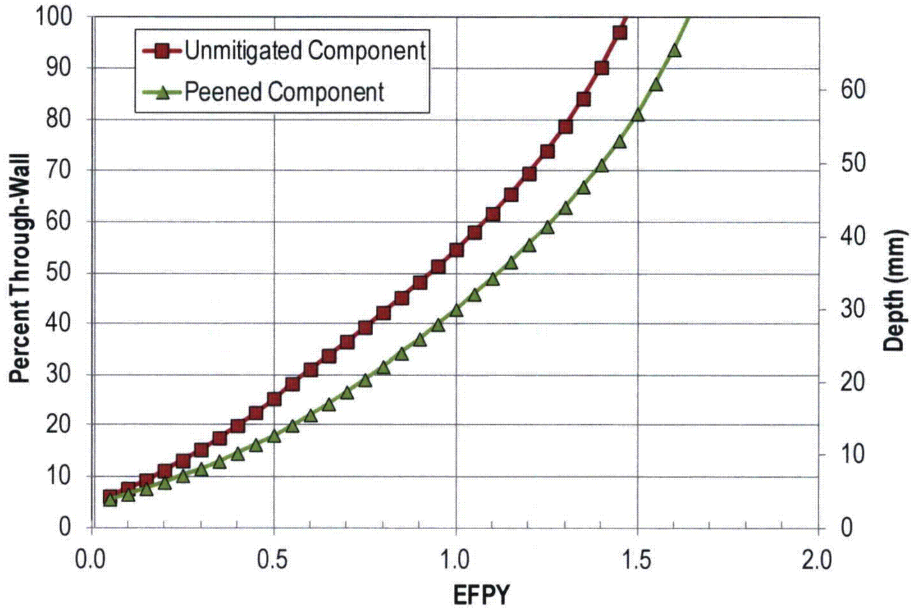

Figure 5-7: Through-Wall Fraction vs. Time for Axial Crack on Unmitigated and Peened Component (a_0/t=5% and $2c_0/a_0$=4.5)

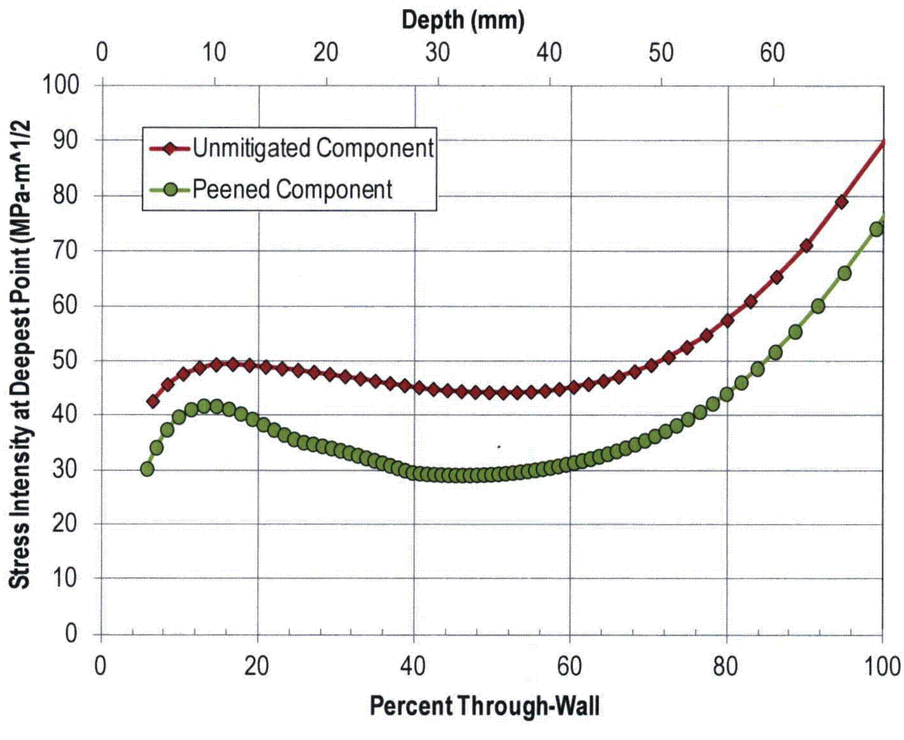

Figure 5-8
Stress Intensity Factor vs. Through-Wall Fraction for Circumferential Crack in Unmitigated and Peened Component (a_0/t=5% and $2c_0/a_0$=8.5)

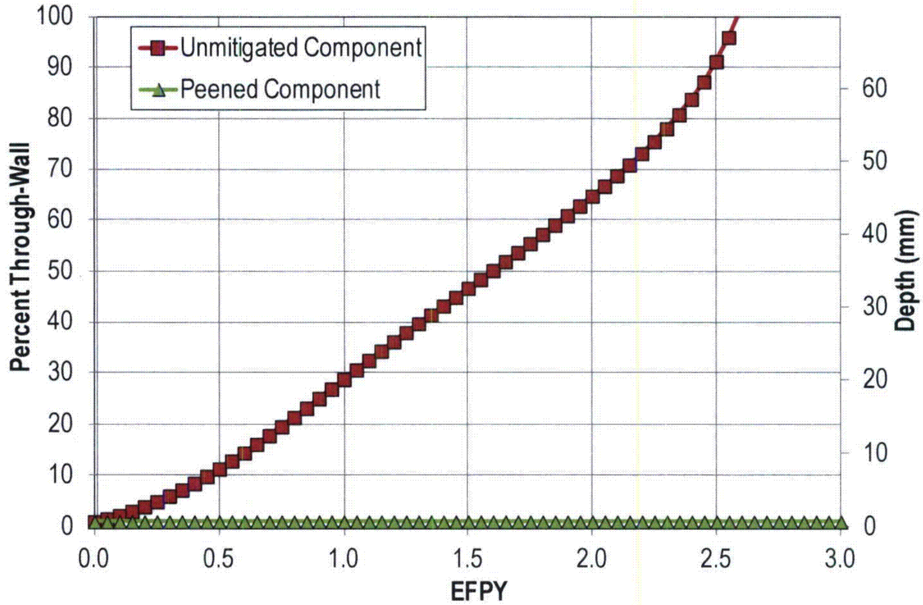

Figure 5-9
Through-Wall Fraction vs. Time for Circumferential Crack on Unmitigated and Peened Component (a_0/t=1% and $2c_0/a_0$=8.5)

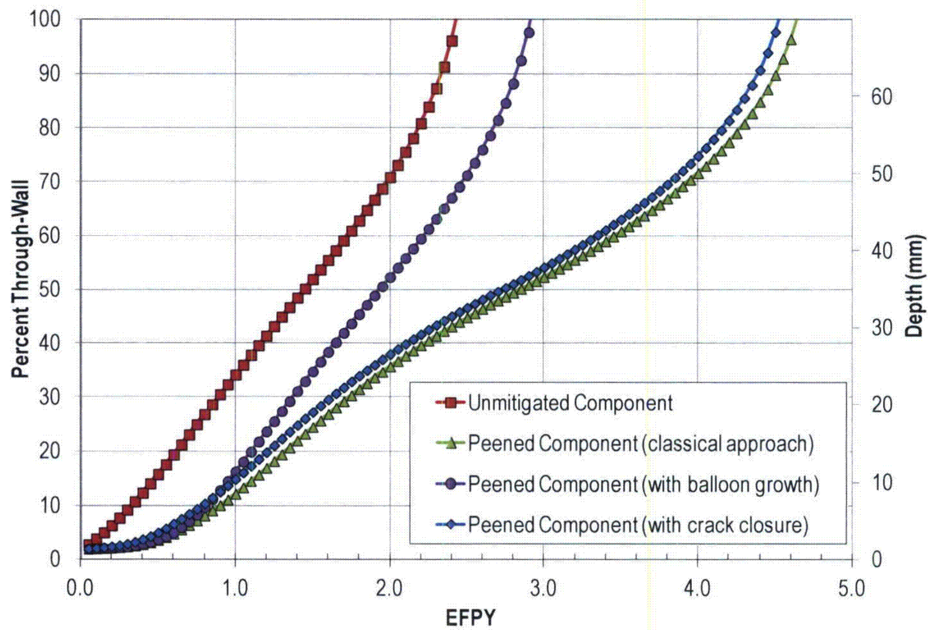

Figure 5-10
Through-Wall Fraction vs. Time for Circumferential Crack on Unmitigated and Peened Component (a_0/t=2% and $2c_0/a_0$=8.5)

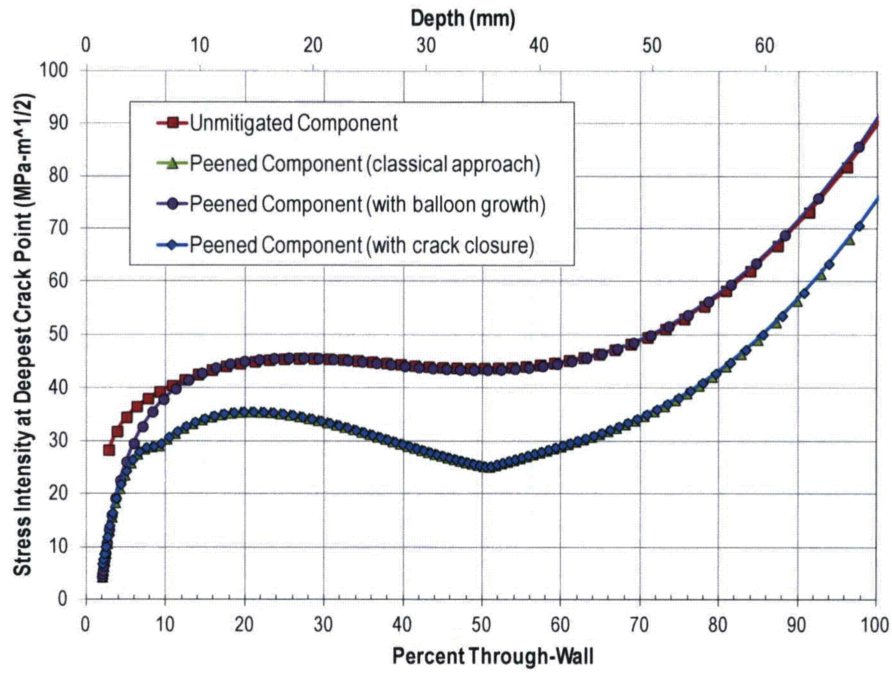

Figure 5-11
Stress Intensity Factor vs. Through-Wall Fraction for Circumferential Crack on Unmitigated and Peened Component (a_0/t=2% and $2c_0/a_0$=8.5)

