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Materials Reliability Program: Topical Report for Primary Water Stress Corrosion Cracking Mitigation by Surface Stress Improvement (MRP-335 Revision 2)

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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 (PWSCC). These requirements apply in the case that relaxation of the applicable inspection requirements for unmitigated components is sought. The requirements of this report are generally not applicable in the case that peening is performed for asset management without request for inspection relief.

Given the demonstrated effectiveness of SSI techniques such as laser peening and water jet peening (aka cavitation 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 assume that the peening process meets applicable minimum performance criteria. The performance criteria are defined, and their technical bases are discussed.

Because the inspection requirements for these components are prescribed by U.S. 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 topical report in support of site-specific relief requests.

Keywords
Alloy 600
Cavitation peening
Laser peening
Mitigation
Primary water stress corrosion cracking (PWSCC)
Relief requests
Surface stress improvement
Water jet peening

ACRONYMS

AEF	Average Ejection Frequency
AHA	Auxiliary Head Adapter
ALF	Average Leakage Frequency
ASME	American Society of Mechanical Engineers
AWJ	Abrasive Water Jet
BMV	Bare Metal Visual
BPVC	[ASME] Boiler and Pressure Vessel Code
BWR	Boiling Water Reactor
CCDP	Conditional Core Damage Probability
CE	Combustion Engineering
CEDM	Control Element Drive Mechanism
CFR	Code of Federal Regulations
CGR	Crack Growth Rate
CPE	Cumulative Probability of Ejection
CPL	Cumulative Probability of Leakage
CRDM	Control Rod Drive Mechanism
DEI	Dominion Engineering, Inc.
DM	Dissimilar Metal [Weld]
DMW	Dissimilar Metal Weld
EDY	Effective Degradation Year
EFPY	Effective Full Power Year
EOC	End of Cycle
EPRI	Electric Power Research Institute
ET	Eddy Current Testing
FEA	Finite Element Analysis

ICI	In-Core Instrumentation
ID	Inner Diameter
IEF	Incremental Ejection Frequency
ILF	Incremental Leakage Frequency
ISI	In-Service Inspection
LP	Laser Peening
MC	Monte Carlo
MLE	Maximum Likelihood Estimator
MRP	[EPRI] Materials Reliability Program
NDE	Non-Destructive Examination
NRC	Nuclear Regulatory Commission
OD	Outer Diameter
PDI	Performance Demonstration Initiative
POD	Probability of Detection
PPRS	Post-Peening Residual Stress
PT	[Liquid] Penetrant Testing
PWR	Pressurized Water Reactor
PWSCC	Primary Water Stress Corrosion Cracking
QA	Quality Assurance
QC	Quality Control
RCP	Reactor Coolant Pump
RIY	Re-Inspection Years, parameter defined by ASME Code Case N-729-1
RPVHPN	Reactor Pressure Vessel Head Penetration Nozzle
RVIN	Reactor Vessel Inlet Nozzle
RVON	Reactor Vessel Outlet Nozzle
SCC	Stress Corrosion Cracking
SSI	Surface Stress Improvement
TW	Through-Wall
UT	Ultrasonic Testing
WJP	Water Jet Peening
WRC	Welding Research Council

WRS	Welding Residual Stress
xLPR	Extremely Low Probability of Rupture [Software]
VE	Direct visual examination of the external metal surface for evidence of leakage, as defined by ASME Code Case N-770-1 for Alloy 82/182 piping butt welds and ASME Code Case N-729-1 for reactor vessel upper heads
VT-2	Visual examination meeting the requirements of ASME Section XI IWA-2212

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1 INTRODUCTION

1.1 Objective

The objective of this report is to present the technical bases for relaxation of inspection requirements based on the surface stress improvement (SSI) provided by peening applied for the purpose of mitigating primary water stress corrosion cracking (PWSCC). For any peening process meeting the applicable performance criteria, this report specifies appropriate inspection requirements and intervals for Alloy 600 reactor pressure vessel head penetration nozzles (RPVHPNs) and for Alloy 82/182 dissimilar metal butt welds (DMWs[1]) in primary system piping that have been treated by SSI methods (that is, peening) for the purpose of mitigating PWSCC. The deterministic and probabilistic calculations herein show that, given an SSI process that meets the applicable performance criteria, relaxation of the inspection intervals for these components is justified after SSI treatment.

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 topical report to provide part of the technical basis for site-specific relief requests. The relaxed inspection intervals and the performance criteria are developed to credit the performance of peening within the framework of the respective Code Cases upon which existing inspection requirements are based. This report may also serve as the technical basis for revision of the respective Code Cases to credit peening.

This topical report specifies requirements that apply in the case that relaxation of the applicable inspection requirements for unmitigated components is sought. The requirements of this report are generally not applicable in the case that peening is performed for asset management without request for inspection relief.

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) and 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)

[1] The term "DMW" is used throughout this report to refer specifically to Alloy 82/182 dissimilar metal butt welds located in PWR primary system piping and falling under the scope of Table 1 of ASME Code Case N-770-1 [1].

through 10 CFR 50.55a.[2] Later versions of these Code Cases have been prepared but have not as yet been accepted by the NRC. Acceptance of this document is not predicated on the review or acceptance of updated versions of these Code Cases, and any mentions of the updated revisions are for information only. The most recent version of the DMW code case (N-770-4) covers the situation where PWSCC has been mitigated using surface stress improvement (SSI) by peening. None of the versions of the RPVHPN code case (N-729, -1, -2, -3, or -4) cover situations where PWSCC has been mitigated by stress relief methods.

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, 82, and/or 182 are the shortest, while intervals for components made with PWSCC-resistant materials are longer. Intervals for components made with Alloys 600, 82, and/or 182 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 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 a peening technique that meets the specified performance criteria. 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 application of a peening technique meeting the specified performance criteria. Peening is effective in mitigating PWSCC by preventing PWSCC crack initiation and arresting growth of shallow flaws located in the surface compressive stress zone where present. Any pre-existing flaws that are not arrested are addressed through the combination of pre-peening and follow-up examinations. 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. The probabilistic and deterministic analyses are performed using bounding stress conditions meeting the peening performance criteria.

Consequently, 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.

1.4 Locations and Peening Methods Addressed

The inspection requirements in this report apply to any peening process meeting the performance criteria specified in Section 4 at the following locations:

- The inner diameter (ID) surfaces of DMW butt welds in PWR reactor coolant system piping.

[2] 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 susceptible surfaces of RPVHPNs:
  - The nozzle ID surfaces of RPVHPNs in the area with high weld residual stresses due to the presence of the J-groove attachment weld.
  - The nozzle outer diameter (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 summarized below in Table 1-1. The table includes the section number of the report and section title where requirements are located. These requirements apply in the case that relaxation of the applicable inspection requirements for unmitigated components is sought. These requirements are generally not applicable in the case that peening is performed for asset management without request for inspection relief.

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

Report Location	Report Section	Summary of Requirements
Section 2.1	Quality Assurance Considerations	This section requires SSI to be performed in accordance with a quality assurance program meeting the requirements of Appendix B to 10 CFR 50 (including the "Control of Special Processes" criterion) and the utility's plant specific commitments.
Table 4-2	List of Requirements in Section 4.2 within the Context of N-770-1	Table 4-2 lists the requirements that are present within Section 4.2 and references Table 4-1. Table 4-1 defines the inspection requirements for Alloy 82/182 DMWs before and after application of peening per the performance criteria required by Section 4.2.8. The performance criteria specify the required minimum nominal depth of the compressive residual stress produced by the peening treatment as well as the analyses or demonstrations that are to be performed.
Table 4-4	List of Requirements in Section 4.3 within the Context of N-729-1	Table 4-4 lists the requirements that are present within Section 4.3 and references Table 4-3. Table 4-3 defines the inspection requirements for RPVHPNs with Alloy 600/82/182 materials before and after application of peening per the performance criteria required by Section 4.3.8. The performance criteria specify the required minimum nominal depth of the compressive residual stress produced by the peening treatment as well as the analyses or demonstrations that are to be performed.
Section 6.3	Application-Specific Information Supporting Inspection Relief	This section lists technical information that shall be included in the relief request and lists additional technical information that shall be included in the peening qualification report. This section also requires a post-peening report to be produced documenting the performance of peening.

1.6 Report Organization

This report is organized as follows:

- This Section 1 describes the purpose of the report, the approach used, and how it is organized. It also includes a table identifying the locations where the specific requirements for crediting peening mitigation of Alloy 600/82/182 components in PWRs are located.
- Section 2 describes how the effectiveness of peening as a PWSCC mitigation measure, without adverse effects, is ensured by meeting the performance criteria contained in Section 4. It also provides requirements for the performance of peening under appropriate quality assurance programs.
- Section 3 supports the development of technical bases to demonstrate that peening processes such as those described in MRP-267R1 [4] meet the performance criteria. The extensive test data and experience documented in MRP-267R1 [4] support the effectiveness of the laser peening and water jet (aka cavitation) peening methods described in that report to mitigate PWSCC.
- Section 4 defines appropriate inspection requirements and intervals for use with peening mitigation of Alloy 82/182 dissimilar metal butt welds in PWR primary system piping and Alloy 600 RPVHPNs. Section 4 also specifies the performance criteria that a peening process shall meet to permit use of the relaxed inspection intervals specified in this report.
- 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 a peening process meeting the specified performance criteria will be effective as a PWSCC mitigation measure without any adverse effects. It then summarizes the bases that support appropriate relaxation of inspection requirements for components that have been peened. Section 6.3 lists the application-specific information needed to support inspection relief.
- 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 pressure boundary rupture are reduced for mitigated components inspected at certain relaxed intervals in comparison to the risks for unmitigated components inspected at the currently required intervals for unmitigated components.
- Appendix C presents the methods and results of an investigation of the magnitude and distribution of tensile stresses developed in response to the peening compressive stresses produced at the treated surface. The technical literature on this subject and the analyses presented show that the peak residual tensile balancing stress is relatively small for the thick-wall components that are the subject of this report.

2
BASES FOR PERFORMANCE CRITERIA

This section describes how the effectiveness of peening as a PWSCC mitigation measure without adverse effects is assured by meeting the performance criteria specified in Section 4.2.8 and Section 4.3.8 of this report.

2.1 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.

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

Section III [5] and Section XI [6] of the ASME Code have 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 applicable to peening processes performed for the purpose of surface stress improvement.

Paragraph NB-4422, Peening, in Section III [5], 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 post weld heat treated." This limitation in the Code is clearly directed at control of the type of peening that is sometimes used to control distortion during the welding process (while the weld is cooling) [7], 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 [6]:

> "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."

IWA-4650, Butter Bead - Temper Bead Welding for Class MC and for Class CC Metallic Liners, Sub-section IWA-4651(g) [6] states that "Controlled peening of welds may be performed to

minimize distortion, provided it is also used on the welds made to qualify the welding procedure and the production test assembly. Peening shall not be used on the initial layer of the weld or on the final layer. If peening is used, it shall be considered as an essential variable in the welding procedure." IWA-4620, Temper Bead Welding of Similar Materials, Sub-section IWA-4621(c) [6] identifies that "Peening may be used except on the initial and final weld layers." These limitations are not applicable to peening for the purpose of SSI for the same reason as Paragraph NB-4422. This conclusion has been confirmed by the ASME Section XI Standards Committee in an inquiry response letter dated November 8, 2012 [9]:

> "Question: Does the prohibition of peening in IWA-4621(c) and IWA-4651(g) apply to peening of austenitic alloys?
>
> Answer: No."

Paragraph NB-4652 in Section III [5] 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.

2.3 Magnitude, Depth, and Coverage of Compressive Stresses

The performance criteria of Section 4.2.8 and of Section 4.3.8 specify the minimum magnitude and depth of compressive stresses that must be met by a peening process in order to apply the relaxed inspection intervals for peened components. A concise summary of the required stress effect is provided by Section 4.2.1 and Section 4.3.1.

The performance criteria require coverage of the entire wetted surface of Alloy 82/182 material (filler weld and butter), plus Alloy 600 base material if present, for DMWs and of the wetted surfaces of the attachment weld, butter, and nozzle base material for RPVHPNs where the residual plus normal operating stress exceeds +20 ksi (tensile) (+140 MPa).

The performance criteria include the requirement that the peening result in a steady-state surface stress within the region required to be peened including the effect of normal operating stress that is either compressive in the case of DMWs or no greater than +10 ksi (tensile) (+70 MPa) in the case of RPVHPNs. Because these stress levels are well below the threshold stress necessary for PWSCC initiation over plant time scales [8], peening meeting the performance criteria prevents subsequent PWSCC initiation. The probabilistic analyses in Section 5 (as detailed in Appendix A and Appendix B) credit the lack of future PWSCC initiation. These analyses assumed the limiting surface stress condition of compression (0 ksi) for DMWs and +10 ksi (tensile) for RPVHPNs based on the range of capabilities of peening mitigation processes available for these components. These analyses demonstrate that the peening residual plus normal operating surface stress conditions and the compressive residual stress depths specified in the performance criteria are effective and sufficient to justify the relaxed inspection intervals of Section 4.

The peened surface of the RPVHPN nozzle ID is required by 4.3.8 to have a compressive residual stress depth that is shallower than that required at other locations. The specific requirement is for a nominal compressive residual stress depth of at least 0.01 inch (0.25 mm). The effectiveness of this compressive residual stress depth to prevent crack initiation is supported by both laboratory testing and plant experience:

- Experience with the abrasive water jet conditioning process since it was qualified in the late 1990s shows that the compressive stresses it develops are sufficient to mitigate against the initiation of PWSCC. Abrasive water jet (AWJ) conditioning uses abrasive particles in a high-pressure water jet to remove a small layer of material and impart compressive residual stresses to a depth of about 0.010 inch (0.25 mm) in Alloy 600 base material and about 0.003 inch (0.08 mm) in Alloy 82/182 weld material [9]. In laboratory testing using thick-wall ring specimens of Alloy 600 [9], zero of six high stressed regions treated with AWJ were found with SCC after accelerated corrosion testing in simulated primary water at 399°C (750°F). Four regions were exposed for 2001 hours while two other regions were exposed for 1403 hours. This compares to eight of 30 untreated regions (control specimens) with SCC initiation exposed to 1300-2200 hours of accelerated corrosion testing. More than 123 RPVHPNs have been repaired using the ID temper bead technique since 2001—which includes abrasive water jet conditioning of the new mid-wall weldment—and 26 of these were still in service as of July 2010 (the rest were taken out of service by head replacement) [10]. Periodic UT examination of the repaired region is required to monitor the integrity of the repaired area (e.g., [11]). The ID temper bead process has been used extensively in the U.S. to repair CRDM nozzles, and no such cases have been identified in which new leaks or cracks were detected (see Section C.7 of MRP-110 [12]).
- Several hundred thousand steam generator tubes have been peened with experience extending more than 30 years, with generally satisfactory results [4]. The typical compressive residual stress depths generated (< 150 μm) are less than that required for the ID of RPVHPNs. Newly detectable cracks occurred in steam generators that had operated prior to peening (most likely due to low POD for flaws less than 500 μm in depth at the time of peening), but only small numbers of PWSCC cracks developed in units peened prior to service (in some cases, due to plastic strain from denting, but possibly due to manufacturing flaws in cases where denting was not present).