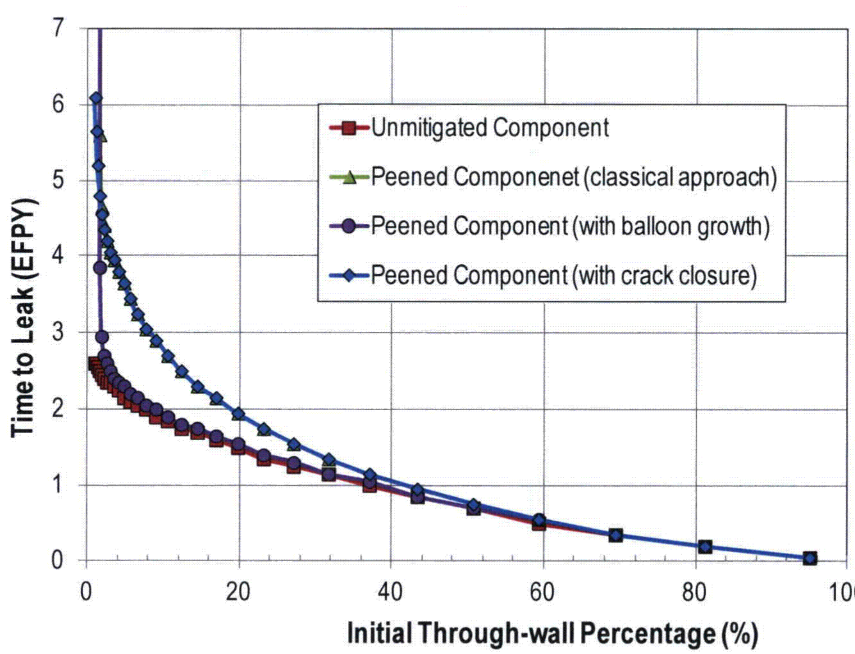

Figure 5-12
Time to Through-Wall Growth vs. Initial Crack Depth for Circumferential Cracks at Location of Maximum Tensile Bending

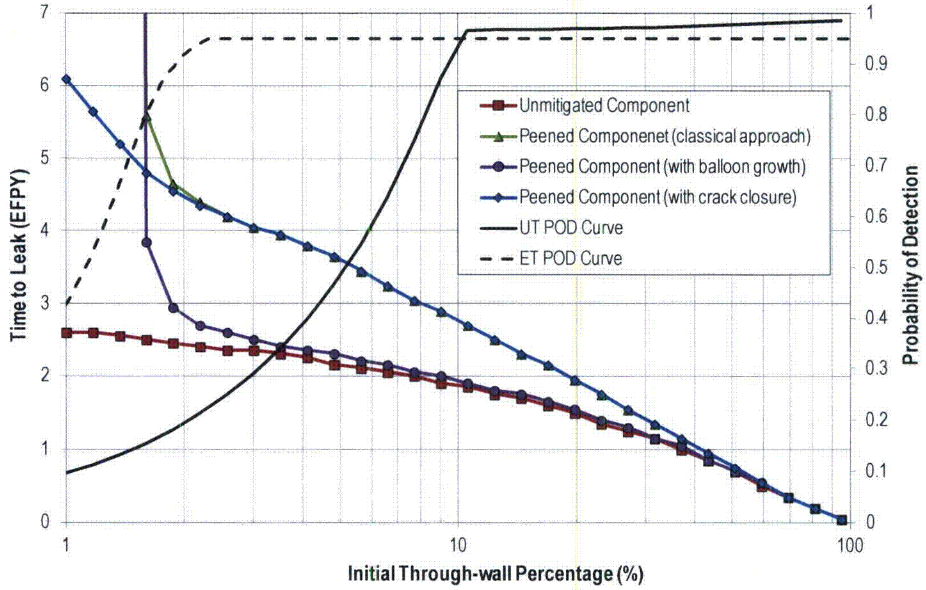

Figure 5-13
Time to Through-Wall Growth vs. Initial Crack Depth for Circumferential Cracks at Location of Maximum Tensile Bending (log-scale)

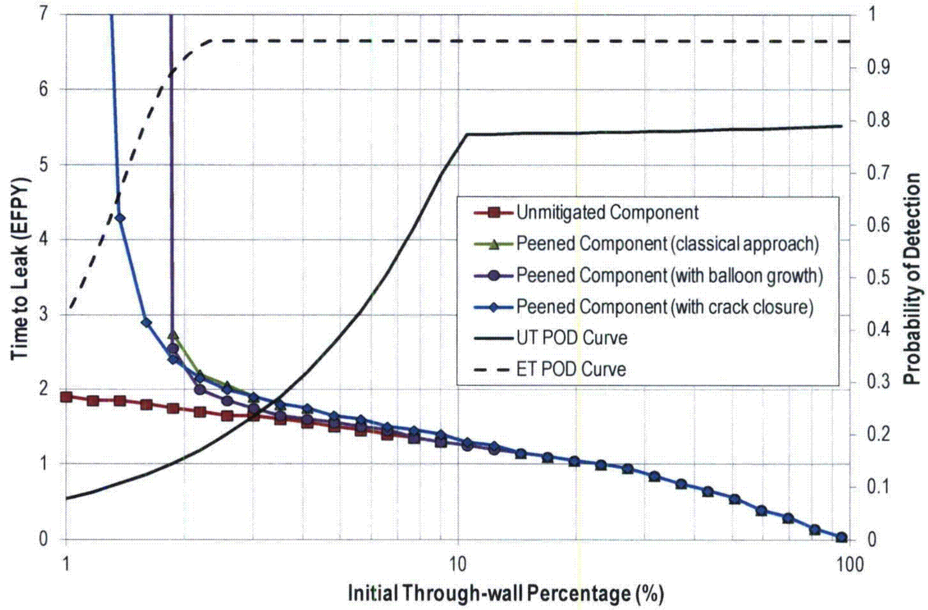

Figure 5-14
Time to Through-Wall Growth vs. Initial Crack Depth for Axial Cracks (log-scale)

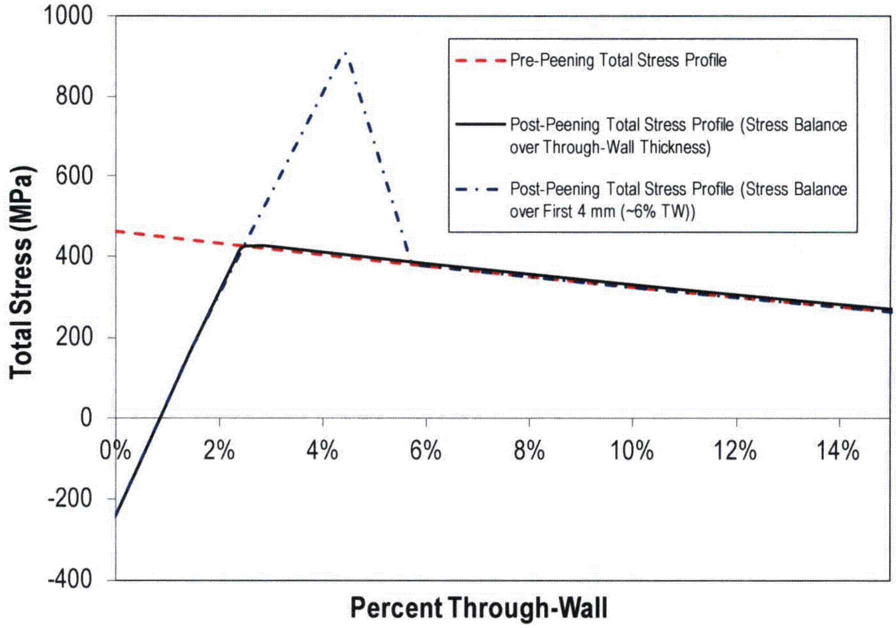

Figure 5-15
Comparison of Stress Profiles near Peened Surface for Concentration of Force Balance Study

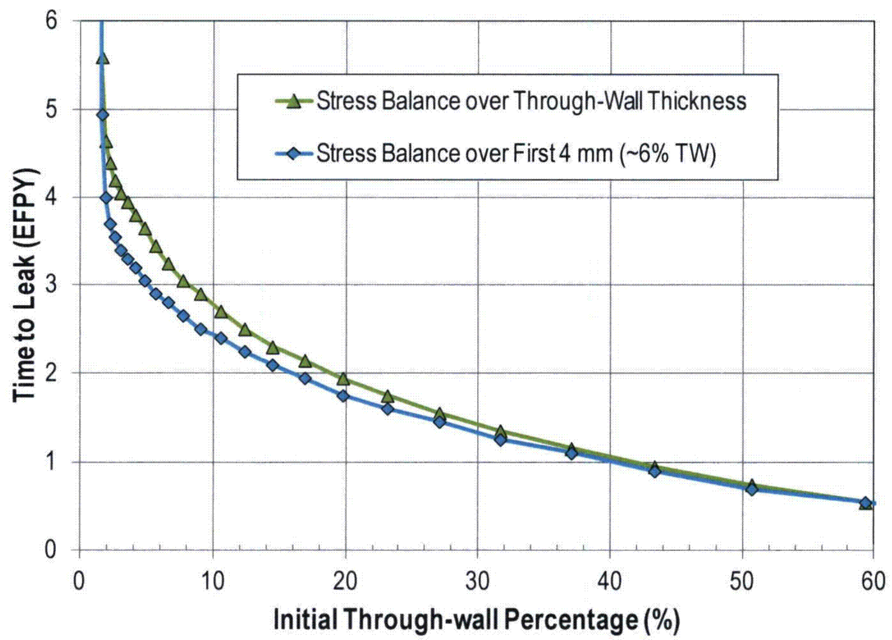

Figure 5-16
Comparing Differences due to Concentration of Force Balance : Time to Through-Wall Growth vs. Initial Crack Depth for Circumferential Cracks at Location of Maximum Tensile Bending