The use of a reduced nominal compressive residual stress depth for the inside surface of RPVHPNs is also supported by the plant experience that shows a low frequency of PWSCC indications detected at that location. This experience supports the lack of a requirement for a pre-peening surface examination on the nozzle ID surfaces (see also Section 2.5.4), as well. Plant experience with RPVHPNs [13] has demonstrated a low frequency of PWSCC on the nozzle ID, even for the most susceptible temperature and material conditions. PWSCC has been detected on the ID of CRDM/CEDM nozzles for only 3 of the 23 heads in the U.S. with reported PWSCC. Only about 15 of the approximate 184 CRDM/CEDM nozzles with detected PWSCC in the U.S. were reported to have PWSCC that originated on the nozzle ID. Furthermore, the probabilistic calculations explicitly model the possibility of pre-existing flaws that were too shallow at the time of the pre-peening UT to be detected, and none of the analysis cases of Section 5 (as detailed in Appendix A and Appendix B) take credit for any eddy current examinations.

2.3.1 Inhibition of PWSCC Initiation

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 a tensile stress of +20 ksi (+140 MPa) is a conservative lower bound of the stress level below which PWSCC initiation

will not occur during plant lifetimes [8].[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.

The following discusses the magnitude of operating stresses that are expected at the surface of each component, for which the compressive residual stress needs to account:

- 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).
- Based on extensive previous weld residual stress FEA work performed by the authors for CRDM/CEDM nozzles in many PWRs (see, e.g. [14]):
  - The peak applied stresses at the ID surfaces of RPVHPNs are relatively low, approximately between 15 and 25 ksi (103-172 MPa) or less.
  - The peak applied stresses at the OD surfaces of RPVHPNs, at either the weld or base material, are relatively low, 5 ksi (35 MPa) or less.

2.3.2 Inhibition of PWSCC Propagation

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 threshold stress intensity factor for SCC, K_{ISCC}, then crack growth will not occur. The threshold stress intensity factor for growth of PWSCC is generally thought to be about 5 to 9 MPa-m$^{1/2}$ (5 to 8 ksi-in$^{1/2}$) but is not well known. For simplicity and to be conservative, K_{ISCC} 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. The stress intensity factor is 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.

2.4 Sustainability of Compressive Stresses for Plant Lifetime

Section 4.2.8.2 and Section 4.3.8.2 require that the residual plus operating stress be maintained below a specified limit for at least the remaining service life of the component. As discussed above in Section 2.3, initiation of PWSCC will not occur during plant lifetimes if the peak stress at the wetted surface during normal operation is below the conservative "threshold" tensile stress of +20 ksi (+140 MPa). The performance criteria require that the peening process results in a stress during steady-state operation (i.e., the residual stress plus normal operating stress) within the area required to be peened that remains well below this conservative measure of the threshold

[3] The 20 ksi (140 MPa) threshold stress corresponds to about 80% of the lower bound yield strength for Alloy 600 materials at operating temperatures.

for at least the remaining service life of the component. The performance criteria require that the effects of both thermal stress relaxation and load cycling (i.e., shakedown) be considered.

Consequently, the compressive residual stresses produced by peening meeting the performance criteria are sufficient to prevent PWSCC crack initiation subsequent to peening for the remaining service life of the component.

2.5 Inspections and Inspectability of Peened Components

Surface stress improvement using peening coupled with examinations using performance demonstrated UT at relaxed schedules specified in Section 4 results in a reduced nuclear safety risk, as well as reduced probability of leakage, compared to the corresponding case for unmitigated components inspected according to standard inspection requirements and intervals. This is demonstrated by the probabilistic safety analyses presented in Appendix A and Appendix B and summarized in Section 5.3. Subsequent to peening mitigation, follow-up UT examinations and ongoing in-service UT examinations are required. Thus, the performance criteria include the requirement to maintain UT inspectability following peening. The same UT qualification requirements applicable to the unmitigated components also apply to the UT performed subsequent to peening.

The sensitivity of UT inspection methods as applied to DMWs in primary system piping and RPVHPNs is discussed in Section A.6 and B.6. 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 [15]. 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, conservatively low UT POD curves were developed for use in the probabilistic analyses of Appendix A and Appendix B based on current Performance Demonstration requirements.

2.5.1 Pre-Peening Inspection

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 DMWs be examined by ET. 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 are to be addressed prior to peening, as permitted by the requirements of Section 4.2.8 and Section 4.3.8.

2.5.2 Follow-Up Inspection(s)

Nevertheless, there is the possibility that some undetected flaws may remain after the pre-peening inspection. Growth of these cracks is controlled by the stress intensity factor at the crack tip, as discussed above in Section 2.3. 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. Under the conservative assumption that the residual plus normal operating stress is at the limit meeting the performance criteria of Section 4.2.8 or Section 4.3.8, a pre-existing flaw of any depth would be modeled to grow via PWSCC. The analyses of this report show that the required follow-up inspections are effective to address this possibility. As concluded in Section 5, the safety risks associated with growth of cracks in mitigated components inspected at the relaxed schedules specified in Section 4 are less than those for unmitigated components inspected at currently required schedules.

2.5.3 In-Service Inspections

The probabilistic safety analyses presented in Appendix A and Appendix B and summarized in Section 5.3 form the bases for the in-service inspection intervals and examination requirements of Table 4-1 and Table 4-3. These analyses show that peening meeting the applicable performance criteria in combination with the inspection requirements defined in Section 4 results in a reduced nuclear safety risk and a reduced probability of through-wall cracking and leakage compared to the case for unmitigated components examined per the requirements of 10 CFR 50.55a.

2.5.4 Surface Examination Requirements

Surface (ET or PT) examinations are not credited in the safety analyses described in Section 5 and Appendix A and Appendix B. Nevertheless, Table 4-1 specifies performance of an ET examination during the pre-peening inspection of DMWs a secondary method providing additional assurance of flaw detection and removal. As a secondary method intended to provide additional assurance of flaw detection and removal, Section 4 specifies that the ET of the DMW inside surface be performed in accordance with IWA-2223 of ASME Section XI.

The reasons for not using ET at the J-groove welds of RPVHPNs are (1) rupture of the head or nozzle ejection due to instability of a flaw located exclusively in the J-groove weld is not a credible concern, (2) experience has shown that PWSCC flaws located in the weld metal often extend into the base metal and are thus detectable via UT from the nozzle ID, (3) 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, and (4) plant owners find ET surface examinations of J-groove welds to be impractical considering the potential for false calls, detection of acceptable fabrication flaws, and high radiation worker dose associated with supplemental PT examinations to characterize ET indications, imposing unnecessary and unwarranted radiation dose to NDE inspection and repair personnel who prepare surfaces for examination and implement repairs. The main 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 conservatively assume that flaws that initiate in the weld are not detectable by volumetric UT examinations and that a 30° through-wall circumferential flaw initiates immediately in the nozzle tube upon growth of the weld flaw to cause leakage. The results of these analyses 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 without the use of surface examination, resulting in a sufficiently small effect on nuclear safety. It is further noted that the probabilistic analysis does not credit the performance of

a surface or volumetric leak path examination which would further increase the likelihood that a leaking penetration is detected by the in-service inspections and that the inspection requirements of Section 4 maintain the same basic VE visual examination intervals as required by Code Case N-729-1 (as conditioned by 10 CFR 50.55a) for unmitigated heads. Finally, it is emphasized that a flaw exclusively located in the J-groove weld metal is unlikely to produce a leak rate of sufficient magnitude to result in significant boric acid corrosion of the head.

2.6 Verification of No Adverse Effects

Section 4.2.8.4 and Section 4.3.8.4 require that analysis or testing be performed to verify that peening will not degrade the peened component or other components in the system or cause undesirable adverse effects. Degradation would include initiating cracks or causing growth of any pre-existing flaws. The relevant undesirable effects are erosion of surfaces, undesirable surface roughening, or detrimental effects in the transition regions adjacent to the peened regions. High tensile surface stresses at the transition regions could promote PWSCC degradation during subsequent operation.

Introducing hardness at the peened surface is not an adverse effect. The somewhat elevated surface hardness resulting from peening reflects the mechanism of peening. The surface hardness is not adverse because the compressive residual stresses at the surface prevent PWSCC degradation in the area of elevated hardness. In addition, the thick-wall components that are the subject of this topical report are not susceptible to large plastic strains that could reverse the compressive residual stress field developed by peening (see Section 4.6.3 of MRP-267R1 [4]).

As discussed in MRP-267R1 [4], neither plant experience nor laboratory tests have identified any adverse effects to parts that have been peened with the peening methods being considered in this report. However, as noted in MRP-267R1, vibration problems have occurred to adjacent small-diameter, thin-walled nozzles and instrument lines in BWRs. The performance criteria require that vibration effects during application be considered when assessing the potential for adverse effects.

3 EFFECTIVENESS OF CANDIDATE PEENING PROCESSES

An application-specific qualification report is required to demonstrate that a given peening process will meet the performance criteria in Section 4.2.8 and Section 4.3.8 of this report. In addition, a post-peening report is required to verify that the intended peening effect was achieved and that any relevant non-conformances are acceptable. Section 3 describes in more general terms how the candidate water jet and laser peening processes covered in MRP-267R1 [4] are capable of meeting the performance criteria, including the required stress improvement effect and lack of adverse effects. Peening is effective to mitigate PWSCC if the intended stress effect is achieved regardless of the details of the process. Thus, it is expected that there are surface stress improvement techniques beyond those covered in MRP-267R1 that are capable of meeting the performance criteria.

3.1 Process Overview and Key Process Application Variables

Laser peening and water jet peening (also known as cavitation peening) operate by impact of a pressure shock wave, leaving the treated surface in a compressive residual stress state. The shock wave may be produced via laser energy (laser peening, LP) or via collapse of vapor bubbles due to a water jet impinging on the surface (water jet peening, WJP). Detailed descriptions of these peening methods and the relevant physical mechanisms are contained in MRP-267R1 [4], but a brief description of the operating principle for each is provided below:

- The LP process uses the laser energy to create plasma that is confined by the inertia of surrounding water and reaches very high pressures and temperatures. This rapid rise in surface pressure creates a shock wave with pressure above the yield strength of the substrate. The shock wave propagates through the ablative layer and into the metal, plastically deforming it as it propagates inward. After the passage of the shock wave, the reaction of the metal surrounding the treated surface leaves the surface in a compressive residual stress state. Different processes vary in energy level, spot size, and beam delivery method.
- Cavitation bubbles are produced in a submerged water jet. The cavitation bubbles are produced by the strong shear force that acts on the boundary between the high-speed jet and the surrounding stationary water, and the bubbles are carried by the high-speed water jet to the material surface. The collapse of the cavitation bubbles generates a large shock pressure that causes local plastic deformation. In the same manner as for laser peening, after the passage of the shock wave, the reaction of the metal surrounding the treated surface leaves the surface in a compressive residual stress state.

Peening is controlled as a special process, as discussed in Section 2.1. The key process application variables for a given peening process as applied to the target component will be established and will be demonstrated by qualification testing to meet the peening performance

criteria. Examples of the key process application variables for WJP and LP are described in Section 3 of MRP-267R1 [4] and are summarized below:

- Water Jet Peening (WJP)
  - Nozzle diameter
  - Jet stand-off distance and nozzle offset in ID applications
  - Water flow rate
  - Water jet traverse time
  - Impingement angle
  - Restricted stationary peening time
  - Water level and water temperature
- Laser Peening (LP)
  - Laser type (wavelength)
  - Pulse energy
  - Pulse repetition rate
  - Pulse duration
  - Laser spot footprint dimensions
  - Pulse number density

3.2 Process Field Experiences

The many locations in numerous plants that have been peened in Japanese BWRs and PWRs using LP and WJP are described in detail in MRP-267R1 [4]. 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 LP at 2 PWRs
- Reactor vessel safety injection nozzle DMWs: WJP at 6 PWRs, and LP at 2 PWRs
- Bottom mounted instrument nozzle ID surfaces: WJP at 20 PWRs, and LP at 2 PWRs.
- Bottom mounted instrument J-groove weld and adjacent nozzle OD base material: WJP at 21 PWRs, and LP 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.

3.3 Attaining the Requisite Stress Improvement Effect

MRP-267R1 [4] describes in detail the magnitude and the depth of the compressive residual stresses that are generated by candidate WJP and LP processes and that are substantially deeper and more compressive than the bounding stress effect required by the performance criteria. WJP and LP methods generally produce compressive residual stress fields with depths of at least 1 mm (0.04 in.) [4], although reduced compressive depths may be expected in restricted geometries such as on the inside surface of RPVHPNs in the case that a thermal sleeve is present within the nozzle.

The following subsections discuss potential limitations on the stress effect of peening.

3.3.1 Geometric Limitations to Peening Process Application

Demonstration of the ability of a peening process to meet the performance criteria of this report over the area of material susceptible to PWSCC initiation is required for use of the relaxed inspection requirements. For the WJP and LP methods considered in MRP-267R1 [4], the following geometric limitations have been identified for DMWs and RPVHPNs:

- No access or other geometric limitations have been identified for peening the ID surface of DMWs.
- No access limitations have been identified for peening the weld wetted surface and wetted surface of the tube OD for RPVHPNs.
- For the region of the RPVHPN tube ID surface to be peened, the limited access because of the presence of the thermal sleeve located inside some nozzles may result in a reduced depth of the compressive stress field for some peening methods.
- In addition, due to geometry, some peening techniques of interest cannot be used to peen the threaded areas that are present in some cases near the bottom of the RPVHPN tube (either on the nozzle OD or nozzle ID). Because any such threaded areas are located below the weld toward the end of the nozzle and inboard of the pressure boundary, the performance criteria do not require that peening be performed of the threaded regions when present.

The processes considered in MRP-267R1 for each geometry have demonstrated an ability to meet the applicable performance criteria.

3.3.2 Surface Condition Considerations

There are no known limitations imposed by surface conditions on the peening applications considered in MRP-267R1 [4]. The successful use of the WJP and LP methods for many BWR and PWR applications confirms that the surface conditions of the Alloy 600/82/182 and stainless 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 considered in MRP-267R1:

- Areas with unusually high levels of local cold work (e.g., due to aggressive grinding) could conceivably reduce the effectiveness of the peening process. Appendix A of MRP-267R1 [4] documents successful application of laser peening to a 20% cold worked stainless steel,

which shows that the levels of cold work present on plant parts are unlikely to interfere with peening. In addition, as also discussed in Appendix A of MRP-267R1, water jet peening and 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 [16] notes that surface condition and surface hardness are generally not limitations for shot peening. Further, shot peening mitigation of PWSCC of Alloy 600 steam generator tubes in areas that were significantly cold worked, e.g., roll overlaps and roll transitions, has been observed to be highly effective as discussed in Section 4.6.5 of MRP-267R1 [4]. Consequently, peening methods 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.