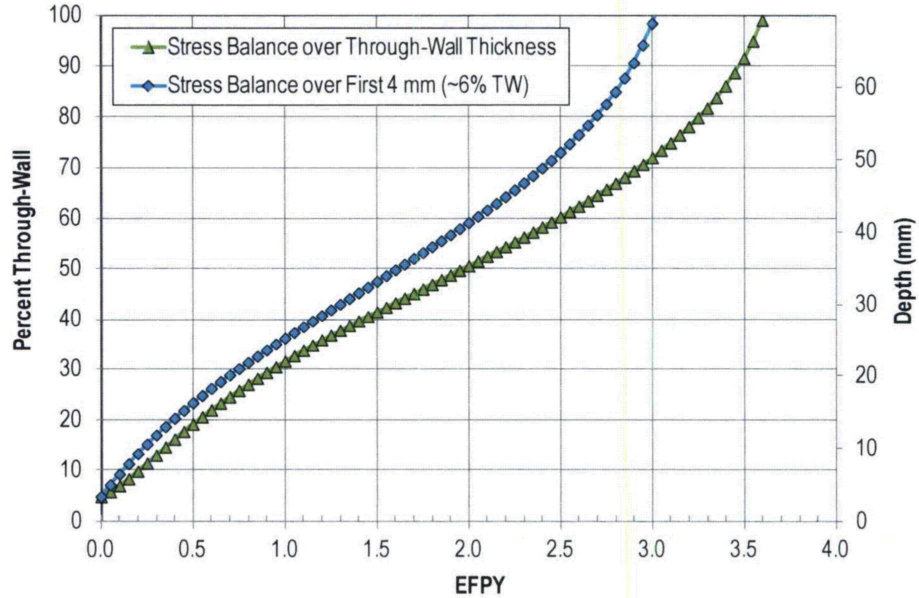

Figure 5-17
Comparing Differences due to Concentration of Force Balance : Through-Wall Fraction vs. Time for a Circumferential Crack at Location of Maximum Tensile Bending with an Initial Through-Wall Depth of 5%

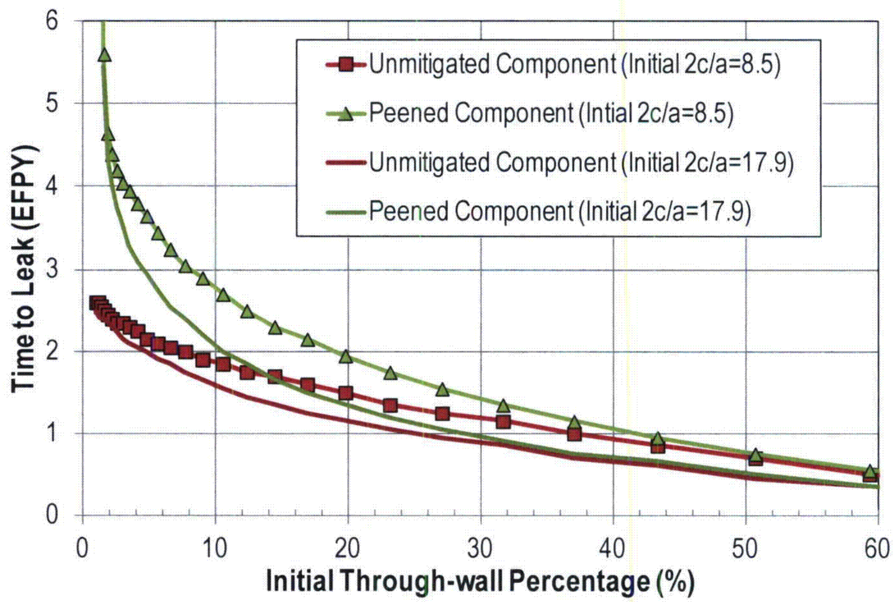

Figure 5-18
Comparing Differences due to Initial Aspect Ratio: Time to Through-Wall Growth vs. Initial Crack Depth for Circumferential Cracks at Location of Maximum Tensile Bending

5.2.3.2 Reactor Pressure Vessel Head Penetration Nozzles (RPVHPNs)

Growth of four distinct RPVHPN crack types were studied deterministically: an axial crack on the penetration nozzle ID initiating above the J-groove weld, an axial crack on the penetration nozzle OD initiating below the J-groove weld, a crack initiating on the J-groove weld, and a circumferential through-wall crack growing along the weld contour. For the first three crack types, growth is predicted until the time of leakage; for the fourth crack type, growth is predicted until the time of ejection.

Growth predictions for each crack type can made for the uphill and downhill locations on the penetration using stress profiles that are representative of each location (as detailed in appendix Section B.3).

The weld-to-weld and heat-to-heat growth variation factors were set to their 75th percentile values (1.39 and 1.98, respectively) to generate these results. The temperature of the component was set to 600°F.

For reference in converting between through-wall fraction and absolute depth, the component thickness in these studies is 15.8 mm. This is representative of a Westinghouse CRDM geometry.

<u>Crack Growth Prior to Leakage</u>

Figure 5-19 shows the growth vs. time calculation for an axial crack on the penetration nozzle ID with an initial through-wall fraction of 5% (0.8 mm). This initial through-wall fraction is the median depth at the time of initiation in the RPVHPN probabilistic base case model[7]. At this initial through-wall fraction, the effect of peening is predicted to be considerable, delaying through-wall growth by approximately 3 EFPY.

Contrary to ID cracks above the weld, through-wall growth of axial cracks on the penetration nozzle OD does not cause leakage. Instead, leakage occurs once an OD axial crack grows in length to reach the OD nozzle annulus. Figure 5-20 shows the length growth vs. time calculations for an axial crack on the penetration nozzle OD with an initial through-wall fraction of approximately 30% (as will be demonstrated shortly, OD cracks less than approximately 20% (3 mm) through-wall at the time of peening are predicted to arrest). In this case,

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[7] This initiation size was selected to remain consistent with the initial through-wall fraction used for the DMW probabilistic model. While this initial depth may be larger than a realistic PWSCC initiation depth, this convention allows crack growth to not be simulated from actual initiation when growth rate estimates would be unreliable due to the very small crack sizes. While this convention is conservative due to larger cracks sizes and less chance of early detection, it may be non-conservative in the case of peening because cracks may be predicted to be larger, and thus more detectable, at the time of the pre-peening and follow-up inspections, (i.e., before entering the relieved inspection schedule). Sensitivity studies are presented in Appendix B to assess this possibility.

even when approximating balloon crack growth, the benefit of peening is large, delaying leakage by 5-6 EFPY[8].

Figure 5-21 shows the growth vs. time calculation for a weld crack with an initial through-wall fraction of 17% (as will be demonstrated shortly, weld cracks smaller than this at the time of peening are predicted to arrest). In this particular case, there is significant improvement with peening, delaying the through-weld growth time by a factor of approximately five.

Figure 5-22 through Figure 5-27 give time to leakage vs. initial crack through-wall fraction, for each of the three partial crack types, at the uphill and downhill sides of the penetration. The POD curves that correspond to the different crack locations are also shown to better illustrate the likelihood of each crack depth (and its corresponding time to through-wall growth) existing after the pre-peening inspection.

The downhill locations tend to grow to leak faster because of characteristically larger weld residual stresses.

As in the DM weld deterministic analyses, peening is predicted to arrest growth for cracks less than then or somewhat (~10-100%) deeper than the compressive layer depth. Peening is predicted to be beneficial for slowing the growth of cracks significantly (~100%-500%) deeper than the compressive layer depth, but the effectiveness depends on the nature of the pre-peening stresses; in some cases, the benefit of peening rapidly fades for weld cracks deeper than the compressive layer depth.

Generally speaking, because penetration nozzles are less thick than DM weld components, the beneficial effect of peening is observed for cracks of greater through-wall percentages.

At the nozzle OD and weld locations, where the peening penetration depth is expected to be approximately 3.0 mm, cracks less than approximately 20% through-wall may be arrested upon the application of peening.

As with DM weld components, the effect of peening on cracks between 100-500% deeper than the compressive layer depth is predicted to be compromised when balloon crack growth is approximated. This effect is not observed at weld locations where crack length growth is constrained by the penetration nozzle and weld butter material interfaces.

The POD curves for ID cracking in Figure 5-22 and Figure 5-23 predict a range of cracks that are likely to be undetected during the pre-inspection that would

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[8] The discontinuous shape of the length vs. time curve for the peened component (without balloon growth) is due to a modeling simplification that allows the growth of *through-wall* axial cracks without the effect of peening. Consequently, the length of the crack is predicted to stay constant by the partial crack growth model until the crack depth grows through-wall, at which point the growth model transitions.

grow at rates similar to an unmitigated component. The use of ET inspection could reduce this range significantly.

The UT POD curves for OD cracking in Figure 5-24 and Figure 5-25 predict that there are very few cracks that would be undetected that would not be arrested, or at least significantly slowed, by the surface stress improvement.

Finally, Figure 5-26 demonstrates some initial crack depths for which the peened component results in earlier leakages. This occurs for relatively deep cracks and is due to the modeling assumption that the effective forces on the cross-section of the peened component balance; i.e., tensile stresses are displaced from the peened surface and are redistributed to deeper locations. This effect is more substantial for the weld locations because of the deeper peening penetration depth.

Circumferential through-wall Crack Growth

Circumferential through-wall crack growth along the weld contour of penetration nozzles is an significant concern when assessing PWSCC risk in reactor heads because, if such cracks grow large enough, they can result in nozzle ejection. In the RPVHPN probabilistic model, circumferential through-wall cracks initiate instantly after leakage (due to any of the crack locations discussed in the previous section). Applying the growth model detailed in appendix Section B.5.4, this section provides crack growth predictions for circumferential through-wall cracks, from initiation until nozzle ejection.

The initial flaw angle is assumed to be 30° (per the convention in MRP-105 [18]). Nozzle ejection is predicted to occur at a flaw angle of approximately 300°, per the calculations in MRP-110 [15].

To generate results for circumferential through-wall cracks, the heat-to-heat growth variation factor was set to its 75th percentile value (1.98), the temperature of the component was set to 600°F, and the environmental growth factor was set to 2.0. No multiplier was applied to the FEA predicted average stress intensity factors (presented in Figure B-7 in Appendix B).

Figure 5-28 shows the growth vs. time prediction for circumferential through-wall cracks initiating on the uphill and downhill side of the penetration nozzle. It is noted that peening stresses are neglected for the growth of circumferential through-wall cracks such that these predictions do not vary after peening.

With the deterministic parameters used for this study, which are more aggressive than the median case in the probabilistic model, downhill cracks are predicted to cause ejection approximately 13.5 EFPY after initiation and uphill cracks are predicted to cause ejection approximately 17.0 EFPY after initiation. In the rare case in which two circumferential through-wall cracks initiate, one from the uphill location and one from the downhill location, ejection is predicted approximately 7.0 EFPY after initiation.

Table 5-2
Inputs for RPVHPN Deterministic Calculations

Symbol	Description	Units	Value
	General Component Inputs		
t	Nozzle thickness	m	0.0158
D_o	Nozzle outer diameter	m	0.1016
t_{head}	Reactor head thickness	m	0.152
T	Operating temperature	°F	600.0
P_{op}	Normal operating pressure	MPa	15.5
$f_{oper,ID}$	Penetration nozzle ID hoop stress concentration factor	Nondim	3.48
N/A	J-groove weld geometries used to simulate crack growth of crack initiation on weld	See mean values given in Appendix Table D-4	
	Growth Rate Inputs		
Q_g	Thermal activation energy for PWSCC flaw propagation	kJ/mole	130.0
$\boldsymbol{f_{ww}}$	**Weld factor**	**Nondim**	**1.39**
$\boldsymbol{f_{weld}}$	**Within weld factor**	**Nondim**	**1.00**
$\boldsymbol{f_{wh}}$	**Heat factor**	**Nondim**	**1.98**
$\boldsymbol{f_{heat}}$	**Within heat factor**	**Nondim**	**1.00**
α_{weld}	Flaw propagation rate equation power law constant for Alloy 182	(m/s)/(MPa-m$^{0.5}$)$^{1.6}$	2.01E-12
α_{heat}	Flaw propagation rate equation power law constant for Alloy 600	(m/s)/(MPa-m$^{0.5}$)$^{1.6}$	1.97E-13
b	Flaw propagation rate equation power law exponent	Nondim	1.6
K_{Ith}	K_I Stress intensity factor threshold	MPa-m$^{0.5}$	0.0
$T_{ref,g}$	Absolute reference temperature to normalize PWSCC flaw propagation data	°F	617.0
$\boldsymbol{K_{circ,mult}}$	**Circumferential through-wall crack *K* curve multiplier**	**Nondim**	**1.0**
$c_{circ,mult}$	Circumferential through-wall crack environmental factor	Nondim	2.0
N/A	Distance below weld toe of OD crack location	in	0.25
$\boldsymbol{\Delta t}$	**Time step size for crack increment**	**yr**	**1/20**
	Residual Stress Inputs		
N/A	Weld residual stress profile parameters	See mean values given in Appendix Table D-5	
$\sigma_{0,PPRS}$	Peening stress on applied surface	MPa	-378.0
$x_{1,PPRS,ID}$	Penetration depth for peening performed on nozzle ID surfaces	mm	0.5
$x_{1,PPRS,ext}$	Penetration depth for peening performed on nozzle OD and weld surfaces	mm	3.0
$f_{1,PPRS}$	See Appendix Section C.3.3 for definition	Nondim	2.0
$f_{2,PPRS}$	See Appendix Section C.3.3 for definition	Nondim	0.7
	Stability Inputs		
$\theta_{circ,init}$	Initial angle for circumfernetial through-wall cracks immediately following leaks	degrees	30.0
$\theta_{circ,crit}$	Critical flaw angle for nozzle ejection	degrees	300.0

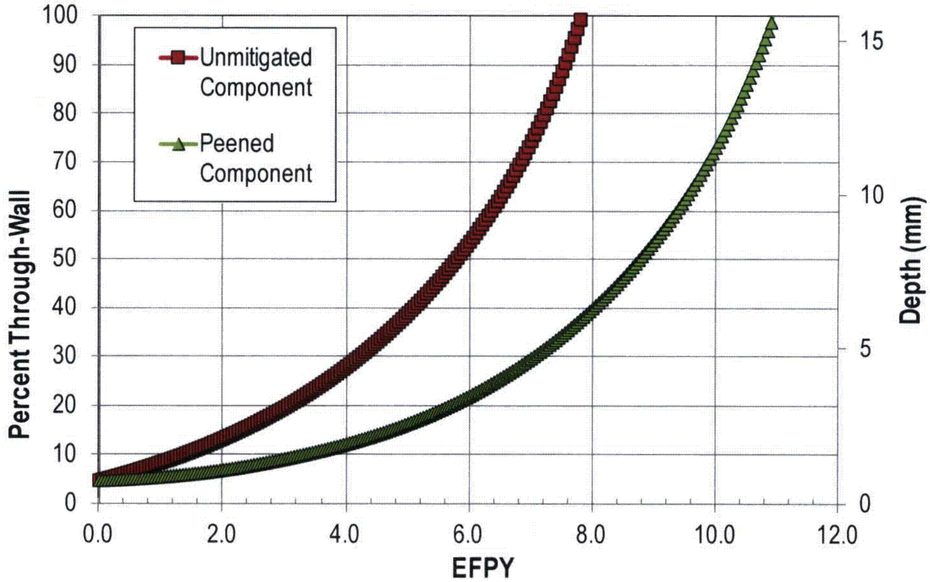

Figure 5-19
Through-Wall Percentage vs. Time for Uphill ID Axial Crack on Unmitigated and Peened Component (a_0/t=5% (0.8 mm) and $2c_0/a_0$=4.5)

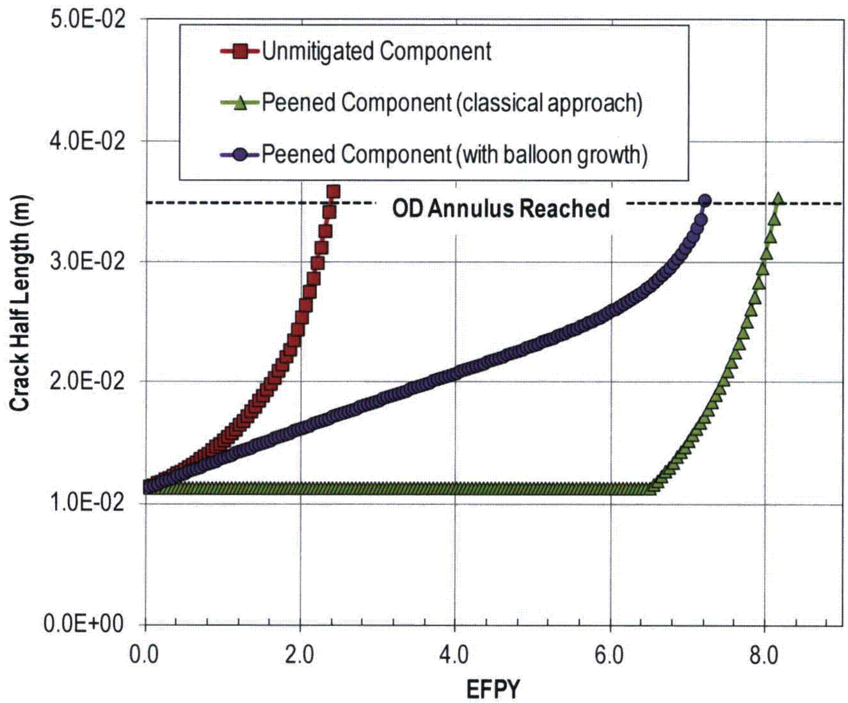

Figure 5-20
Half-Length vs. Time for Uphill OD Axial Crack on Unmitigated and Peened Component (a_0/t=30% (4.8 mm) and $2c_0/a_0$=4.5)

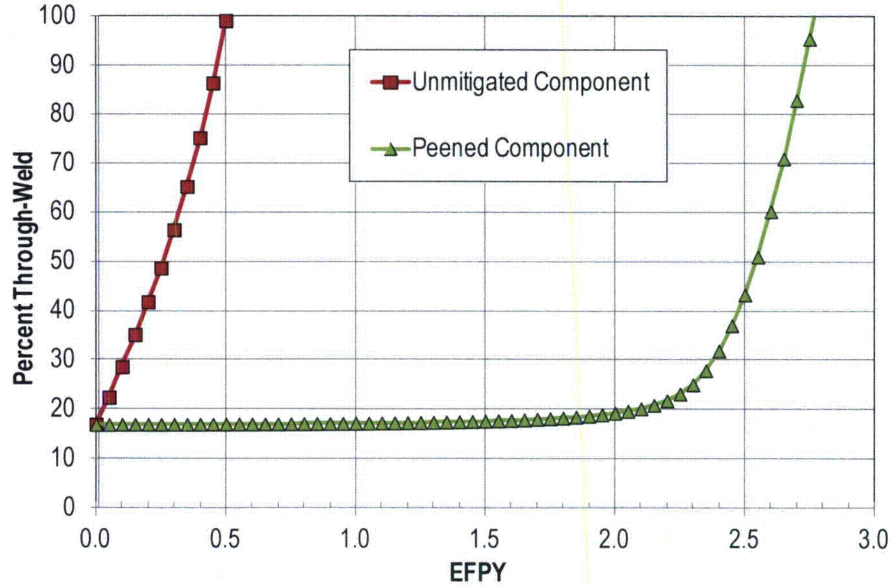

Figure 5-21
Through-Weld Percentage vs. Time for Downhill Weld Crack on Unmitigated and Peened Component (a_0/t=17% (2.7 mm) and $2c_0/a_0$=4.5)

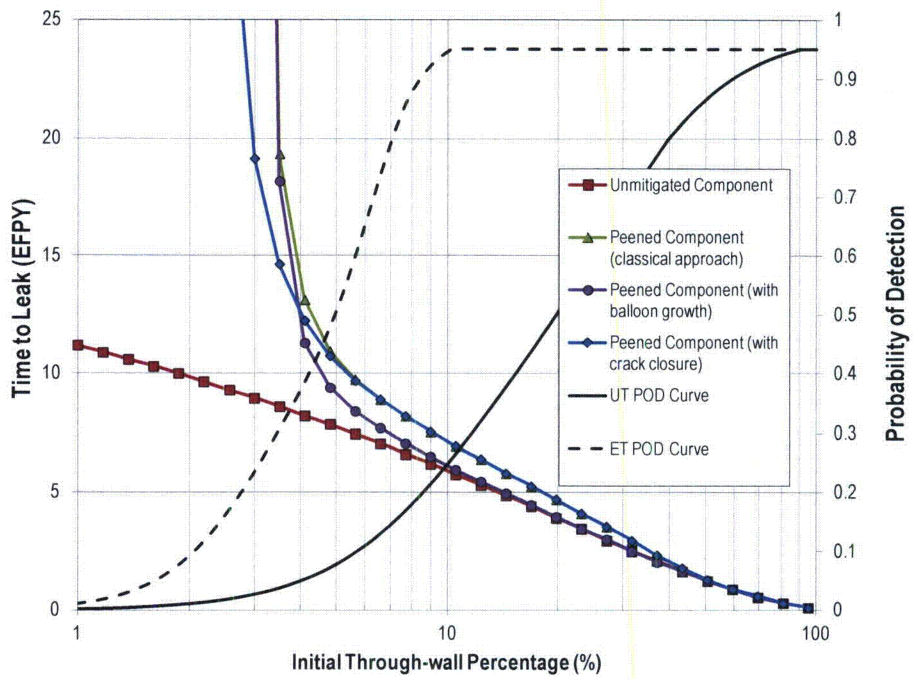

Figure 5-22
Time to Through-Wall Growth vs. Initial Crack Depth for Axial Crack on Uphill Penetration Nozzle ID (log-scale)