3.3.3 Effect of Pre-Peening Stress

The peening effect is self-normalizing as the effect is enhanced for areas with relatively high tensile initial residual stress and attenuated for areas with compressive initial residual stress. The stress measurements below illustrate the relative insensitivity to the initial residual stress state and illustrate that the largest post-peening surface compressive stress corresponds to the point of maximum tensile initial residual stress.

Although it is not necessary that the compressive stresses from peening be uniform for peening to be effective, the peening compressive stresses do tend to be relatively uniform due to this self-normalizing behavior.

As described in Section 4.5 of MRP-267R1 [4], a surface that is in high tension relaxes more when it is peened vs. a surface that has low tension. Likewise a material that is already in compression does not relax as much when it is peened. The conclusion is peening on a material has about the same final result regardless of the initial residual stress state of the material.

The pre-peening through-wall stress profile does dominate the post-peening stress profile in the region beyond the peening compressive residual stress layer near the treated surface. In this regard, a conservative stress condition is assumed in the analyses of Section 5 and Appendix A for the Alloy 82/182 piping butt weld cases based on the effect of a deep ID weld repair. High tensile weld residual stresses are predicted for RPVHPNs regardless of the presence of weld repairs because of the constraint of the J-groove geometry.

The following is a description of X-ray diffraction measurements of the residual stress state of a bottom mounted nozzle OD test block before and after peening [17]. The surface axial stresses on the Alloy 82/182 material ranged from -64 ksi to+68 ksi (-441 MPa to +469 MPa). Two locations (A7 and A9) also had depth residual stress measurements taken:

- Location A7 was at -64 ksi (-441 MPa) before peening and went to -74 ksi (-510 MPa) after peening.

- Location A8 was at -29 ksi (-200 MPa) before peening and went to -63 ksi (-434 MPa) after peening.
- Location A9 was at +68 ksi (469 MPa) before peening and went to -81 ksi (-558 MPa) after peening.
- Location A10 was at -22 ksi (-152 MPa) before peening and went to -80 ksi (-552 MPa) after peening.

The data show the greatest peening response occurred with the highest amount of initial tension. Regardless of the initial state, high tension or high compression, the final compressive stresses ended up within a -63 ksi to -81 ksi (-434 MPa to -558 MPa) range.

3.4 Coverage Verification

Examples of the approaches taken to ensure 100% coverage of the areas being peened for WJP and LP are described in Sections 5.3.2, 3.1.3.1, and 5.4.2 of MRP-267R1 [4]. In summary, they are as follows:

- Complete coverage of the areas designated for peening are assured by use of overlapping passes and by extending the peening out to 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 the desired length of time or for the desired number of pulses per unit area, as applicable.
- After the peening is completed, the records are given a QA/QC or an independent review to ensure that 100% coverage was achieved. Alternatively, verification of complete coverage may be performed automatically by use of a 3D computer model with as-built dimensions, in which the main process parameters are recorded for each successful laser firing.
- In addition, a visual inspection of laser peened surfaces may be performed to ensure that all of the desired surface shows visible signs of peening (LP changes the surface enough to make obvious the difference between peened and unpeened areas).

3.5 Sustainability of the Stress Effect

A detailed evaluation is contained in Section 4 of MRP-267R1 [4] that describes the experimental and analytical evaluations that show that the required stress effect will be sustained for extended operating periods to ensure the long-term effectiveness of 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 a thermal activation energy approach that concludes that the results of these experiments show that the peening will remain effective for more than 60 years of operation.

Detailed finite-element stress relaxation analyses as applied to RPVHPNs have shown that substantial compressive residual stresses at the peened surface are sustained for 1,000,000 hours (114 years) at operating pressure and temperature [18].

As discussed in Section 3 of MRP-267R1 [4], plant experience with shot peened steam generator tubes also demonstrates that compressive stresses remain high after long periods of operation.

3.6 Inspectability After Peening

General background information regarding the effects of peening on inspectability is provided in Section A.4.1 of MRP-267R1 [4]. As discussed in that report, tests were performed of a flat plate specimen of Alloy 600 welded to Type 304 stainless steel using Alloy 182 in which cracks had been induced using potassium tetrathionate. These tests showed that the detectability of the cracks by phased array ultrasonic testing (UT) was not adversely affected by water jet peening. These tests were performed with the UT probe located on the peened surface. MRP-267R1 also notes that extensive experience for more than 20 years with inspections by ET and UT of steam generator tubes that have been shot peened in the tube expansion and tube expansion transition regions has also demonstrated that inspectability is not adversely affected by peening. Again, the probes in steam generator tubes are applied to the peened surface.

Tests of the inspectability by UT and ET of dissimilar metal butt welds were performed by EPRI as described in EPRI reports 3002000656 [30] and 3002002952 [31]. These tests used coupons with dissimilar metal welds, e.g., an Alloy 82/182 butt weld between stainless steel and carbon steel. These tests show that UT and ET qualified for use on unmitigated DMWs are reliable for use on peened DMWs.

With regard to UT of RPVHPNs, EPRI has initiated a project to confirm that previous qualifications of time-of-flight (TOF) UT per 10 CFR 50.55a(g)(6)(ii)(D)(*4*) using unpeened mockups remain valid when the UT procedures are applied to peened RPVHPNs. The project is expected to demonstrate the equivalency of peened and unpeened mockups that meet the requirements of 10 CFR 50.55a(g)(6)(ii)(D)(*4*) and the sections of Appendix VIII of ASME Section XI referenced by this regulation. UT will be performed before and after peening of a nozzle mockup. This project is currently scheduled to be completed in calendar year 2015.

3.7 Assessment of Potential Crack Growth During Operation after Peening

Tests have been performed 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 [4]. 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. The probabilistic analyses in Section 5 and Appendix A and Appendix B are used to develop a follow-up inspection regimen that addresses such flaws in the event they are not detected during the pre-peening inspection.

3.8 Basis for No Adverse Effects

The following discussion provides evidence that there will not be adverse effects in U.S. PWRs associated with peening for PWSCC mitigation:

- WJP and LP have been used extensively in Japanese PWRs and BWRs for over 10 years with no reported adverse effects to the peened parts. However, in Japanese BWRs, there have been vibration-induced failures of small-diameter, thin-wall nozzles and instrument lines with pre-existing flaws and located close to the peened areas, as discussed in MRP-267R1 [4] and further in MRP 2014-027 (response to NRC Request for Additional Information No. 4-4) [17]. In response to this experience, 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 industry review there are no thin-wall lines near the areas to be peened in PWRs. However, when vibration effects are present, the performance criteria of Section 4.2.8.4 and Section 4.3.8.4 require analysis or testing to verify that the mitigation process does not result in vibration-induced degradation, including when peening RPVHPNs to any thermal sleeves present inside the nozzle.
- Extensive qualification testing, including examination of many peened samples and test blocks, has been performed of the WJP and LP processes as described in MRP-267R1 [4]. No adverse 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, with no adverse effects being identified. The peened surfaces have not experienced unusual corrosion nor have they interfered with normal eddy current test inspections and occasional ultrasonic inspections.

4 EXAMINATION REQUIREMENTS

Section XI of the ASME Boiler and Pressure Vessel Code specifies periodic in-service inspections of safety-significant light water reactor 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 U.S. 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[4] and Alloy 600 RPVHPNs mitigated by surface stress improvement (SSI) (i.e., peening). 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.

Section 4.1 contains a summary of the current inspection requirements for DMWs and RPVHPNs with unmitigated Alloy 600/82/182 materials as specified by Code Cases N-770-1 [1] and N-729-1 [2], respectively, as conditioned by 10 CFR 50.55a(g)(6)(ii). 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, are defined in Section 4.2 for DMWs and in Section 4.3 for RPVHPNs.

For peened components, three different categories of inspection requirements are defined:

- The pre-mitigation inspection is performed in the same outage during which peening is applied. The pre-peening inspection is considered to be the pre-service baseline inspection.
- A follow-up examination is performed a certain number of cycles after the peening application to address the possibility of flaws that were neither detected in the pre-peening examination of the DMW or the RPVHPN tube base metal nor sufficiently shallow to have been arrested by the peening process. The required timing of the follow-up inspection(s) was

[4] The term DMW is used here to refer specifically to Alloy 82/182 dissimilar metal butt welds located in PWR primary system piping and falling under the scope of Table 1 of ASME Code Case N-770-1 [1].

established on the basis of the detailed probabilistic calculations and is supported by the deterministic analyses.

- Finally, in-service inspections (ISIs) are required to be performed regularly at the intervals prescribed in Table 4-1 for DMWs and Table 4-3 for RPVHPNs.

Further inspection requirements for Alloy 600/82/182 PWR primary pressure boundary components are specified by ASME Code Case N-722-1 [3] as conditioned by 10 CFR 50.55a(g)(6)(ii)(E). This code case requires periodic direct visual examinations of the exterior metal surface of Alloy 600/82/182 components for evidence of pressure boundary leakage. Code Case N-722-1 excludes the reactor vessel top head nozzles in deference to Code Case N-729-1. For the case of Alloy 82/182 piping butt welds, the requirements of Code Case N-770-1 (as conditioned by 10 CFR 50.55a) generally bound the requirements of Code Case N-722-1 (as conditioned by 10 CFR 50.55a).

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 for information only.

4.1.1 Dissimilar Metal Butt 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 U.S. NRC through regulation 10 CFR 50.55a(g)(6)(ii)(F), subject to the conditions detailed in this regulation.[5] 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 [19].

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 using specific methods. These requirements are currently not directly applicable to SSI treatments. The SSI treatment methods described in this report are not addressed by Code Case N-770-1, although SSI treatment is

[5] An update of N-770-1 (Code Case N-770-4, May 7, 2014) 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 2015. N-770-4 incorporates inspection requirements for components mitigated using SSI. N-770-1 is the only version of this code case currently accepted by U.S. NRC.

similar to mechanical stress improvement without welding, which is addressed in N-770-1. For stress improvement methods for which the N-770-1 requirements are currently 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.

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 two calculated parameters — 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 acceptance criteria for visual examinations that detect evidence of reactor coolant leakage or boric acid corrosion and for volumetric or surface examinations that detect indications of planar flaws. The technical bases for the requirements of N-729-1 are documented in MRP-117 [20], the top-level safety assessment report MRP-110 [12], and lower-level safety assessment reports MRP-103 [21], MRP-104 [22], and MRP-105 [23]. In the fall of 2014, the technical basis for inspections of unmitigated heads with Alloy 600 nozzles was updated by MRP [13] to consider the most recent set of plant experience, including part-depth PWSCC indications detected in several heads operating at reactor cold-leg temperature. MRP-395 [13] concluded that the current inspection requirements for unmitigated heads with Alloy 600 nozzles remain valid. This code case has been made mandatory by the U.S. NRC through regulation 10 CFR 50.55a(g)(6)(ii)(D), subject to the conditions detailed in this regulation.[6] 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 2015, there are heads with Alloy 600 nozzles in service at 24 U.S. PWRs. The heads at 41 currently operating U.S. PWRs have been replaced with heads using PWSCC-resistant nozzles made of Alloy 690. Of the 24 Alloy 600 heads remaining in service, 19 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

[6] An update of N-729-1 (Code Case N-729-4, June 22, 2012) 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 2015. N-729-4 incorporates within the Code Case the conditions applied to N-729-1 by the NRC in 10 CFR 50.55a(g)(6)(ii)(D). N-729-1 is the only version of this code case currently accepted by U.S. NRC.

Alloy 600 nozzles is typically every four or five 18-month fuel cycles, or three or four 24-month fuel cycles. More frequent volumetric or surface examinations may be required if PWSCC has previously been detected in the subject head.

4.2 Requirements for Dissimilar Metal Butt Welds (DMWs) in Primary System Piping Mitigated by Peening

Item L of Table 4-1 defines alternative inspection requirements for uncracked Alloy 82/182 dissimilar metal piping butt welds mitigated by a peening mitigation technique meeting the performance criteria of Section 4.2.8. The inspection requirements in Table 4-1 include a pre-peening inspection (Section 4.2.2), follow-up inspection (Section 4.2.3), and long-term in-service inspections (Section 4.2.4). Within the context of this section, the term "uncracked" refers to a component examined in accordance with the requirements of N-770-1-2500 with no planar surface-connected flaws in contact with the reactor coolant environment during normal operation.

Within the context of Section 4.2, references to portions of ASME Code Case N-770-1 are indicated using a hyphen followed by the relevant location within this code case (e.g. -2000). Section 4.2 defines inspection requirements relevant to peening by specifying additions to ASME Code Case N-770-1. A listing of such additions and other requirements in this section is provided by Table 4-2.

4.2.1 Summary of Performance Criteria of Section 4.2.8

The performance criteria of Section 4.2.8 shall be satisfied. For information only, brief summaries of the requirements of Section 4.2.8 are provided below.

Peening Coverage

The required coverage is the full area of the susceptible material along the entire wetted surface under steady-state operation. Susceptible material includes the weld, butter, and base material, as applicable.

Stress Magnitude

The residual stress plus normal operating stress is compressive on all peened surfaces.

Depth of Effect

The compressive residual stress field extends to a minimum nominal depth of 0.04 in. (1.0mm) on the susceptible material along the wetted surface unless the alternative performance criterion is used, with inspection relief subject to review and approval by the regulatory authority having jurisdiction at the plant site.

Sustainability of Effect

The mitigation process is effective for at least the remaining service life of the component, i.e., the residual plus normal operating surface stress state after considering the effects of thermal relaxation and load cycling (i.e., shakedown) must remain compressive.

Inspectability

The capability to perform ultrasonic examinations of the relevant volume of the component is not adversely affected, and the relevant volume is inspectable using a qualified process. The capability to perform eddy current examinations of the relevant surface of the component is not adversely affected.

Lack of Adverse Effects

As verified by analysis or testing, the mitigation process is not to have degraded the component, caused detrimental surface conditions, or adversely affected other components in the system.

4.2.2 Pre-Peening Inspection

Prior to performance of peening but during the same outage, the following examinations are to be performed in accordance with the requirements in Table 4-1.

- An ultrasonic examination is to be performed of the weld.
- An eddy current (ET) inspection is also to be performed of the weld inner surface.

It is emphasized that the surface examination that is required in this report for use prior to peening is not credited in the safety analyses described in Section 5 and Appendix A.

4.2.3 Follow-Up Inspection

During the follow up inspection(s), volumetric examination of the required volume and surface examination of the required area are performed in accordance with the requirements in Table 4-1. The follow-up inspection schedule depends on the operating temperature of the weld:

- For hot leg piping, the follow-up inspections are in the second refueling outage following the application of peening and a second examination occurs within 10 years following the application of peening.
- For cold leg piping, the follow-up inspection is once within 10 years following the application of peening.

4.2.4 Subsequent ISI Program

The in-service inspection requirements for peened welds after completion of the follow-up inspection(s) are shown in Table 4-1.

Peened welds that show no indications of cracking in follow-up examinations are placed into a population to be examined on a sample basis, with 25% examined once each Section XI inspection interval (nominally 10 years).

Furthermore, the following shall apply for the purpose of establishing populations of welds for the performance of the 25% sample program in accordance with -2410:

(d) If more than one mitigation technique is used, a population of welds mitigated using each technique shall be established in accordance with Table 4-1 and with Table 1 of N-770-1 (as conditioned by 10 CFR 50.55a(g)(6)(ii)(F)). Each Inspection Item population, or a sample of each Inspection Item population as required by Table 4-1 or by Table 1 of

N-770-1 (as conditioned by 10 CFR 50.55a(g)(6)(ii)(F)), shall be added to the ISI Program in accordance with -2410(c) and shall be examined in accordance with Table 4-1 and with Table 1 of N-770-1 (as conditioned by 10 CFR 50.55a(g)(6)(ii)(F)).

4.2.5 Examination Coverage and Acceptance Criteria for Inspection Results

Examination Coverage

The required examination volume is defined by volume C-D-E-F of Figure 1 in ASME Code Case N-770-1. The required examination surface shall be surface E-F in the same figure.

In accordance with 10 CFR 50.55a(g)(6)(ii)(F)(*4*) and for U.S. plants, essentially 100% coverage is required for the examination for axial flaws instead of the requirements in -2500(c).

Acceptance Criteria for Item L of Table 4-1

The volumetric acceptance standards for Item L of Table 4-1 are in accordance with Paragraph -3130 of N-770-1 with the addition of the following requirements:

Added to Subparagraph -3132.2:

(d) If examinations of weld volumes or areas reveal unacceptable flaws in accordance with -3132.3(e) in a weld that has been previously mitigated by peening, the weld is unacceptable for continued service until corrected in accordance with (a). If corrected by a mitigation technique in Table 1 of ASME Code Case N-770-1, the weld shall be placed in the Inspection Item for the repair/replacement activity or corrective measure used for acceptance of the flaw.

(e) As an alternative to the -3132.3(e) reclassification of a weld previously mitigated by peening containing acceptable flaws, the weld shall be corrected by repair/replacement activity in accordance with IWA-4000 or by other mitigation techniques in accordance with the requirements of Table 1 of ASME Code Case N-770-1 during the outage in which the flaw was identified. If corrected by a mitigation technique in Table 1 of ASME Code Case N-770-1, the weld shall be placed in the Inspection Item for the repair/replacement activity or corrective measure used for acceptance in the flaw.

Added to Subparagraph -3132.3:

(e) If volumetric or surface examination of the weld previously mitigated by peening detects new planar surface flaws in the butt weld or base metal inside surface, the weld is acceptable for continued service without additional repair/replacement activity or corrective measures, provided an analytical evaluation meets the requirements of IWB-3600, and the additional examinations of -2430 are performed in the current outage. In this analytical evaluation, the beneficial effects of peening shall not be considered, the weld shall not be considered mitigated; and the weld shall be reclassified as Inspection Items A-1, A-2, or B, as applicable, and re-examined in accordance with Note (5) of Table 1 of ASME Code Case N-770-1.

In accordance with 10 CFR 50.55a(g)(6)(ii)(F)(*6*) and for U.S. plants, for any mitigated weld for which volumetric examination detects growth of existing flaws in the required examination volume that exceed the previous ASME Section XI IWB–3600 flaw evaluations or new flaws, a report summarizing the evaluation, along with inputs, methodologies, assumptions, and causes of

the new flaw or flaw growth is to be provided to the NRC prior to the weld being placed in service other than modes 5 or 6.

4.2.6 NDE Qualification Requirements

Volumetric examinations shall be qualified to the performance demonstration requirements of ASME Section XI, Mandatory Appendix VIII per Note (4) of Table 1 in ASME Code Case N-770-1.

Eddy current examinations shall be performed in accordance with Section XI IWA-2223 and Section 4.2.8.3.2.

4.2.7 Inspection Expansion

Examinations performed in accordance with Table 4-1 that reveal unacceptable flaws shall be extended to include examinations of additional welds during the current outage. The use of IWB-3514 is for the purpose of determination of scope expansion and not the purpose of determining acceptability of the flaws. Acceptability of flaws is determined in accordance with -3132.

The specific requirements are defined in -2430 of ASME Code Case N-770-1 (specifically -2430(a), -2430(a)(5), the unnumbered paragraph below -2430(a)(6), and -2430(b)) with the addition of the following bullet:

- For Table 4-1 Inspection Item L and the examination volume of Figure 1 of N-770-1, additional mitigated welds from the same Inspection Item and using the same peening method shall be examined during the current outage, if planar surface flaws are revealed in the butt weld or base metal inside surface.

For other than the flaws in -2430(a)(1), (2), (3), (4), (5), or the above bullet, the additional examination requirements of IWB-2430 apply.

4.2.8 APPENDIX: Performance Criteria and Measurement or Quantification Criteria for Mitigation by Surface Stress Improvement (Peening) of Alloy 82/182 Piping Butt Welds in PWR Primary System Piping

It is noted that Section 2.1 discusses quality assurance considerations with regard to implementation of peening mitigation:

> "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."

Thus peening shall be performed and qualified per requirements meeting the quality assurance criteria of 10 CFR 50 Appendix B. As such, the analysis and demonstration testing required

below are performed in accordance with these quality assurance requirements, which provide adequate controls.

4.2.8.1 Stress Effect

To minimize the likelihood of crack initiation, the process shall have resulted in a compressive stress in the full area of the susceptible UNS N06600, UNS N06082, and UNS W86182 material along the entire wetted surface under steady-state operation. Susceptible material includes the weld, butter, and base material, as applicable. The residual stress plus normal operating stress on surfaces required to be peened shall be included in the evaluation. The boundaries of the area required to be effectively peened shall be extended beyond the PWSCC susceptible area a suitable distance to provide high assurance that the areas susceptible to PWSCC receive the required peening effect.

A combination of demonstration testing and analysis shall be performed to demonstrate the required capability of the peening method to produce the required post-mitigation stress state:

(a) Demonstration testing shall be performed to determine the residual stress state at the surface to be peened. Specimens representative of the geometry, accessibility, and surface condition of the component to be peened shall be used. For peening of main loop piping welds, it is acceptable to use welded flat plate specimens. The nominal wall thickness of the specimen shall be no greater than that of the component to be peened.

(b) Analysis shall be performed to determine the effect of normal operating loads on the steady-state operating axial and hoop direction stresses.

The testing shall be used to demonstrate the critical process parameters and define acceptable ranges of the parameters needed to ensure that the required residual stress field (exclusive of normal operating stresses) has been produced on the mitigated surface.

4.2.8.1.1 Magnitude of Surface Stress

The combination of demonstration testing and analysis shall show that the steady-state operating axial and hoop direction stresses combined with residual stresses are compressive at the inside surface of susceptible material.[7]

[7] Some advanced peening processes result in a very thin surface layer (i.e., within 0.001 to 0.002 inch (25 to 50 μm) from the surface) where the residual stress is tensile or not as compressive as the residual stress deeper into the material. For example, see Figures A-14, A-42, and A-43 of MRP-267, Rev. 1 [4]. The underlying compressive residual stresses prevent development of significant PWSCC cracks at the surface. Thus, the residual stresses in this very thin surface layer may be excluded when showing that the requirement of Section 4.2.8.1.1 is met. The combination of demonstration testing and analysis shall show that the steady-state operating axial and hoop direction stresses combined with residual stresses are compressive immediately beyond the very thin surface zone of elevated residual stress.

4.2.8.1.2 Nominal Depth of Compressive Residual Stress

The testing shall demonstrate that the nominal depth of the compressive surface residual stress field produced by the peening technique is at least 0.04 in. (1.0 mm),[8] unless the alternative of Section 4.2.8.1.3 is used. The nominal depth refers to the depth of the compressive residual stress that is reliably obtained in demonstration testing, i.e., for at least 90% of the locations measured.

4.2.8.1.3 Alternative Requirement for Nominal Depth of Compressive Residual Stress

For peening techniques where the nominal compressive surface stress field applied is less than 0.04 in. (1.0 mm), the following shall apply:

(a) Testing shall establish the nominal depth of compressive residual stress.

(b) Pre-peening surface examinations required by Table 4-1 shall be qualified in accordance with Mandatory Appendix IV Supplement 2 of ASME Section XI except that the flawed grading unit specimens shall use crack or compressed notch depths no greater than the nominal peening depth or machined notches with a maximum depth of one-half the nominal peening depth.

(c) Prior to categorization of the weld as Table 4-1 Inspection Item L, the alternative and its technical basis shall be reviewed and approved by the regulatory authority having jurisdiction at the plant site.

4.2.8.2 Sustainability

Analysis or testing shall be performed to verify that the peening process maintains the compressive surface stress condition (normal operating and residual stress) for at least the remaining service life of the component. The analysis or demonstration test plan shall include startup and shutdown stresses, normal operating pressure stress, thermal cyclic stresses, transient stresses, and residual stresses. The analysis or demonstration test shall account for:

(a) load combinations that could relieve stress due to shakedown

(b) any material properties related to stress relaxation over time

4.2.8.3 Inspectability

4.2.8.3.1 UT Inspectability

The capability to perform ultrasonic examinations of the relevant volume of the component shall not be adversely affected. Nondestructive examination qualified to Section XI, Mandatory Appendix VIII, performance demonstration requirements using representative weld specimens shall have been performed to demonstrate that a qualified examination of the relevant volume of

[8] Some advanced peening processes result in a very thin surface layer (i.e., within 0.001 to 0.002 inch (25 to 50 μm) from the surface) where the residual stress is tensile. The tensile residual stresses in this very thin surface layer may be excluded when showing that the requirement of Section 4.2.8.1.2 is met. The testing shall demonstrate that the nominal depth of the compressive surface residual stress field, excluding the very thin layer of tensile stress at the surface, is at least 0.04 in. (1.0 mm), unless the alternative of Section 4.2.8.1.3 is used. The depth measurement shall be from the surface to the point where the compressive residual stress becomes neutral.

the mitigated component can be accomplished subsequent to the mitigation including changes to component geometry, material properties, or other factors.

4.2.8.3.2 ET Inspectability

The capability to perform eddy current examinations of the relevant surface of the component shall not have been adversely affected.

4.2.8.4 Lack of Adverse Effects

Analysis or testing shall be performed to verify the following:

(a) The mitigation process, including any vibration effects during application, does not degrade the component or adversely affect other components in the system.

(b) The mitigation process does not cause erosion of surfaces, undesirable surface roughening, or detrimental effects in the transition regions adjacent to the peened regions.

4.2.8.5 UT Qualification

The mitigated weld shall be inspectable by a qualified process. An evaluation shall be performed to confirm that the required examination volume of the mitigated configuration is within the scope of a Section XI, Mandatory Appendix VIII, supplement or supplements and that the examination procedures to be used have been qualified in accordance with Mandatory Appendix VIII. The evaluation shall confirm that the geometric limitations (e.g., weld crown, nozzle contour) of a Mandatory Appendix VIII qualification are not exceeded for the mitigated weld.

4.2.8.6 Pre-Peening UT and ET

A volumetric examination qualified to Section XI Mandatory Appendix VIII, performance demonstration requirements and a surface examination in accordance with IWA-2223 shall have been performed in accordance with Table 4-1 to assure the absence of planar surface flaws before the application of the peening mitigation.

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

EXAMINATION CATEGORIES						
CLASS 1 PWR PRESSURE RETAINING DISSIMILAR METAL PIPING AND VESSEL NOZZLE BUTT WELDS CONTAINING ALLOY 82/182						
Item No.	**Parts Examined**	**Examination Requirements/ Fig. No.**	**Examination Method**	**Acceptance Standard**	**Extent and Frequency of Examination**	**Deferral of Examination to End of Interval**
L	Uncracked butt weld mitigated by peening (19)	Figure 1 of N-770-1	Volumetric (4), (19), (21); Surface (19), (20)	Section 4.2.5	Perform a volumetric examination (21) and a surface examination (20) of all hot leg welds in the 2nd refueling outage following the application of peening and a second examination within 10 yr following the application of peening. Examinations that show no indications of cracking shall be placed into a population to be examined on a sample basis. Twenty-five percent of this population shall receive a surface examination (20) performed from the weld inside surface and a volumetric examination (21) performed from either the inside or outside surface. The 25% sample shall be added to the ISI Program in accordance with -2410 and shall be examined once each inspection interval (10). Perform a volumetric examination (21) and a surface examination (20) of all cold leg welds once within 10 yr following application of peening. Examinations that show no indications of cracking shall be placed into a population to be examined on a sample basis. Twenty-five percent of this population shall receive a surface examination (20) performed from the weld inside surface and a volumetric examination (21) performed from either the inside or outside surface. The 25% sample shall be added to the ISI Program in accordance with -2410 and shall be examined once each inspection interval (10).	(11)

NOTES: (1) through (5) and (10) are identical to those in ASME Code Case N-770-1 [1]. Notes (6) through (9) and notes (12) through (18) are not applicable. Note (11) modifies Note (11) in N-770-1, and the other notes below are in addition to those in N-770-1.

(11) Deferral of Examinations

- (a) Examinations of welds originally classified Table IWB-2500-1, Category B-J welds prior to mitigation are not permitted to be deferred to the end of the interval.
- (b) Examinations of welds originally classified Table IWB-2500-1, Category B-F welds, Item Numbers B5.10, and B5.20 prior to mitigation, may be deferred following peening, as follows:
  - (1) Not applicable.
  - (2) The first examinations following peening for Inspection Item L shall be performed as specified. The second examination of hot leg welds of Inspection Item L shall be performed as specified. Subsequent examinations for Inspection Item L may be performed coincident with the vessel nozzle examinations required by Category B-D.
  - (3) For successive inspection intervals following peening, subsequent examinations may be deferred to the end of the interval, provided no additional repair/replacement activities have been performed on the examination item, and no flaws or relevant conditions requiring successive examination in accordance with Table 4-1 are contained in the mitigated weld.

(c) Welds that were classified in accordance with Nonmandatory Appendix R, prior to mitigation shall be reclassified based on the configuration of each piping structural element and the postulated degradation mechanisms if any remaining after the mitigation. Deferral of examinations shall be according to (a) and (b), above.

(d) Not applicable

(19) If peening techniques are used, the following shall be met:

(a) Volumetric (21) examination from either the inside or outside surface and surface (20) examinations from the inside surface shall be performed on these welds prior to the application of peening techniques and as a pre-service examination in accordance with -2220. The pre-peening examination shall be conducted in the same outage as the application of peening. The examination volume of Figure 1 in N-770-1 and examination surface defined by points E-F of Figure 1 in N-770-1 apply. Eddy current examination in accordance with IWA-2223 is required.