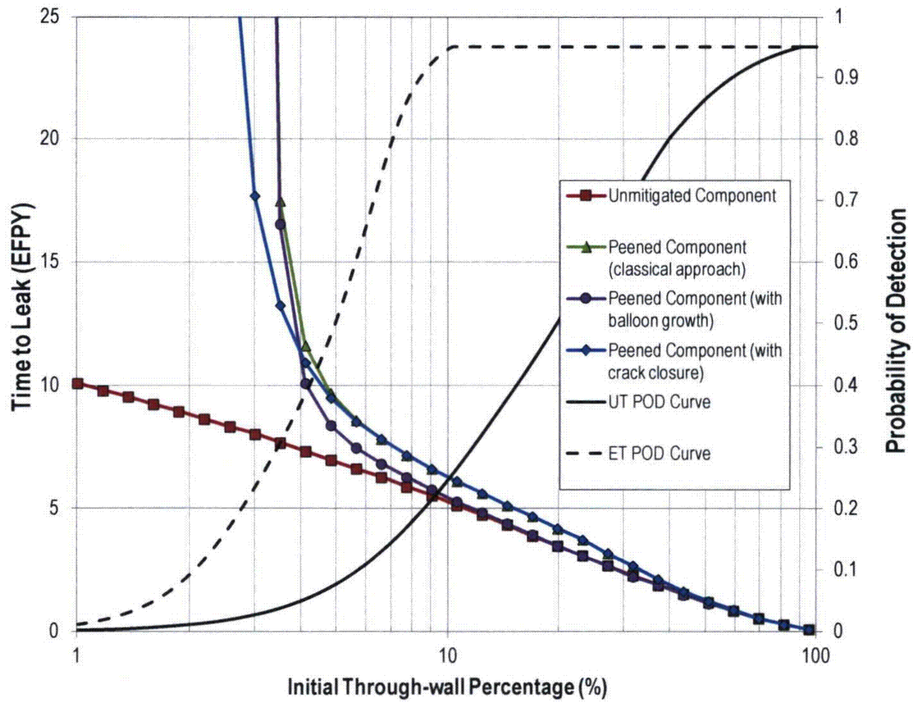

Figure 5-23
Time to Through-Wall Growth vs. Initial Crack Depth for Axial Crack on Downhill Penetration Nozzle ID (log-scale)

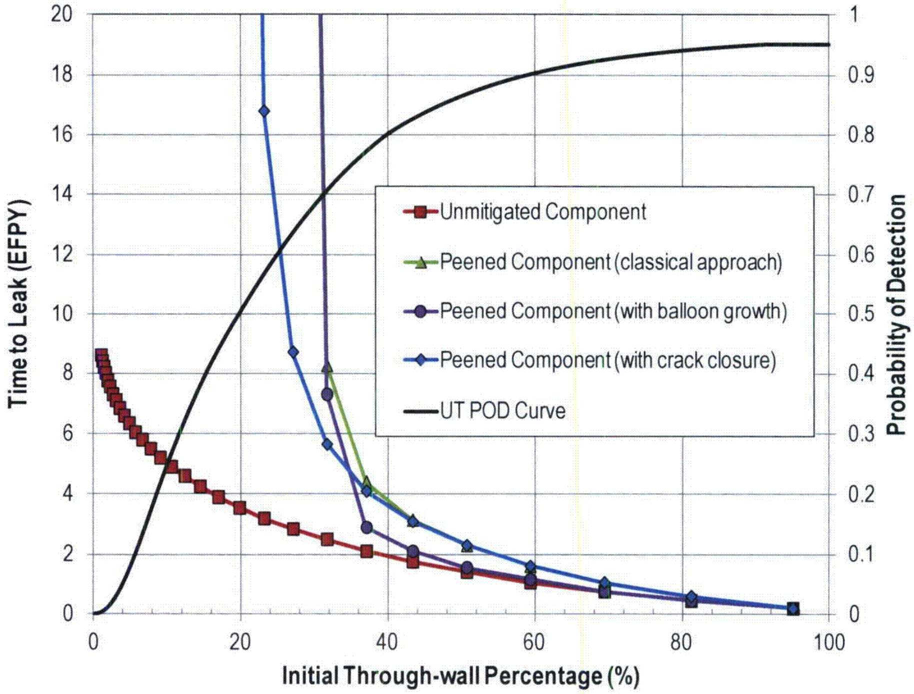

Figure 5-24
Time to OD Nozzle Annulus vs. Initial Crack Depth for Axial Crack on Uphill Penetration Nozzle OD

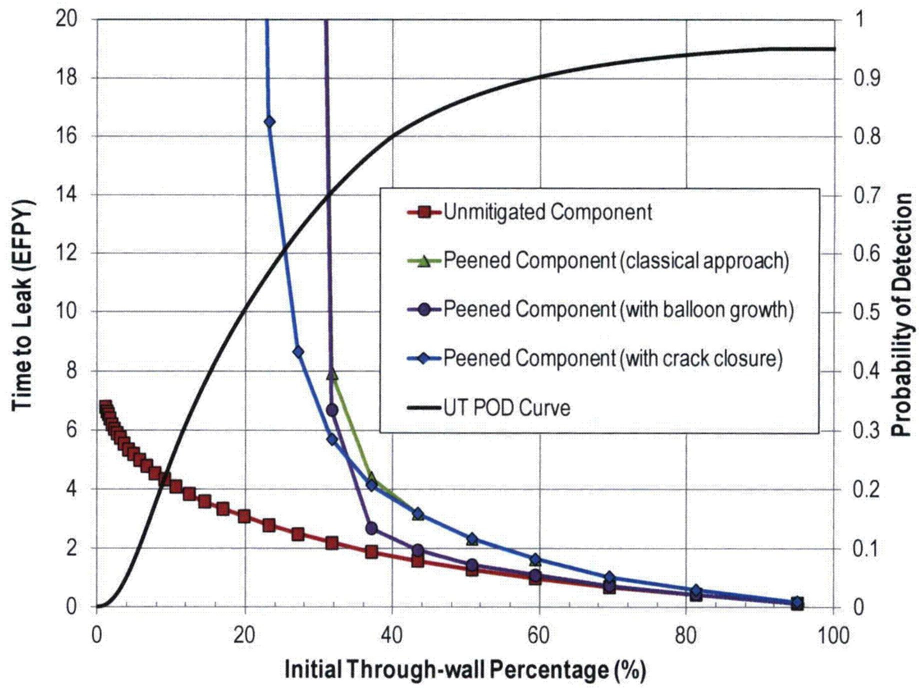

Figure 5-25
Time to OD Nozzle Annulus vs. Initial Crack Depth for Axial Crack on Downhill Penetration Nozzle OD

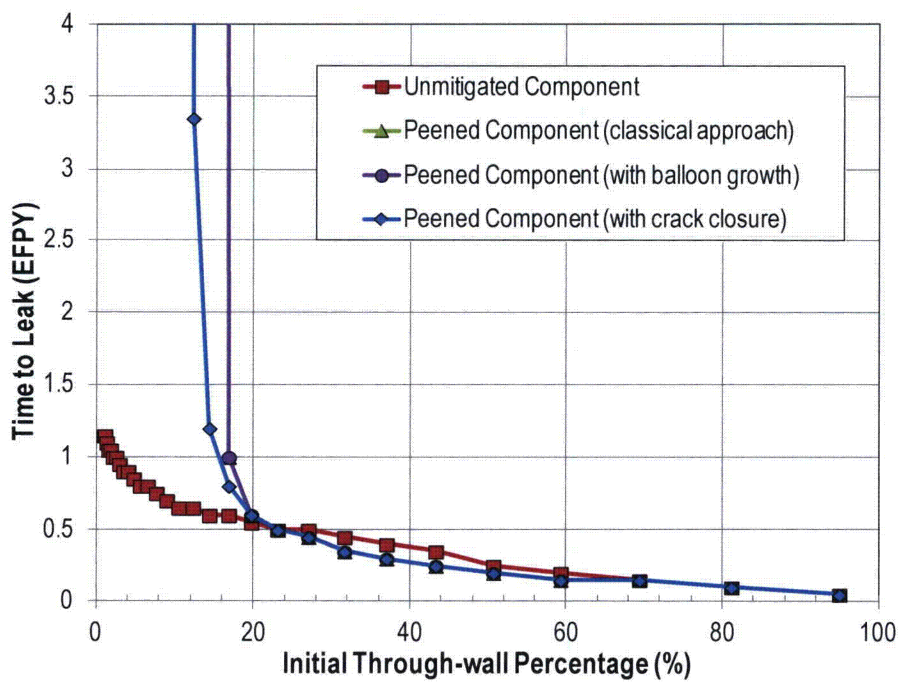

Figure 5-26
Time to Through-Weld Growth vs. Initial Crack Depth for Weld Crack on Uphill J-Groove Weld