(b) The pre-peening examination shall be considered the pre-service baseline examination. The following acceptance standards apply:

(1) No planar surface flaws are acceptable for Inspection Item L welds. If any planar surface flaws are detected, the requirements of (c) shall be met.

(2) Flaws other than planar surface flaws detected in the butt weld or base metal inside surface shall be acceptable for continued service in accordance with the requirements of -3132.1(b).

(c) A weld with a planar surface flaw shall be acceptable for continued service in accordance with -3132.2(a) or -3132.3(a) and be categorized by Inspection Item in accordance with Table 4-1 or Table 1 of N-770-1 as follows:

(1) If the flaw is removed by repair/replacement activity in accordance with IWA-4000 prior to the application of peening, the weld may be peened and be placed into Inspection Item L.

(2) If the flaw is not removed, the weld may be peened while acceptability for continued service in accordance with -3132.3(a) is determined. If the weld is acceptable for continued service in accordance with -3132.3(a), the weld shall be placed into Inspection Items A-1, A-2, or B, and shall be re-examined in accordance with Note (5) of Table 1 of N-770-1. The flaw may subsequently be made acceptable for continued service in a subsequent outage in accordance with (3).

(3) If the flaw will be made acceptable for continued service in accordance with -3132.2(a), Table 4-1, and Table 1 of N-770-1, peening may be performed over the flaw prior to or following the repair/replacement activity or corrective measure. The weld shall be placed in the Table 1 of N-770-1 Inspection Item category for the repair/replacement activity or corrective measure used for acceptance of the flaw.

(20) In-service Surface Examination for Peening

(a) Surface examinations shall be performed on the examination area defined by points E-F in Figure 1 of N-770-1. Surface examinations shall be performed using eddy current examination in accordance with IWA-2223.

(b) If new surface flaws are detected, the weld shall be reclassified as Inspection Items A-1, A-2, or B, as applicable, and shall be re-examined in accordance with Note (5) of Table 1 of N-770-1. Alternatively, the flaw may be made acceptable by a repair/replacement activity or other mitigation techniques in accordance with -3132.2(e), as stated in Section 4.2.5.

(21) In-service Volumetric Examination for Peening

(a) The examination volume of Figure 1 of N-770-1 shall be ultrasonically examined.

(b) The acceptance standards of -3000 apply for the peened dissimilar metal weld.

(c) If in-service examinations of (a) reveal new cracking, the surface examination [Note (20)] shall be performed to confirm that the flaw is not surface-connected. If the flaw is not surface-connected, the weld shall be re-examined during each of the next three refueling outages.

(d) If the examinations required by (c) reveal that the flaw remains essentially unchanged for three successive examinations, the weld schedule may revert to the schedule of examinations identified in Table 4-1.

(e) If an indication is found to be surface-connected, the weld shall be reclassified as Inspection Items A-1, A-2, or B, as applicable, and shall be re-examined in accordance with Note (5) of Table 1 of N-770-1. Alternatively, the flaw may be made acceptable by a repair/replacement activity or other mitigation techniques in accordance with -3132.2(e), as stated in Section 4.2.5.

Table 4-2
List of Requirements in Section 4.2 within the Context of N-770-1

Report Section	Referenced Part of N-770-1	Insertion / Replace N-770-1 Material	Summary of Requirement
4.2.4	-2410(d)	Insertion	Provides sample inspection requirements when more than one mitigation method is used
4.2.5	[Caption of Figure 1]	Insertion	Defines examination surface
4.2.5	-2500(c)	Modification	Changes inspection coverage in accordance with 10 CFR 50.55a(g)(6)(ii)(F)(*4*)
4.2.5	-3131.2(d) -3131.2(e)	Insertion	Provide requirements for reclassification of a weld previously mitigated by peening that is subsequently found to contain flaws
4.2.5	-3131.3(e)	Insertion	Provides requirements for reclassification of a weld previously mitigated by peening upon subsequent detection of planar surface flaws
4.2.5		Insertion	Incorporation of 10 CFR 50.55a(g)(6)(ii)(F)(*6*)
4.2.7	-2430(a)	Insertion	Specifies inspection expansion requirement for peened components
Subsections of 4.2.8	Mandatory Appendix I	Insertion	Provides the performance criteria that a peening method must meet to use the inspection requirements of Table 4-1
Table 4-1	Table 1	Insertion, Except modification of Note (11)	Specifies inspection requirements for uncracked butt welds mitigated by peening

4.3 Requirements for Reactor Pressure Vessel Head Penetration Nozzles (RPVHPNs) Mitigated by Peening

Items B4.50 and B4.60 of Table 4-3 define alternative inspection requirements for Alloy 600 reactor pressure vessel head penetration nozzles and Alloy 82/182 partial-penetration welds mitigated by a peening mitigation technique meeting the performance criteria of Section 4.3.8. The inspection requirements in Table 4-3 include a pre-peening inspection (Section 4.3.2), follow-up inspection(s) (Section 4.3.3), and long-term in-service inspections (Section 4.3.4).

Within the context of Section 4.3, references to portions of ASME Code Case N-729-1 are indicated using a hyphen followed by the relevant location within this code case (e.g. -2000). Section 4.3 defines inspection requirements relevant to peening by specifying additions to ASME Code Case N-729-1. A listing of such additions and other requirements in this section is provided by Table 4-4.

4.3.1 Summary of Performance Criteria of Section 4.3.8

The performance criteria of Section 4.3.8 shall be satisfied. For information only, brief summaries of the requirements of Section 4.3.8 are provided below.

Peening Coverage

The required coverage is the full wetted area of the susceptible material with surface stress (residual plus normal operating stress) of at least +20 ksi (+140 MPa) (tensile), which is a conservative measure of the threshold for PWSCC initiation over plant time scales [8]. The susceptible material locations to be considered are the wetted surface of the Alloy 82/182 J-groove weld and butter material and the surfaces of the Alloy 600 nozzle tube material in the region of the J-groove weld.

Stress Magnitude

The stress prior to consideration of operating stresses must be compressive on all peened surfaces. The residual stress plus normal operating stress on peened surfaces must not exceed +10 ksi (+70 MPa) tensile stress.

Depth of Effect

The compressive residual stress field extends a nominal minimum depth of:

- 0.04 in. (1.0 mm) on the susceptible area of the nozzle outside surface and weld surface
- 0.01 in. (0.25 mm) on the susceptible area of the nozzle inside surface

Sustainability of Effect

The mitigation process is effective for at least the remaining service life of the component, i.e., the residual plus normal operating surface stress state after considering the effects of thermal relaxation and load cycling (i.e., shakedown) must remain no greater than +10 ksi (+70 MPa) tensile.

Inspectability

The capability to perform ultrasonic examinations of the relevant volume of the component is not adversely affected, and the relevant volume or surface is inspectable using a qualified process.

Lack of Adverse Effects

As verified by analysis or testing, the mitigation process is not to have degraded the component, caused detrimental surface conditions, or adversely affected other components in the system.

4.3.2 Pre-Peening Baseline Inspection

Prior to performance of peening but during the same outage, the following examinations are to be performed in accordance with the requirements in Table 4-3:

- A volumetric examination of each nozzle tube is to be performed as the baseline inspection. As an alternative, surface examination of the nozzle inner surface and the wetted surface of the nozzle outside and weld may be performed and considered the baseline inspection.
- Additionally, a demonstrated volumetric or surface leak path assessment through all J-groove welds is to be 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 analyses in Section 5 and Appendix B conservatively do not take credit for the leak path examination.

4.3.3 Follow-Up Inspection

During the follow-up inspection(s), a volumetric examination of 100% of the required volume or equivalent surfaces of the nozzle tube is to be performed and a leak path examination is also to be performed. The follow-up inspection requirements are contained in Table 4-3, which provides different inspection schedules depending on the value of the EDY parameter (defined in N-729-1) at the time of peening:

- For plants where EDY $\geq$ 8, a follow-up inspection is to be performed in the first and second refueling outages subsequent to peening.
- For plants where EDY < 8, a follow-up inspection is to be performed in the second refueling outage subsequent to peening.

4.3.4 Subsequent ISI Program

The in-service inspection requirements are shown in Table 4-3 and are summarized as follows:

Visual Examinations

The base requirement is a VE visual examination for evidence of leakage each refueling outage. This interval may be extended in the following cases:

- For heads where the VE interval immediately prior to peening is permitted to be at least two refueling outages, the interval for performance of VE after peening is every second refueling

outage. In this case, a VE must be performed either during the refueling outage of the peening or during the subsequent refueling outage.

- If EDY < 8 at the time of peening and no unacceptable flaws are detected in the two refueling outages following peening, the interval for performance of VE may be extended to every third refueling outage or 5 calendar years, whichever is less.

VT-2 examinations under the insulation through multiple access points are required to be performed during refueling outages in which the VE is not completed.

Volumetric or Surface Examinations

The following ISI program occurs after completion of the follow-up inspection(s):

- Volumetric or surface examinations of peened penetrations are to be performed at an interval not to exceed one inspection interval (nominally 10 years).
- A demonstrated volumetric or surface leak path assessment through all J-groove welds is performed each time the periodic volumetric or surface examination is performed.

4.3.5 Examination Coverage and Acceptance Criteria for Inspection Results

Examination Coverage

The required examination volume and the required examination surface (as applicable) are defined in Figure 2 of ASME Code Case N-729-1. In accordance with 10 CFR 50.55a(g)(6)(ii)(D)(*6*) and for U.S. plants, implementation of Note (5) of Table 4-3 requires prior NRC approval.

Acceptance Criteria for Item B4.50 of Table 4-3

The visual examination acceptance standards for Item B4.50 of Table 4-3 are in accordance with Subsubarticle -3140 of N-729-1 with the addition of the following to Paragraph -3141:

(d)(1) For examinations performed prior to application of peening mitigation flaws exceeding the criteria of -3142 of N-729-1 shall be considered defects and shall be corrected in accordance with IWA-4000 prior to the application of peening mitigation.

(d)(2) For examinations performed following application of peening mitigation indications exceeding the acceptance criteria of -3142 of N-729-1 are unacceptable. If an indication is identified, the indication shall be evaluated under -3142 of N-729-1 and the head shall be identified as Item B4.10 of N-729-1 until the indication has been corrected in accordance with IWA-4000. Following repair/replacement activities the corrected area of the head, plus 0.5 in. (12.7 mm) beyond the corrected area, may be re-peened and re-examined. If no relevant indications are identified, the head may be returned to Examination Category Item B4.50.

Acceptance Criteria for Item B4.60 of Table 4-3

The surface and volumetric examination acceptance standards for Item B4.60 of Table 4-3 are in accordance with Subsubarticle -3130 of N-729-1 with the addition of the following to Paragraph -3131:

(d)(1) For examinations performed prior to the application of peening mitigation flaws exceeding the criteria of -3132 of N-729-1 shall be considered defects and shall be corrected in accordance with IWA-4000 prior to the application of peening mitigation.

(d)(2) For examinations performed following the application of peening mitigation, flaws exceeding the criteria of -3132 of N-729-1 shall be considered defects and shall be corrected in accordance with IWA-4000. If an acceptable flaw is found the nozzle shall be identified as Item B4.20 of N-729-1 until the flaw has been corrected in accordance with IWA-4000. Following repair/replacement activities, the corrected area of the nozzle, plus 0.5 in. (12.7 mm) beyond the corrected area may be re-peened and re-examined. If no relevant indications are identified the nozzle may be identified as Item B4.60.

Additionally, the phrase "of the 2004 Edition" is omitted from the second to last sentence of paragraph -3132.3 of N-729-1.

4.3.6 NDE Qualification Requirements

Ultrasonic examinations shall be performed using personnel, procedures, and equipment that have been qualified by blind demonstration on representative mockups using a methodology that meets the conditions specified in 10 CFR 50.55a(g)(6)(ii)(D)(*4*).

Visual examinations for evidence of leakage shall be performed in accordance with IWA-2200 and Notes (1) and (2) of Table 1 in ASME Code Case N-729-1.

If performed, surface examinations shall be performed in accordance with Section XI IWA-2200 and Section 4.3.8.5.

4.3.7 Previously Repaired Top Head Nozzles Mitigated by Peening

If the requirements of this Section 4.3 are satisfied, a top head nozzle with flaws that have been corrected may be subsequently peened using a process meeting the performance criteria of Section 4.3.8. In that case, the head and nozzle may be identified as Item B4.50 and Item B4.60, respectively, in Table 4-3.

From the perspective of susceptibility to PWSCC degradation, a penetration repaired using the embedded flaw repair technique (i.e., with an Alloy 52 weld overlay applied to the outer and/or inner penetration surfaces) and subsequently peened is bounded by the analyses of Section 5 and Appendix B for unrepaired penetrations. Subsequent to peening, the areas with Alloy 600/82/182 material in contact with reactor coolant will have a residual plus normal operating surface stress well below that necessary to initiate PWSCC flaws. Even if exposed areas of Alloy 52 weld metal are not peened, the improved PWSCC resistance of Alloy 52 material in comparison to Alloys 600/82/182 conservatively supports the nominal 10-year interval for volumetric or surface examinations of Item B4.60 in Table 4-3 (based on the assessments in MRP-375 [27]). It is also noted that at least one follow-up volumetric or surface examination is required within the first two refueling outages subsequent to the peening outage. Follow-up inspections have the benefit of checking the condition of any previously repaired nozzles.

4.3.8 APPENDIX: Performance Criteria and Measurement or Quantification Criteria for Mitigation by Surface Stress Improvement (Peening) of PWR Reactor Vessel Upper Head Penetrations and Attachment Welds

It is noted that Section 2.1 discusses quality assurance considerations with regard to implementation of peening mitigation:

> "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."

Thus peening shall be performed and qualified per requirements meeting the quality assurance criteria of 10 CFR 50 Appendix B. As such, the analysis and demonstration testing required below are performed in accordance with these quality assurance requirements, which provide adequate controls.

4.3.8.1 Stress Effect

To minimize the likelihood of crack initiation, the process shall have resulted in a compressive stress in the full area of the susceptible UNS N06600, UNS N06082, and UNS W86182 material prior to consideration of operating stresses. Material is considered susceptible if residual plus normal operating stresses on the surface in contact with the reactor coolant fluid exceeds +20 ksi (+140 MPa). The susceptible material locations are the attachment weld, butter, and nozzle base material, including the inside surface region of nozzle penetrations in areas adjacent to the attachment weld, as applicable. The residual stress plus normal operating stress on surfaces required to be peened shall be included in the evaluation and shall not exceed +10 ksi (+70 MPa).

The boundaries of the area required to be effectively peened shall be extended beyond the PWSCC susceptible area defined herein a suitable distance to provide high assurance that the areas susceptible to PWSCC receive the required peening effect. Due to geometry, some peening techniques of interest cannot be used to peen the threaded areas that are present in some cases near the bottom of the nozzle tube. Because any such threaded areas are located below the weld toward the end of the nozzle and inboard of the pressure boundary, it is not necessary that peening be performed of the threaded regions when present.

A combination of demonstration testing and analysis shall be performed to demonstrate the required capability of the peening method to produce the required post-mitigation stress state:

(a) Demonstration testing shall be performed to determine the residual stress state at the surfaces required to be peened. Test sections representative of the geometry, accessibility, and surface condition of the component to be peened shall be used. Each test section shall include a cylindrical tube representative of the nozzle tube and a thick-wall section representative of the low-alloy steel head material. The nominal wall thickness of the

thick-wall section shall be no greater than that of the actual head. Multiple test sections shall be used to bound the range of nozzle incidence angles.

(b) Analysis shall be performed to determine the effect of normal operating loads on the steady-state operating stresses at the surfaces required to be peened.

The testing shall be used to demonstrate the critical process parameters and define acceptable ranges of the parameters needed to ensure that the required residual stress field (exclusive of normal operating stresses) has been produced on the mitigated surface.

4.3.8.1.1 Magnitude of Surface Stress

The combination of demonstration testing and analysis shall show that the steady-state operating stresses combined with residual stresses do not exceed +10 ksi (+70 MPa) (tensile) on the required application surface.[9]

4.3.8.1.2 Nominal Depth of Compressive Residual Stress

The testing shall demonstrate that the nominal depth of the compressive surface residual stress field produced by the peening technique is at least:[10]

a) 0.04 in. (1.0 mm) on the outside surface of the nozzle and wetted surface of the attachment weld and butter susceptible to PWSCC initiation as defined in Section 4.3.8.1.

b) 0.01 in. (0.25 mm) on the inside surface of the nozzle susceptible to PWSCC initiation as defined in Section 4.3.8.1.

The nominal depth refers to the depth of the compressive residual stress that is reliably obtained in demonstration testing, i.e., for at least 90% of the locations measured.

4.3.8.2 Sustainability

Analysis or testing shall be performed to verify that the peening process maintains the surface stress state no greater than +10 ksi (+70 MPa) tensile (normal operating and residual stress) for at least the remaining service life of the component. The analysis or demonstration test plan shall

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[9] Some advanced peening processes result in a very thin surface layer (i.e., within 0.001 to 0.002 inch (25 to 50 μm) from the surface) where the residual stress is tensile or not as compressive as the residual stress deeper into the material. For example, see Figures A-14, A-42, and A-43 of MRP-267, Rev. 1 [4]. The underlying compressive residual stresses prevent development of significant PWSCC cracks at the surface. Thus, the residual stresses in this very thin surface layer may be excluded when showing that the requirement of Section 4.3.8.1.1 is met. The combination of demonstration testing and analysis shall show that the steady-state operating stresses combined with residual stresses do not exceed +10 ksi (+70 MPa) (tensile) immediately beyond the very thin surface zone of elevated residual stress.

[10] Some advanced peening processes result in a very thin surface layer (i.e., within 0.001 to 0.002 inch (25 to 50 μm) from the surface) where the residual stress is tensile. The tensile residual stresses in this very thin surface layer may be excluded when showing that the requirement of Section 4.3.8.1.2 is met. The testing shall demonstrate that the nominal depth of the compressive surface residual stress field, excluding the very thin layer of tensile stress at the surface, is at least 0.04 in. (1.0 mm) or 0.01 in. (0.25 mm) as defined in Section 4.3.8.1.2. The depth measurement shall be from the surface to the point where the compressive residual stress becomes neutral.

include startup and shutdown stresses, normal operating pressure stress, thermal cyclic stresses, transient stresses, and residual stresses. The analysis or demonstration test shall account for:

(a) load combinations that could relieve stress due to shakedown

(b) any material properties related to stress relaxation over time

4.3.8.3 UT Inspectability

The capability to perform ultrasonic examinations of the relevant volume of the component shall not be adversely affected. Ultrasonic examinations shall be performed using personnel, procedures, and equipment qualified by blind demonstration on representative mockups that meet the requirements of –2500 and the conditions in 10 CFR 50.55a(g)(6)(ii)(D)(*4*). Testing shall be performed to demonstrate that the examination volume of the mitigated component can be examined subsequent to mitigation, including changes to component geometry, material properties, or other factors.

4.3.8.4 Lack of Adverse Effects

Analysis or testing shall be performed to verify the following:

(a) The mitigation process, including any vibration effects during application, does not degrade the component or adversely affect other components in the system, including but not limited to any thermal sleeve present within the nozzle or funnel directly attached to the end of the nozzle.

(b) The mitigation process does not cause erosion of surfaces, undesirable surface roughening, or detrimental effects in the transition regions adjacent to the peened regions.

4.3.8.5 NDE Qualification

The relevant volume or surface shall be inspectable using a qualified process. An evaluation shall be performed to confirm that the required examination volume and surfaces of the mitigated configuration are within the scope of the qualification.

Table 4-3
Inspection Requirements for Alloy 600 RPVHPNs Mitigated by Peening

EXAMINATION CATEGORIES						
CLASS 1 PWR REACTOR VESSEL UPPER HEAD						
Item No.	Parts Examined	Examination Requirements/ Fig. No.	Examination Method	Acceptance Standard	Extent and Frequency of Examination	Deferral of Examination to End of Interval
B4.50	Head with UNS N06600 nozzles and UNS N06082 or UNS W86182 partial-penetration welds mitigated by peening qualified in accordance with Section 4.3.8	Figure 1 of N-729-1	Visual, VE (1), (2)	Section 4.3.5	Each refueling outage (3), (10), (12), (13)	Not permissible
B4.60	UNS N06600 nozzles and UNS N06082 or UNS W86182 partial-penetration welds mitigated by peening in accordance with Section 4.3.8	Figure 2 of N-729-1 (5)	Volumetric (6) Surface (6)	Section 4.3.5	All Nozzles, not to exceed one inspection interval (nominally 10 calendar years) (9), (11), (12), (13)	Not permissible

NOTES: (1) through (5) and (7) are identical to those in ASME Code Case N-729-1 [2]

(6) Volumetric or surface examinations shall be performed on essentially 100% of the required volume or equivalent surfaces of the nozzle tube, as identified by Figure 2 of N-729-1. A demonstrated volumetric or surface leak path assessment through all J-groove welds shall be performed. For leaking penetrations, the meandering fluid stream pattern of the ultrasonic data display represents the leak path of the primary coolant from the pressure vessel to the atmosphere. If a surface examination is being substituted for a volumetric examination on a portion of a penetration nozzle that is below the toe of the J-groove weld (Point E in Figure 2 of N-729-1) the surface examination shall be on the penetration nozzle inside and outside wetted surface.

(8) If flaws are attributed to PWSCC, whether or not acceptable for continued service in accordance with -3130 or -3140 of N-729-1, the re-inspection interval shall be each refueling outage. Additionally, repaired areas shall be examined during the next refueling outage following the repair.

(9) Includes essentially 100% of surface or volume.

(10) The frequency of the VE may be extended in the following cases:

- (a) If N-729-1 as conditioned by 10 CFR 50.55a(g)(6)(ii)(D) permits a VE interval immediately prior to peening of at least two refueling outages, the interval for performance of a VE may be extended to every second refueling outage, provided a VT-2 visual examination of the vessel head is performed under the insulation through multiple access points during refueling outages in which the VE is not completed. If the interval is extended to every second refueling outage, a VE must be performed either during the refueling outage of the peening or during the subsequent refueling outage. The VT-2 visual examination may be performed with the reactor vessel depressurized.
- (b) If EDY < 8 at the time of peening and no flaws unacceptable for continued service under -3130 or 3140 of N-729-1 have been detected in the first or second refueling outage following peening mitigation, the interval for performance of a VE may be extended to every third refueling outage or 5 calendar years, whichever is less, provided a IWA-2212 VT-2 visual examination of the vessel head is performed under the insulation through multiple access points during refueling outages in which the VE is not completed. The VT-2 visual examination may be performed with the reactor vessel depressurized. The VE may be delayed one refueling outage so it can be performed in conjunction with the volumetric examination.

(11) An examination meeting the inspection requirements of Note 6 shall be performed:

- (a) for plants with EDY ≥ 8 at the time of peening, in the first and second refueling outages following peening mitigation.
- (b) for plants with EDY < 8 at the time of peening, in the second refueling outage following peening mitigation.

(12) If flaws are detected that are unacceptable for continued service in accordance with -3132.3 or -3142.3(a), they shall be corrected by repair/replacement activity of -3132.2 or -3142.3(b). The head or nozzle shall be identified as Item B4.10 or Item B4.20 of N-729-1. If peening mitigation is performed, the head or nozzle may be identified as Item B4.50 or Item B4.60.

(13) If peening mitigation techniques qualified in accordance with Section 4.3.8 are used, the following shall be met:

- (a) Volumetric examination of the volume (A-B-C-D) as identified in Figure 2 of N-729-1 shall be performed prior to application of peening mitigation techniques. This examination shall be considered the pre-service baseline examination.
- (b) Prior to peening mitigation, a documented leak path evaluation shall be performed of each penetration capable of being examined by the leak path evaluation method.
- (c) As an alternative to (a) and (b), a surface examination of A-D and C-G may be performed and considered the pre-service examination.
- (d) A documented evaluation shall be completed demonstrating that the peening mitigation techniques meet the performance criteria in Section 4.3.8.
- (e) Prior to peening, flaws detected during the pre-mitigation inspection shall be corrected by a repair/replacement activity of -3132.2.
- (f) The surfaces to be mitigated shall include the regions of the J-groove attachment weld and penetration tubing (outside and inside) susceptible to PWSCC initiation and growth.

Table 4-4
List of Requirements in Section 4.3 within the Context of N-729-1

Report Section	Referenced Part of N-729-1	Insertion / Replace N-729-1 Material	Summary of Requirement
4.3.5	Note (5) of Table 4-3	Modification	Incorporation of the NRC condition specified in 10 CFR 50.55a(g)(6)(ii)(D)(*6*)
4.3.5	-3141(d)(1) -3141(d)(2)	Insertion	Visual examination acceptance standards, and requirements for returning a penetration to inspection per Item B4.50 following detection of an indication subsequent to peening
4.3.5	-3131(d)(1) -3131(d)(2)	Insertion	Surface and volumetric examination acceptance standards, and requirements for returning a penetration to inspection per Item B4.60 following detection of an indication subsequent to peening
4.3.5	-3132.3	Modification	Omit the phrase "of the 2004 Edition" from the second to last sentence of paragraph -3132.3
4.3.6	-2500	Modification	Incorporation of the NRC condition specified in 10 CFR 50.55a(g)(6)(ii)(D)(*4*)
4.3.6	-2500	Insertion	Provides performance requirements for any surface examinations performed
Subsections of 4.3.8	Mandatory Appendix II	Insertion	Provides the performance criteria that a peening method must be performed in accordance with to use the inspection requirements of Table 4-3
Table 4-3	Table 1	Insertion, Except modification of Notes (6), (8), (9), (10)	Specifies inspection requirements for Alloy 600 RPVHPNs mitigated by peening

5 SUPPORTING ANALYSES

5.1 Approach

To demonstrate the benefit 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 the PWSCC degradation process. This section, in conjunction with the additional detail provided in Appendix A and Appendix B, provides the technical bases for the inspection requirements of Section 4.

The deterministic analyses specifically investigate the effect 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. Stress profiles representative of those present in components before peening and after peening are considered. The main beneficial effect of peening comes from the arrest of shallow cracks and prevention of PWSCC initiation. The deterministic crack growth analyses demonstrate that flaws significantly deeper than the peening compressive residual stress layer tend to grow in depth at a rate similar to that for the unmitigated case. The deterministic crack growth calculation methodology is implemented within the probabilistic framework for the purpose of assessing the effectiveness of follow-up and ongoing ISI examinations in addressing the potential effects of any pre-existing flaws not detected in the pre-peening examination.

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. The probabilistic analyses show that the application of peening coupled with the required post-peening in-service inspection schedules results in reduced safety risk as compared to that associated with unpeened components inspected at the currently required schedules.

The benefit of peening in the deterministic and probabilistic analyses is modeled on the basis of the compressive residual stress field assumed to be induced at the treated surface by peening. The main analysis cases apply the bounding stress conditions meeting the performance criteria of Section 4, i.e., the minimum acceptable nominal depth of the compressive residual stress layer and the limiting magnitude of the residual plus normal operating stress at the peened surface.

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 stress profiles assumed before and after peening. In areas where the superposition of peening residual stress and operating stress results in a layer of compressive stresses near the peened surface, shallow cracks located within this compressive layer do not grow via PWSCC because of the lack of tensile forces acting on the crack flanks and the lack of a positive stress intensity factor at the crack tip. The bounding peening stress effect meeting the performance criteria of Section 4 are used in the main calculation cases.

Section 5.2.2 gives deterministic growth calculations for cracks assumed to remain active after an outage in which inspection and peening occur. In addition to the bounding cases meeting the performance criteria, cases are shown for stress profiles reflecting a larger peening stress effect based on stress measurements documented in MRP-267 Rev. 1 [4].

Section 5.2.3 documents a validation study demonstrating congruity of stress intensity factors calculated with an analytical weight function method and with a high-fidelity finite element approach.

5.2.1 Effect of Peening on Stress Profile

The modeled post-peening residual stress profile is characterized by a thin compressive region near the peened surface followed by a rapid transition to the pre-peening residual stresses. The key attributes of this stress profile are the compressive stress magnitude at the surface and the penetration depth – the depth to which peening imparts compressive stresses. These attributes are assumed to be the same in orthogonal directions (i.e. hoop and axial stresses). An example post-peening stress profile is shown in Figure 5-1 and is repeated for the region near the peened surface in Figure 5-2 (the details of which are given in Appendix A). The quantities given in the remainder of this subsection are assumed for the deterministic crack growth analyses in Section 5.2.2. Input values corresponding to the bounding performance criteria for the post-peening residual stress are assumed for the deterministic crack growth analyses.

Bounding Peening Stress Profile

The magnitude of the peening compressive residual stress on the peened surfaces is chosen to obtain the bounding surface stress allowed in Section 4:

- For piping dissimilar metal butt welds (DMWs), the residual plus normal operating stress remains compressive for all wetted surfaces along the susceptible material. Thus, the peening compressive stress at the surface is set to result in a total (operating plus residual) stress of zero at the circumferential location and for the principal stress direction with the maximum operating stress.
- For reactor pressure vessel head penetration nozzles (RPVHPNs), the residual plus normal operating stress on the peened surface does not exceed +70 MPa (+10 ksi), and the residual stress on the peened surface is compressive. Thus, the peening compressive stress at the surface is set to result in a net tensile stress of +70 MPa (+10 ksi) in the direction of maximum operating stress for flaws on the nozzle ID surface, and a residual stress value that results in a net stress of 0 MPa (0 ksi) is assumed for the peened surface of the nozzle OD and weld since the operating stress in those regions is small.