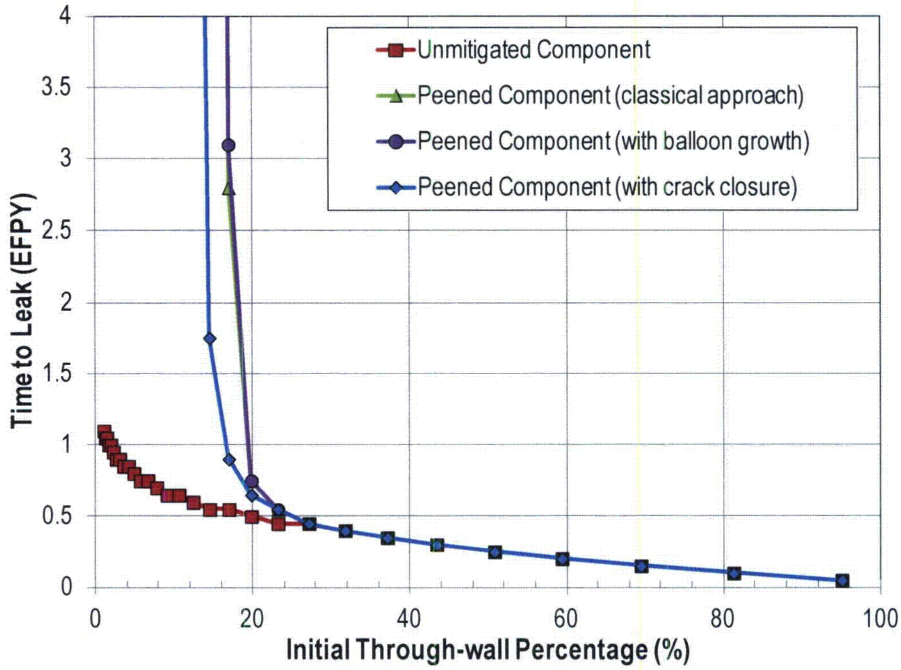

Figure 5-27
Time to Through-Weld Growth vs. Initial Crack Depth for Weld Crack on Downhill J-Groove Weld

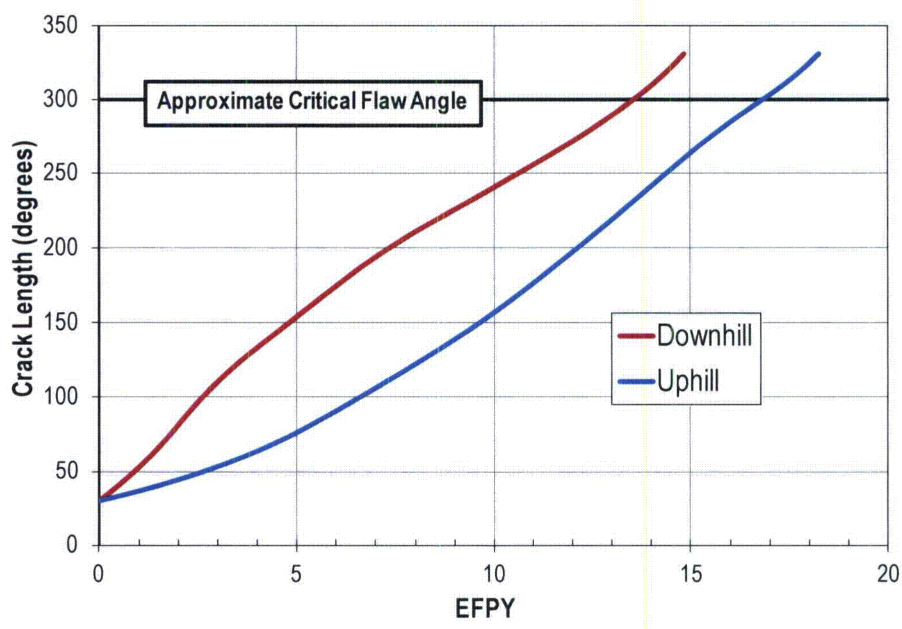

Figure 5-28
Crack Length vs. Time for Circumferential through-wall Cracks along the Weld Contour

5.2.3.3 Validation Study for the Weight Function Method Stress Intensity Factor Calculation

The weight function method for the calculation of crack stress intensity factors is detailed in appendix sections A.5 and B.5; especially section A.5.2. Like the classic influence coefficient method, this method relies on the superposition method of linear elastic fracture mechanics and a parameterized set of finite element results. However, the weight function method is more general than the influence coefficient method, allowing for the calculation of stress intensity factor in the presence of a stress profile with a general functional form (i.e., the functional form is not required to be a polynomial of some degree).

The weight function method demands substantial implementation effort and complexity, including numerical quadrature routines (or alternatively, analytical indefinite integration leading to complicated algebraic routines). To validate the weight function method implementation that is used to generate results in this report, the stress intensity factor calculation at the deepest crack point, for various crack sizes in the presence of a stress profile typical of a peened component (thickness of 69.9 mm; compressive layer depth of 1 mm; surface stress of -600 MPa), was performed and compared to FEA Crack [20] solutions for identical cracks in the presence of identical stress profiles. The results of this validation study are depicted in Figure 5-29.

As shown, as the crack depth gets closer to the compressive layer depth, the classical weight function method (i.e., no accounting for the balancing effects of partial crack closure) underestimates the stress intensity factor at the deepest crack point. When partial crack closure is accounted for, the largest observed relative error (as compared to the FEA solution) is 3.9% across cracks between 2.5% and 30% through-wall with aspect ratios of 2 or 40. This degree of agreement between the analytical methods and FEA results is considered adequate for the purposes of this report.

Further details to demonstrate sound implementation of the stress intensity factor calculation methodology are withheld here. More rigorous stress intensity factor calculation validation has been performed and is documented internally.

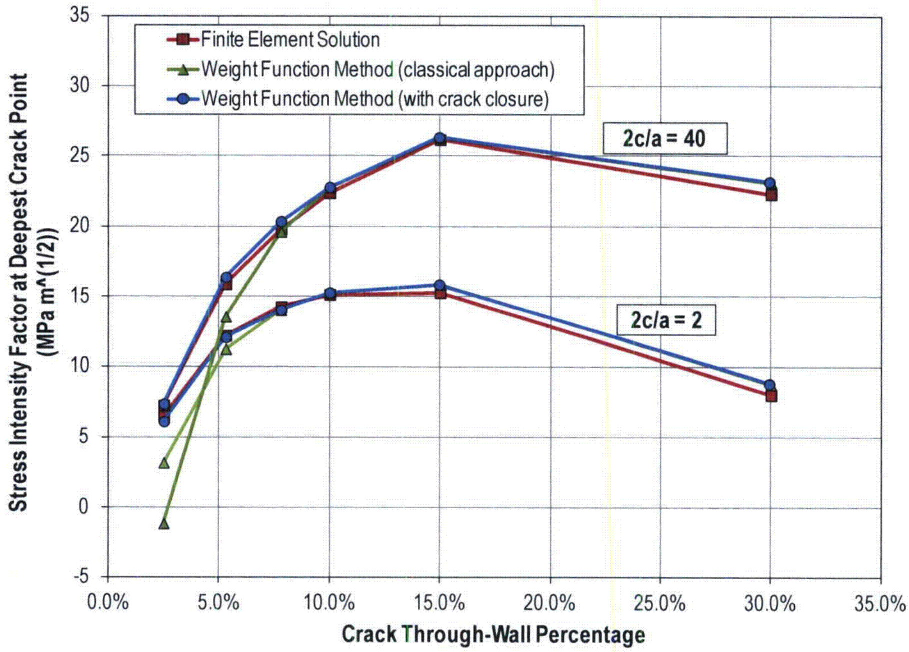

Figure 5-29
Results of Stress Intensity Factor Calculation Method Validation Study

5.3 Probabilistic Analysis of Peening Effects

The probabilistic analyses of PWSCC in DMWs and RPVHPNs are discussed in the following sections. For both component types, a unique integrated probabilistic model has been developed that is capable of accepting plant- and industry-specific inputs (distributed or deterministic), conducting lifetime analysis of PWSCC manifesting in various forms at various locations, and returning statistics to describe the risks of key failure modes (e.g., leakage and/or rupture).

The integrated probabilistic models include modules for simulating component loading and stress, PWSCC initiation, PWSCC growth, flaw examination, etc. All modules have been augmented to include special considerations for peening such that failure risks may be predicted, compared, and contrasted for unmitigated and peened components.

5.3.1 Dissimilar Metal Welds (DMWs)

The reader is directed to Appendix A for a detailed description of the DMW PWSCC integrated probabilistic model, including example analyses and results. Figure A-1 and Figure A-2 give flow diagrams to concisely describe the DMW program.

Figure 5-30 provides an important example result depicting cumulative leakage probability versus post-peening inspection schedule characteristics (i.e., the

number of cycles between peening and the follow-up inspection; the in-service inspection frequency) for a hot leg DMW component.

For both the hot and cold DM weld components, the predicted likelihood of cracks existing after the pre-peening inspection was very low; less than 3E-04. The probability of leakage after the follow-up inspection was predicted to be substantially lower; less than 7E-05 in all cases. This result predicted that a majority of the leakage risk would be compounded between the application of peening and the follow-up inspection.

For the RVON, the program predicted that the cumulative probability of leakage after peening would be reduced by a factor between 120 and 200, (compared to cumulative leakage probabilities on same span of time for an unmitigated RVON). While there is some small trend with respect to follow-up time, in general the degree of improvement was not significantly influenced by the follow-up time or the ISI frequency. The former is the result of the fact that most of the cracks that go undetected at the pre-peening inspection are small, and accordingly grow slowly after peening (see deterministic calculations that demonstrate this in Section 5.2); the latter is a result of the fact that nearly all cracks are detected during the pre-peening or follow-up inspection and no new cracks are expected to initiate after peening.

For the RCP nozzle, the program predicted that the cumulative probability of leakage after peening would be reduced by a factor between 9 and 12, (compared to cumulative leakage probabilities on same span of time for an unmitigated RCP nozzle). This degree of improvement is smaller than that predicted for the hot leg component because the inspection schedule for an unmitigated cold leg component conservatively takes little credit for its reduced temperature in comparison to that for hot-leg locations.

5.3.2 Reactor Pressure Vessel Head Penetration Nozzles (RPVHPNs)

The reader is directed to Appendix B for a detailed description of the RPVHPN PWSCC integrated probabilistic model, including example analyses and results. Figure B-2 and Figure B-3 give flow diagrams to concisely describe the DMW program.

Figure 5-31 provides an important example result depicting cumulative leakage probability versus post-peening inspection schedule characteristics (i.e., the number of cycles between peening and the follow-up inspection; the in-service inspection frequency) for a hot reactor head. Figure 5-32 provides an important example result depicting average ejection frequency versus post-peening inspection schedule characteristics for a hot reactor head.

The RPVHPN results demonstrated a larger trend with respect to the ISI frequency than the DM weld results. This is due in large part to the higher likelihood of cracks existing after the pre-peening inspection. It was predicted that one in approximately 800 cold heads and one in approximately 200 hot reactor heads would have unrepaired cracks after the pre-peening inspection.

For both the cold and hot reactor heads, the cumulative probability of leakage after peening was predicted to be reduced by a factor between 7 and 14 times, depending on the post-peening schedule. For example, using a ten-year (one interval) UT inspection frequency, the cumulative probability of leakage after peening was predicted to decrease by a factor of approximately 11.