The penetration depth of peening is expected to vary depending on the component and location being peened. The depths of the peening compressive residual stress layer in the analyses are

assumed to be commensurate with the bounding performance criteria meeting the minimum acceptable stress effect described in Section 4:

- For the ID of a DMW component, a 1.0 mm (0.04 inch) deep layer of compressive residual stress is assumed.
- For the ID of a RPVHPN, a 0.25 mm (0.01 inch) deep layer of compressive residual stress is assumed.
- For the nozzle OD and weld wetted surfaces of a RPVHPN, a 1.0 mm (0.04 inch) deep layer of compressive residual stress is assumed.

It is noted that after the superposition of operational loads (e.g., pressure loads) with the residual stresses, the depth of the compressive layer during operation 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. For most of the bounding calculations in Section 5.2.2, the compressive residual stress layers are modeled as becoming almost entirely tensile during operation.

Example Representative Peening Stress Profile

In addition to the bounding case based on the bounding stress effect meeting the performance criteria, cases are also evaluated using a peening residual stress profile representative of stress measurements documented in MRP-267 Rev. 1 [4]:

- For all components, a compressive residual stress magnitude at the surface of 689.5 MPa (100 ksi) is assumed. 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. While thermal and load cycling may reduce the compressive stress magnitude over the operating lifetime of the plant (with a large majority of relaxation occurring during the first operational cycle after peening), the stress magnitude for these cases is chosen to demonstrate the crack growth behavior in components where peening induces a highly compressive residual stress.
- For the ID of a DMW component, a compressive residual stress depth of approximately 1.0 mm (0.04 inch) is assumed, based on the expected capability of applicable peening techniques.
- For the ID of a RPVHPN, a compressive residual stress depth of approximately 0.5 mm (0.02 inch) is assumed.
- For the outer surface locations (weld and nozzle OD) of a RPVHPN, the compressive residual stress depth is assumed to be approximately 3.0 mm (0.12 inch).

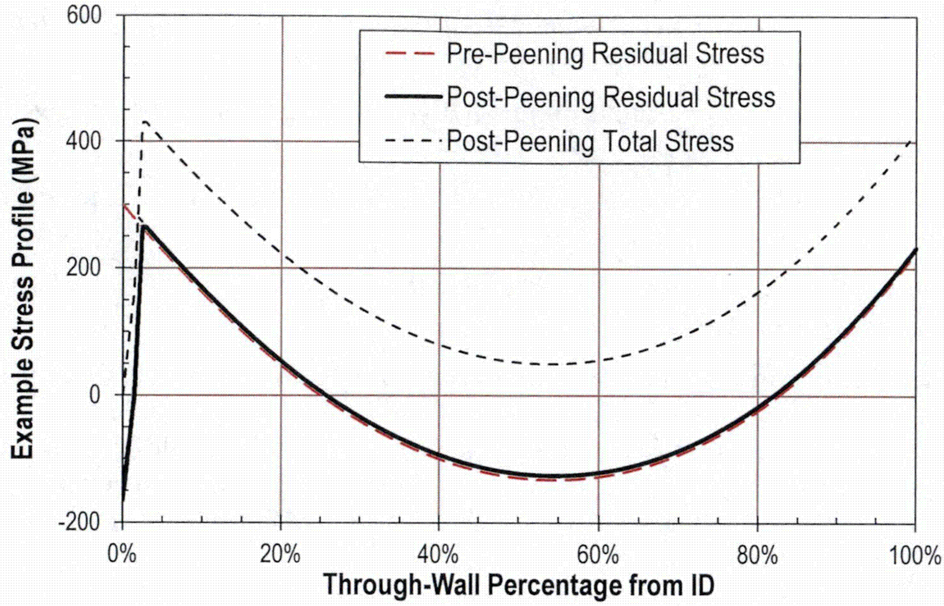

Figure 5-1
Example Post-Peening Stress Profile for Circumferential Crack in a DMW Component

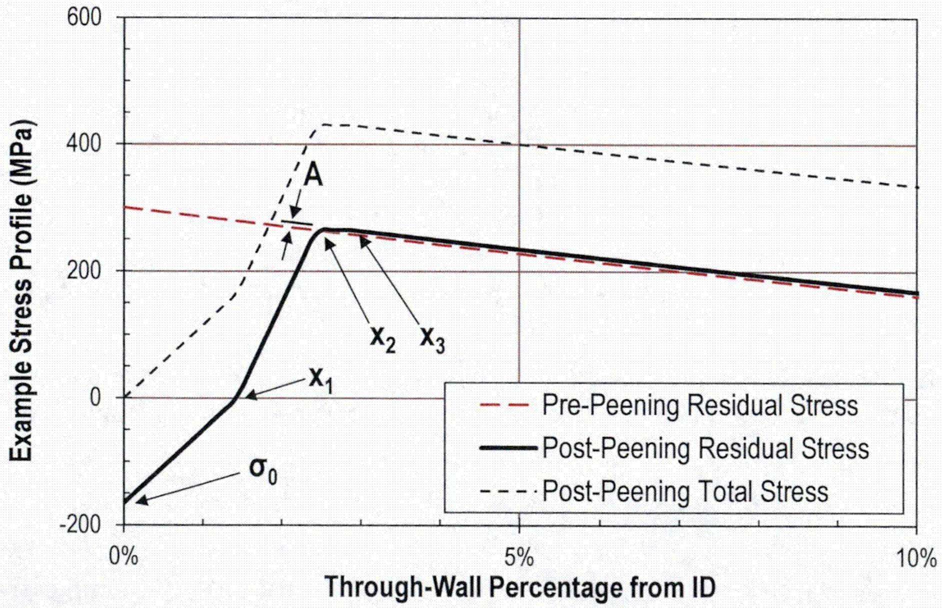

Figure 5-2
Example Post-Peening Stress Profile near Surface of Circumferential Crack in a DMW Component

5.2.2 Crack Growth

This section presents predictions for crack growth in unmitigated and peened components so as to demonstrate the effects of peening. Growth predictions are given for cracks on the inner diameter of DMW components (Section 5.2.2.1) and at various locations on reactor vessel head

penetrations (Section 5.2.2.2). 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 5-3 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. Accounting for crack closure has no effect when the surface stress is modeled to be tensile during operation. 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. One exception is that the 75th percentile of material variability is used to model the crack growth rates, in line with MRP-55 [24] and MRP-115 [25]. 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 instances in which they do not match the median of their analogous distributed input are bolded. The selection and/or derivation of the distributed inputs, and effectively the deterministic inputs, are detailed in appendix Sections A.8 and B.8.

5.2.2.1 Dissimilar Metal Welds (DMWs)

Two distinct DMW crack morphologies 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 variation factor for crack growth is set to its 75th percentile value (1.49) to generate these results. The temperature of the component is set to 625°F for the deterministic crack growth calculations, corresponding to bounding reactor vessel outlet nozzle operating conditions.

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.

<u>Bounding Peening Stress Profile</u>

For a flaw with an initial through-wall fraction of 10% (7.0 mm), Figure 5-4 shows the calculated growth vs. time for a circumferential crack, and Figure 5-5 shows the equivalent calculation for an axial crack. This initial through-wall fraction is the threshold below which the POD is conservatively assumed to be zero. At this initial through-wall fraction, peening has a small effect on the rate of growth, delaying through-wall growth by approximately 7 months for the circumferential crack and by less than 1 month for the axial crack.

Peening has a greater effect on the through-wall growth rates of cracks that are smaller at the time of peening. Despite the bounding compressive residual stress profile that is assumed, Figure 5-6 and Figure 5-8 (initial through-wall fraction of 1.3% (0.9 mm)) show the effect peening can have on cracks with depths similar to the depth of the peening penetration depth, nearly doubling (70% longer for circumferential flaw and about 100% longer for axial flaw) the time to through-wall growth. For an axial crack with an initial through-wall fraction of 0.7% (0.5 mm) the peening stresses are predicted to arrest growth entirely. Figure 5-7 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 lower and this acts to slow or stop growth.

Figure 5-6 through Figure 5-8 also include 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 along the surface, which increases the stress intensity factor at the deepest point on the crack (as demonstrated in Figure 5-7). Accounting for partial crack closure has a minor effect for this weakly compressive peening stress profile; it has a greater effect for highly compressive peening residual stress profiles but still only effects growth when the crack depth is similar to the peening penetration depth.

The subsequent figures, Figure 5-9 through Figure 5-11, present the results for a range of initial crack sizes by plotting the calculated time for a crack to grow through-wall as a function of the initial through-wall fraction. Figure 5-10 and Figure 5-11 provide a log-scale presentation to better detail the initial through-wall fractions for which peening has a greater effect.

Figure 5-12 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% to 40% faster than the shorter crack.

Figure 5-13 shows that the lower operating temperature of a reactor vessel inlet nozzle (RVIN) results in a much greater period of growth before a crack penetrates through-wall. As expected, the results scale directly with the Arrhenius factor for crack growth (changing from 625°F to 563°F scales the time to leakage by a factor of 4.8).

<u>Example Representative Peening Stress Profile</u>

Using the example representative peening compressive residual stress profile with a compressive residual stress maximum value of 689.5 MPa (100 ksi) and compressive layer depth of 1.0 mm,

the analysis results are more in-line with experimental data and other information provided by vendors. In Figure 5-14 and Figure 5-15, peening is predicted to arrest growth for circumferential DMW cracks less than or somewhat (up to 50%) deeper than the compressive residual stress layer depth, depending on the calculation method for stress intensity factor. Peening can be beneficial for slowing the growth of cracks significantly (~50%-2000%) deeper than the compressive residual stress layer depth, but the effective depth depends on the nature of the stresses beyond the peening affected zone. Peening has a greater effect on growth rate of initially deep cracks in circumferential flaws because the pre-peening residual stresses are compressive in the center of the wall while axial flaws are subject to tensile pre-peening residual stresses for the entire thickness.

Approximating balloon crack growth reduces the predicted effect of peening on the CGR for cracks significantly (>50%) deeper than the compressive residual layer depth but does not affect whether a crack arrests. 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 influences growth predictions for cracks of a similar (within about 30%) depth to the compressive residual stress layer depth. As demonstrated in Figure 5-14, 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 and because the weakly compressive assumed peening stress profile for probabilistic base cases is not influenced by crack closure, it is not applied for base case probabilistic analyses, but is included for a sensitivity case.

Stress Profile with Alternate Stress Balance

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. For the prior deterministic cases, 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 for circumferential cracking with a post-peening stress profile that balances both the force and the moment imparted by the peening affected zone. This effect is obtained by introducing a linear offset term to the stress profile beyond the peening affected zone in addition to the constant offset that is shown in Figure 5-2. The modified stress profile, shown in Figure 5-16, results in slightly (less than 8%) more tensile stresses near the inner surface and more compressive stresses near the outer surface. Results for these calculations are compared with the standard approach (force balanced) in Figure 5-17. As expected, the effect is small with less than 7% difference in time to leakage between the two re-balancing conventions.

The same base modeling convention in Section 5.2.1 of balancing the axial and hoop force imparted by peening using a constant offset of the residual stress profile beyond the peening affected zone is used for the probabilistic modeling. The base modeling simplification in Section 5.2.1 is appropriate for the relatively large wall thickness of reactor vessel outlet and inlet nozzles in comparison to the depth of the peening compressive residual stress layer. This behavior was confirmed by the sensitivity case that considered the effect of the balancing

through-wall bending moment on the tensile stress profile. A small difference in the crack-tip stress intensity factor and crack growth time (< 7% in time) resulted versus the base case. Furthermore, it is emphasized that the time for through-wall crack growth is not a key factor for the effectiveness of peening mitigation.

Table 5-1
Inputs for DMW Deterministic Calculations

Symbol	Description	Units	Value	Units	Value
	General Component Inputs				
t	Component wall thickness	in	2.750	m	0.0699
D_o	Component outer diameter	in	35.500	m	0.9017
w	DM weld width	in	1.752	m	0.0445
T	Operating temperature - Hot Case	°F	625	°C	329
	Operating temperature - Cold Case		563		295
P_{op}	Normal operating pressure	ksi	2.25	MPa	15.5
F_x	Effective loads for Westinghouse RVON / RVIN (including deadweight, thermal expansion, and thermal stratification loading)	kips	100	kN	444.8
M_x		in-kips	0	kN-m	0
M_y		in-kips	40000	kN-m	4519.4
M_z		in-kips	0	kN-m	0
	Growth Rate Inputs				
Q_g	Thermal activation energy for PWSCC flaw propagation	kcal/mole	31.1	kJ/mole	130.0
f_{weld}	**Weld-to-weld factor (75th percentile value)**	**Nondim**	**1.49**	**Nondim**	**1.49**
f_{ww}	**Within weld factor (median value)**	**Nondim**	**1.00**	**Nondim**	**1.00**
α	Flaw propagation rate equation power law constant	(in/hr)(ksi-in$^{0.5}$)$^{-1.6}$	1.62E-07	(m/s)(MPa-m$^{0.5}$)$^{-1.6}$	9.82E-13
b	Flaw propagation rate equation power law exponent	Nondim	1.6	Nondim	1.6
$K_{I,th}$	K_I Stress intensity factor threshold	ksi-in$^{0.5}$	0.0	MPa-m$^{0.5}$	0.0
$T_{ref,g}$	Absolute reference temperature to normalize PWSCC flaw propagation data	°F	617	°C	325
Δt	**Time step size for crack increment**	**yr**	**1/20**	**yr**	**1/20**
	Residual Stress Inputs				
σ_{0WRSa}	Weld residual axial stress on ID surface	ksi	43.6	MPa	300.3
X_c	Fractional through-thickness at which weld residual axial stress profile crosses zero	Nondim	0.25	Nondim	0.25
f_{WRSa}	Scaling factor for weld residual axial stress on OD surface	Nondim	0.75	Nondim	0.75
σ_{0WRSh}	Weld residual hoop stress on ID surface	ksi	43.6	MPa	300.3
X_{min}	Fractional through-thickness at which weld residual hoop stress is minimum	Nondim	0.5	Nondim	0.5
f_{WRSh1}	Scaling factor for minimum weld residual hoop stress	Nondim	0.5	Nondim	0.5
f_{WRSh2}	Scaling factor for weld residual hoop stress on OD surface	Nondim	1.0	Nondim	1.0
$\sigma_{0,PPRS}$	Sum of residual plus normal operating stress at the peened surfaces	ksi	0.0	MPa	0.0
$x_{1,PPRS}$	Penetration depth (depth beyond which residual stress is tensile)	in	0.04	mm	1.0
$f_{1,PPRS}$	Ratio of minimally-affected depth to penetration depth (See Section A.3.3)	Nondim	2.0	Nondim	2.0
$f_{2,PPRS}$	Fraction of depth between penetration depth and minimally affected depth where peening results in no effect (See Section A.3.3)	Nondim	0.7	Nondim	0.7