For the cold head reactor, the AEF after peening was predicted to improve compared to the unmitigated case when a post-peening ISI frequency of every ten years (one interval) was used. A post-peening ISI of two intervals resulted in similar ejection risks compared to the unmitigated case: 157%, 97%, and 90% of the unmitigated risk for follow-up inspections scheduled one, two, and three cycles after peening, respectively. This result suggests that it may be beneficial to delay the follow-up inspection to allow more significant cracks to grow such that they are more easily detected at the follow-up inspection, i.e., before entering the ISI schedule.

For the hot head reactor, the AEF after peening was predicted to improve compared to the unmitigated case when using a follow-up time of one or two cycles after peening and a post-peening ISI inspection interval of 3 two-year cycles. Using a post-peening ISI interval of ten years (1 interval) with a follow-up time of one or two cycles after peening resulted in similar ejection risks compared to the unmitigated case: 102% and 132% of the unmitigated reactor head risk, for follow-up inspections scheduled one and two cycles after peening, respectively.

It is important to consider the maximum incremental frequency of ejection (IEF) for any cycle, in addition to the AEF, in order to understand how concentrated the risk may be over particular spans of time and if there are particular cycles with considerably higher risk. For instance, for a peened cold reactor head (with a follow-up inspection two cycles after peening and an ISI interval of 10 cycles), the ratio of maximum IEF to AEF was 3.05. The same ratio for the unmitigated cold reactor head was 2.36. For a peened hot reactor head (with a follow-up inspection one cycle after peening and an ISI interval of 5 cycles), the ratio of maximum IEF to AEF was 2.56. The same ratio for the unmitigated hot reactor head was 1.38. The risk concentration was not substantially worse for the peened case than for the unmitigated case.

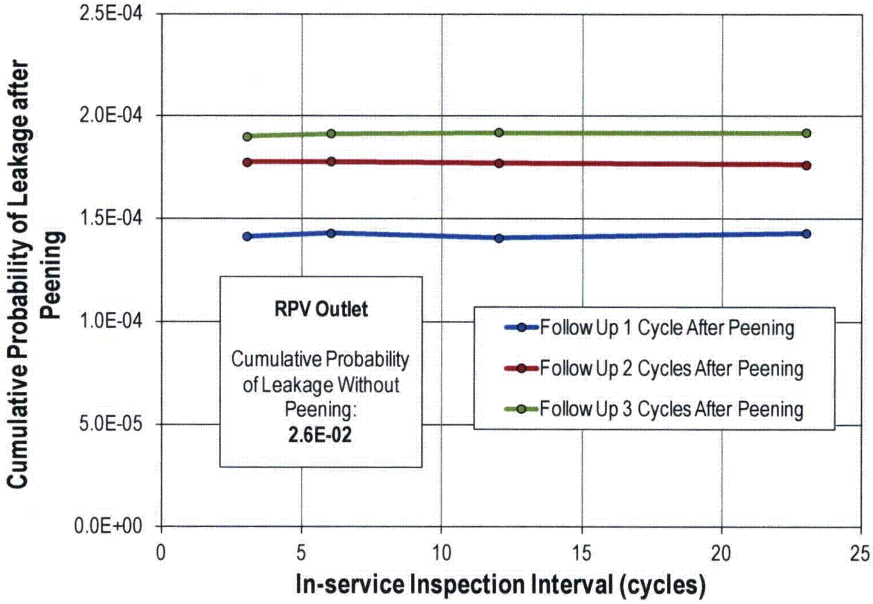

Figure 5-30
Cumulative Probability of Leakage after Hypothetical Time of Peening vs. ISI Frequency for a RVON

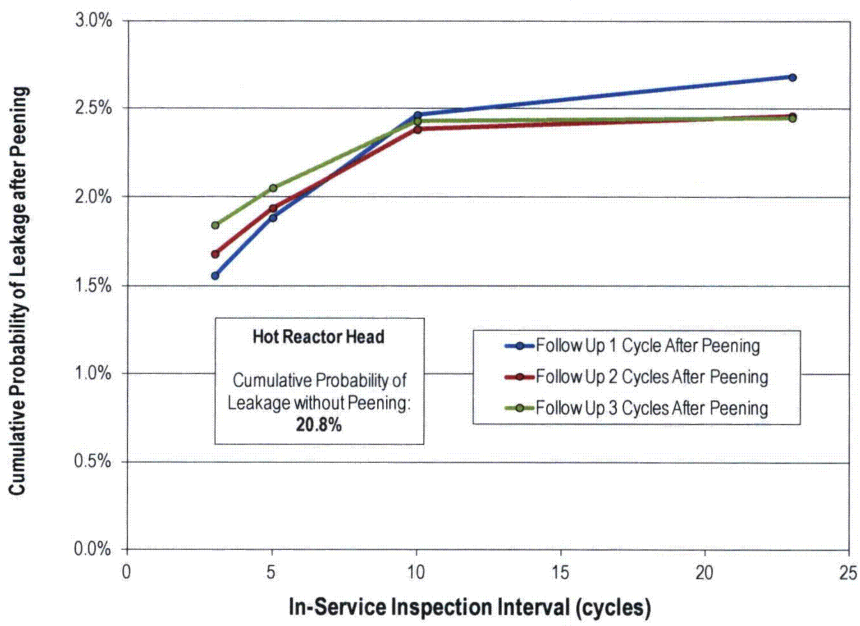

Figure 5-31
Cumulative Probability of Leakage after Hypothetical Time of Peening vs. ISI Frequency for Hot Reactor Head

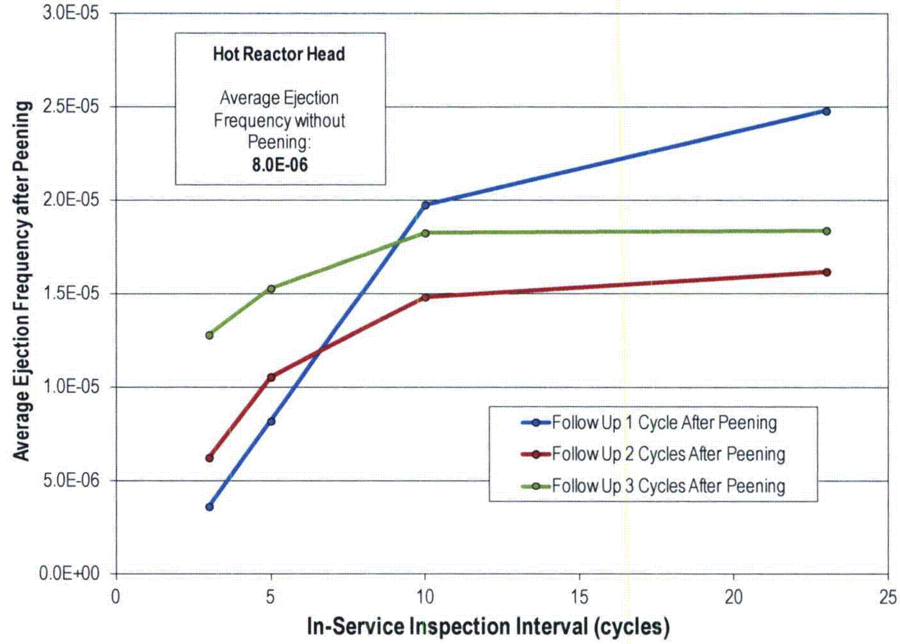

Figure 5-32
Average Ejection Frequency after Hypothetical Time of Peening vs. ISI Frequency for Hot Reactor Head

5.4 Conclusions

Peening imparts a compressive layer near the surface where it is applied. The impact of this compressive layer on PWSCC has been studied using deterministic and probabilistic analyses.

The effect of peening on PWSCC on Alloy 600/82/182 components is modeled in the following key ways:

- No new PWSCC initiation is allowed to occur on a surface after peening application. In other words, there is high confidence, for all component locations studied in this report, that the combination of worst-case (low) compressive peening surface stress, worst-case (high) tensile operating loads, and worst-case (high) residual stress relaxation do not result in a surface stress with a tensile magnitude greater than approximately 20 ksi (which is considered the threshold for PWSCC to form [11]). In fact, the likelihood of not achieving compression at or near a peened surface during operation is low.[9]

[9] It is noted that ALP without a sacrificial ablative layer results in a very thin (~15 μm) layer of high tension at the component surface. As discussed in MRP-267R1, these stresses rapidly decrease to highly compressive values within about 35 μm. The stresses then remain compressive until at least a depth of 1.5 mm. This very thin region of tensile stress is not reflected in the detailed probabilistic model in this study but is not expected to have any significant effect since the high compressive stresses just below this thin layer will dominate the stress intensity factor at the tips of any cracks and thus also control crack growth behavior.

- Cracks present at the time of peening that have depths less than the compressive layer imparted by peening are assumed to be arrested. Such cracks are not acted on by tensile stresses.
- Cracks present at the time of peening that have depths greater than the compressive layer imparted by peening continue to grow, but at a generally slower rate. The deterministic calculations in Section 5.2 detail the ability of peening to slow crack growth for cracks of various sizes and shapes.
- After peening application, components may be eligible for a new, relieved inspection schedule. Flexibility is built into the integrated modeling framework to allow the investigation of such new inspection schedules.

The deterministic analyses presented in this chapter support the efficacy of peening to slow crack growth, especially for cracks with depths similar to the compressive layer imparted by peening. As expected, peening is generally ineffective for large cracks (50%-100% through-wall). Balloon crack growth, i.e., length growth below the peening layer, is predicted to compromise the effectiveness of peening significantly for cracks more than twice the depth of the compressive stress layer.

Comparison of peening depths and POD curves reveals a range of cracks sizes that are likely to be missed during inspection but would continue to grow at approximately the same rate as prior to peening, and could result in leaking. Such cracks are key in the risks predicted after peening by the probabilistic model.

The results predicted with the probabilistic models presented in this chapter, and detailed in Appendix A and Appendix B, support the inspection requirements listed in Section 4 for use with peened Alloy 82/182 DMWs and RPVHPNs in primary system piping:

- Alloy 82/182 DMWs: The results of Appendix A show that peening mitigation with assumed inspections consistent with those specified in Section 4 results in a relatively large reduction in the probability/frequency of leakage (i.e., through-wall crack penetration). The benefit shown is greater for the case of DMWs operating at reactor hot-leg temperature. The probability of leakage is an appropriate surrogate for the rupture frequency because, as is the case for leakage, relatively large flaws must be produced in order for a rupture to occur. Similarly, leakage is a necessary precursor for any concern for boric acid corrosion of the outside of the primary pressure boundary. The large reduction in leakage probability with peening (roughly between a factor of 10 and 150) supports the conclusion that rupture frequency (and boric acid wastage potential) is also reduced through the program of peening with the reduced frequency inspections specified in Section 4.
- Alloy 600 RPVHPNs: The results of Appendix B show that peening mitigation with assumed inspections consistent with those specified in Section 4 results in an average nozzle ejection frequency (roughly 1×10^{-5} per reactor year or less) that is well below the level resulting in a core damage frequency of 1×10^{-6} per reactor year, the criterion of NRC

Regulatory Guide 1.174 for permanent changes in plant equipment, etc. (see appendix Section B.7). In addition, the peak nozzle ejection frequency calculated in Appendix B is acceptably larger than (only 2-3 times) the average value. Thus, the peening mitigation in combination with the inspection requirements defined in Section 4 are concluded to maintain the appropriate level of nuclear safety. Furthermore, the peening cases of Appendix B were shown to approximately maintain the average nozzle ejection frequency compared to the case of no mitigation and inspection performed per the requirements of 10 CFR 50.55a and N-729-1. Thus, the inspection requirements developed for use with peening mitigation are acceptable from both absolute and risk-neutral risk perspectives.

Lastly, cumulative probability of nozzle leakage (after peening) is reduced by a factor of roughly 10 for the case of peening mitigation compared to the no mitigation case. This demonstrates that the concern for boric acid corrosion of the low-alloy steel head material, as well as defense-in-depth support, is addressed by the required program of peening mitigation and inspections defined in Section 4 (which maintains the same periodic direct visual examinations as without mitigation).

These conclusions are maintained despite the following key conservatisms:

- No credit is given to peening for slowing the growth of through-wall circumferential cracks along the weld contour of RPVHPNs.
- A through-wall 30° circumferential flaw located at the top of the weld is assumed to be produced immediately upon nozzle leakage (i.e., through-wall cracking to the nozzle annulus). This assumption was maintained from the approach taken in MRP-105 [18] as part of the technical basis for the inspection requirements for unmitigated RPVHPNs in N-729-1 [2]. In most cases, circumferential cracking in the nozzle tube at or near the top of the weld has not been detected for leaking RPVHPNs [15].
- No credit is given to peening for slowing the growth of axial through-wall cracks growing toward the OD annulus from the below the J-groove weld on RPVHPNs.
- Growth under the peening layer, which may manifest as balloon crack growth, is given full credit by neglecting peening stresses for the calculation of surface growth of cracks.
- For the base case, surface ET inspection is not modeled at the pre-inspection prior to entering the relieved inspection schedule.

Section 6 Conclusions

6.1 Bases for effectiveness of peening

The main bases for concluding that peening can serve as an effective SSI mitigation method against PWSCC at Alloy 82/182 DM welds and at Alloy 600 RPVHPNs are as follows:

- There is extensive industrial experience that shows that peening of many types is effective at inhibiting the initiation of both fatigue and stress corrosion cracks. For this reason, peening of many types is used in various industrial applications to improve resistance to these modes of cracking.
- Over 25 years of service experience with shot peening of steam generator tubes has shown that the peening provides large benefits with regard to mitigation of PWSCC of the tubes.
- The deterministic and probabilistic analyses discussed in Section 5 and Appendix A and Appendix B conservatively model the effects of peening on PWSCC. These analyses show that the peening provides large benefits in terms of preventing initiation of new PWSCC and arresting the growth of shallow cracks that could be present after pre-peening inspections and repairs.
- As described in MRP-267R1 [5], extensive laboratory tests have been performed of samples exposed to the ULP and WJP processes being considered for use on DMWs and RPVHPNs. These tests have shown that these peening processes do not result in growth of any pre-existing flaws during peening, and that they prevent growth of flaws with depths less than the depth of the compressive stress field developed by peening. Demonstration testing of the ALP process is not as complete as for the ULP and WJP processes, but results are encouraging thus far. Its successful use in other critical industrial applications also indicates that it will be successful in PWSCC mitigation applications.
- As stated in MRP-267R1 [5], the ULP and WJP processes are considered to be demonstrated for the large-diameter piping DMW and PWR reactor vessel bottom-mounted nozzle (BMN) geometries. The BMN geometry is generally considered to bound the RPVHPN geometry, although, unlike the top head, the bottom head is normally in an underwater environment during maintenance activities. As of summer 2012, additional work including testing on mockups representative of actual PWR component geometries is necessary to demonstrate the ALP process for mitigation of PWSCC in PWRs.

6.2 Bases for no unacceptable side effects

The bases for concluding that SSI using the peening methods discussed in this report will not cause unacceptable side effects in U.S. PWRs are reviewed in Section 2.3. In summary, these bases are as follows:

- WJP and ULP have been extensively used in Japanese PWRs and BWRs for 13 years with no reported unacceptable side effects to the peened parts. However, in Japanese BWRs, there have been flow induced vibration (FIV) failures of nozzles and instrument lines located close to the peened areas, as noted in MRP-267R1 [5]. In response to the FIV problems, the Japanese have instituted pre-peening evaluations to ensure that such problems do not occur and have also instituted post-peening inspections to verify that problems did not occur. Based on this experience, this document requires evaluations to identify susceptibility to FIV, and if susceptible, require post-peening inspections to verify that problems did not occur.
- Extensive testing, including examination of many peened samples and mockups, has been performed of the WJP and ULP processes as described in MRP-267R1 [5]. No unacceptable side effects have been identified in this testing.
- Shot peening has been widely used since the mid-1980s in steam generator tubes as a PWSCC mitigation method, and has not resulted in any unacceptable side effects. The peened surfaces have not experienced unusual corrosion nor have they interfered with normal eddy current test inspections and occasional ultrasonic inspections.

Testing of the ALP process is not complete, and there has not been any experience with using this method in PWR or BWR reactor coolant applications. Thus, conclusive statements about its possible side effects in PWR applications cannot be made at this time. However, the fact that it is widely and successfully used in critical aerospace applications as discussed in MRP-267R1 [5] indicates that unacceptable side effects are unlikely.

6.3 Bases for appropriate relaxation of inspection requirements after peening

Appropriate relaxed in-service inspection requirements for Alloy 82/182 DMWs and Alloy 600 RPVHPNs that have been mitigated by peening are shown in Table 4-1. The main bases for concluding that the defined relaxations of the in-service inspection requirements are appropriate are as follows:

- The probabilistic analyses discussed in Section 5 and Appendix A and Appendix B show that risks of leakage and nozzle ejection are reduced or similar for mitigated components inspected at the relaxed schedule in comparison to them for unmitigated components inspected at currently required schedules.
- The probabilistic analyses include significant conservatisms such that the benefits of peening tend to be under predicted. This provides confidence that

the combination of SSI using peening coupled with the relaxed schedule for inspections will ensure that nuclear safety is maintained.

6.4 Application-specific information supporting inspection relief

The following technical information shall be developed by the licensee to support inspection relief based on surface stress improvement achieved by the peening processes discussed in this report:

- Identification of the components to be given surface stress improvement peening treatments, together with identification of the specific areas to be treated.
- Identification of the specific processes that will be used for each area of each component.
- Discussion of how the specific processes that will be used have been demonstrated to be effective with no unacceptable side effects per the criteria discussed in this report. It is assumed that this discussion will rely heavily on MRP-267R1 [5] and on this MRP-335 report, i.e., will indicate that the processes to be used are within the ranges of the parameters shown to be effective and to not result in undesirable side effects in MRP-267R1 and MRP-335. If any process parameters are outside the ranges qualified per these reports, they shall be identified and justified.
- Plant- and application-specific assessment of the potential for fatigue crack growth of shallow flaws located in the peening compressive residual stress zone. As discussed in Section 3.1, fatigue effects due to cyclic stresses could possibly act to cause growth of cracks that are too shallow to grow by PWSCC. The fatigue assessment shall consider the applied stress cycles that occur at the specific location, in combination with the levels of compressive stress expected from the selected peening method (adjusted for temperature and load cycling induced relaxation). If the compressive stresses from peening are sufficient to always keep the stress intensity factor at the crack tip negative, then no fatigue-induced crack growth will occur. However, if the stress intensity factor becomes positive for some part of the stress cycle, then some crack growth could occur, but less than would occur in the absence of peening. The purpose of the fatigue assessment is to show that the relaxed schedule of in-service inspections following peening is sufficient to address this potential concern. Finally, note that fatigue growth of shallow flaws is not expected to be a concern for RPVHPNs because of the relatively low cyclic stresses at these nozzles.
- Identification of the specific changes in inspection requirements that are requested based on application of surface stress improvement by peening.

Section 7 References

1. ASME Code Case N-770-1, "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," Section XI, Division 1, American Society of Mechanical Engineers, New York, Approval Date: December 25, 2009.
2. ASME Code Case N-729-1, "Alternative Examination Requirements for PWR Reactor Vessel Upper Heads With Nozzles Having Pressure-Retaining Partial-Penetration Welds," Section XI, Division 1, American Society of Mechanical Engineers, New York, Approval Date: March 28, 2006.
3. ASME Code Case N-722-1, "Additional Examinations for PWR Pressure Retaining Welds in Class 1 Components Fabricated with Alloy 600/182/82 Materials," Section XI, Division 1, American Society of Mechanical Engineers, New York, Approval Date: January 26, 2009.
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15. *Materials Reliability Program: Reactor Vessel Closure Head Penetration Safety Assessment for U.S. PWR Plants (MRP-110): Evaluations Supporting the MRP Inspection Plan*, EPRI, Palo Alto, CA: 2004. 1009807.

16. *Materials Reliability Program: Reactor Vessel Head Nozzle and Weld Safety Assessment (MRP-103)*, EPRI, Palo Alto, CA: 2004. 1009402.

17. *Materials Reliability Program: RV Head Nozzle and Weld Safety Assessment for Westinghouse and Combustion Engineering Plants (MRP-104)*, EPRI, Palo Alto, CA: 2004. 1009403.

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19. *Materials Reliability Program: Development of Probability of Detection Curves for Ultrasonic Examination of Dissimilar Metal Welds (MRP-262, Revision 1) – Typical PWR Leak-Before-Break Line Locations*, EPRI, Palo Alto, CA: 2009. 1020451.

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