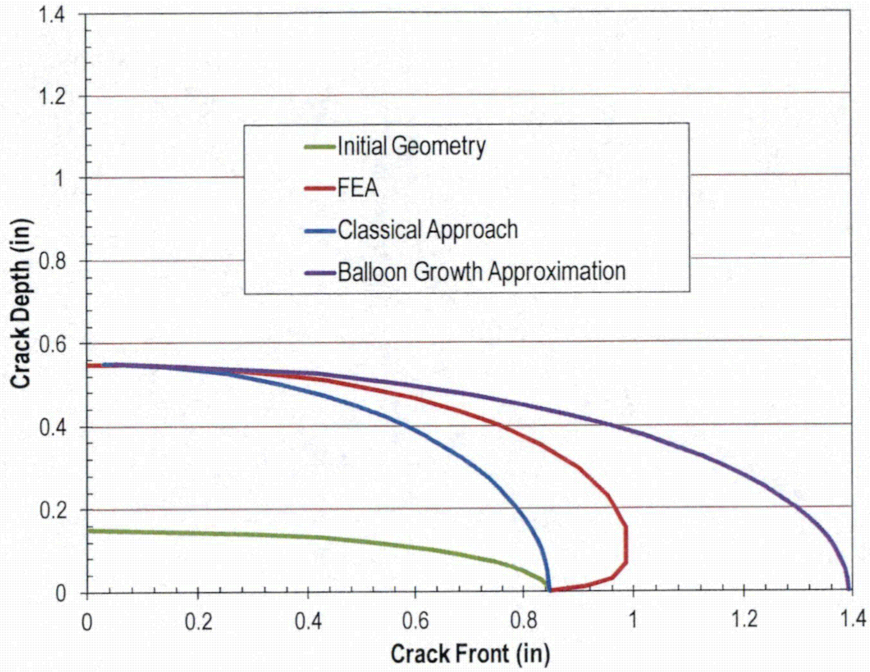

Figure 5-3
Example of Crack Front Shapes Predicted in a Peened Component with: a) FEA, b) Classical Analytical Methods, or c) the Balloon Growth Approximation

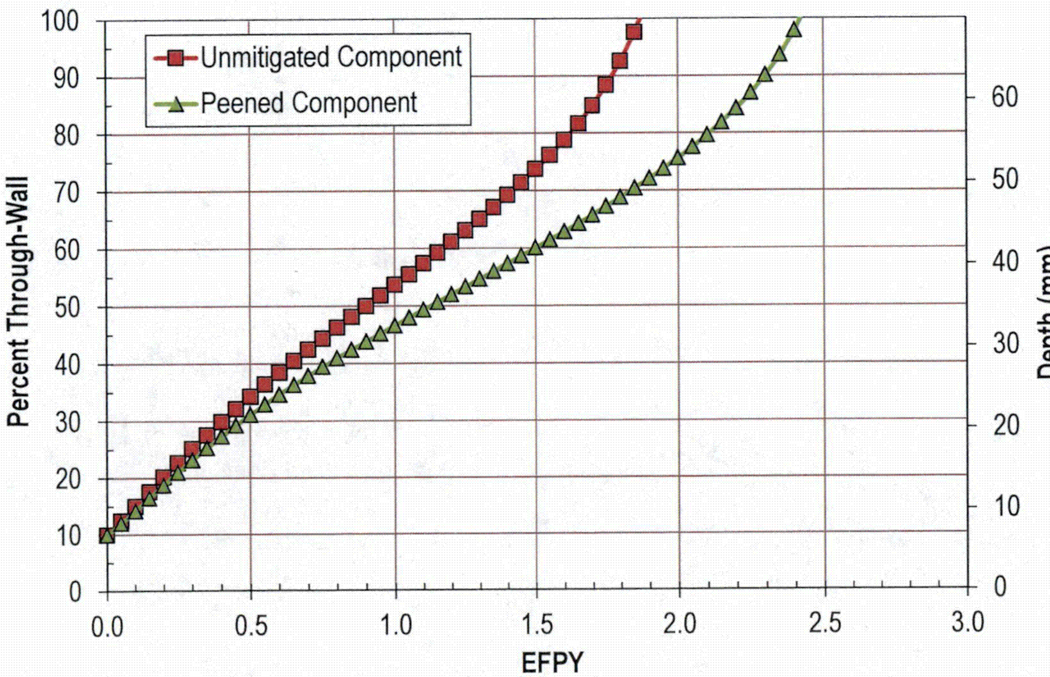

Figure 5-4
Through-Wall Fraction vs. Time for Circumferential Crack on Unmitigated and Peened Component (a_0/t=10% [7.0 mm] and $2c_0/a_0$=8.5)

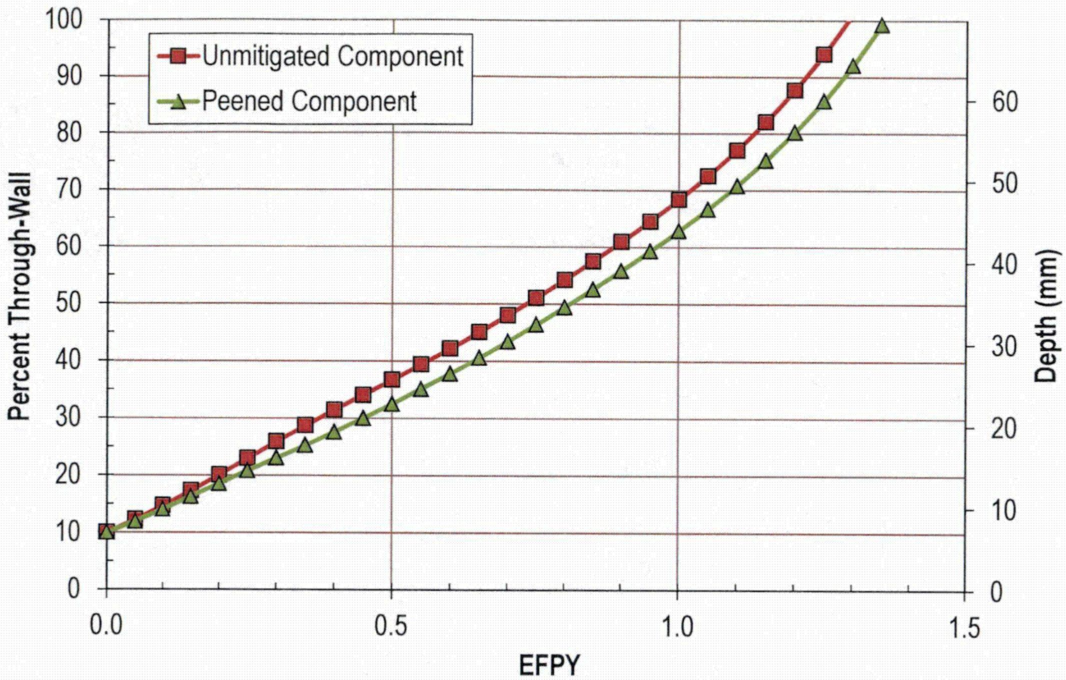

Figure 5-5: Through-Wall Fraction vs. Time for Axial Crack on Unmitigated and Peened Component (a_0/t=10% [7.0 mm] and $2c_0/a_0$=4.5)

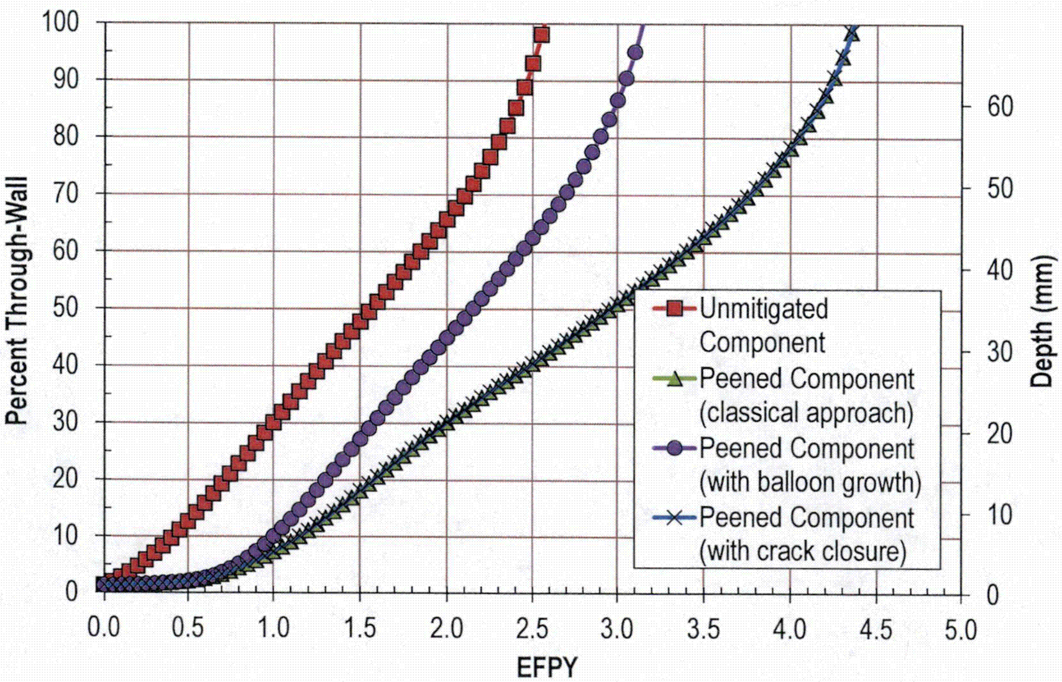

Figure 5-6
Through-Wall Fraction vs. Time for Circumferential Crack on Unmitigated and Peened Component (a_0/t=1.3% [0.9 mm] and $2c_0/a_0$=8.5)

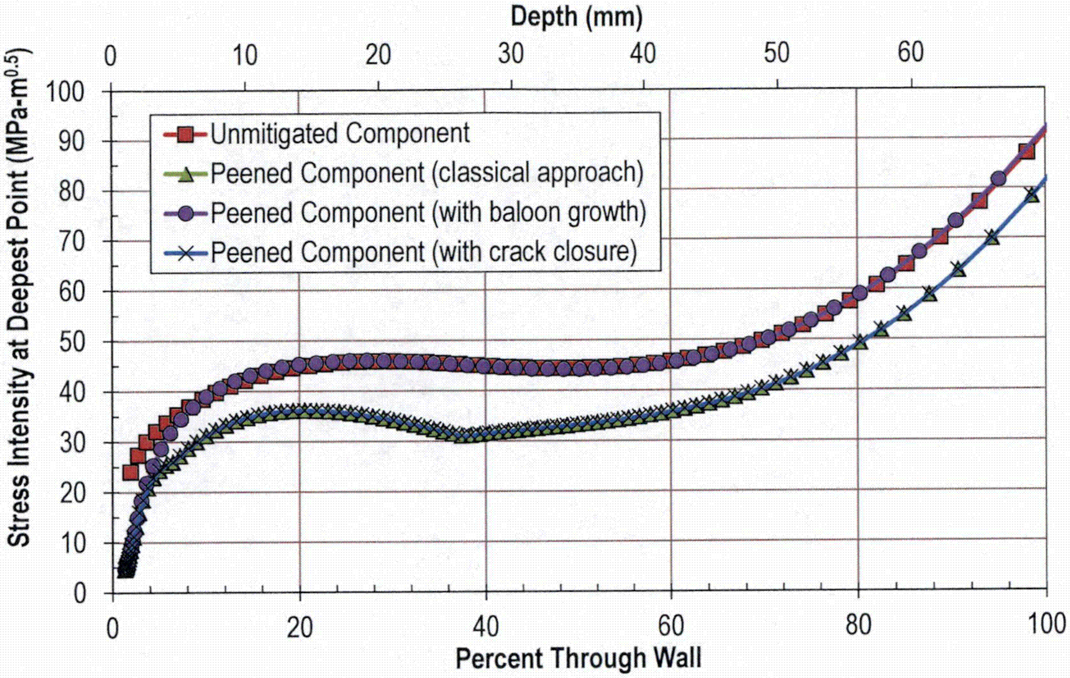

Figure 5-7
Stress Intensity Factor vs. Through-Wall Fraction for Circumferential Crack on Unmitigated and Peened Component (a_0/t=1.3% [0.9 mm] and $2c_0/a_0$=8.5)

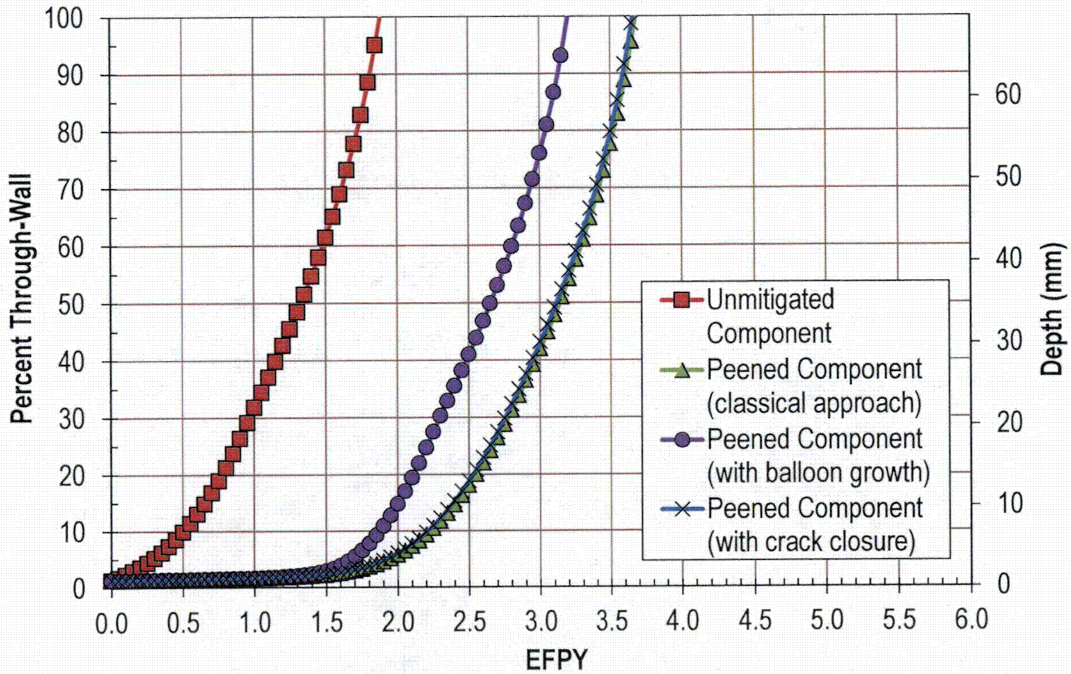

Figure 5-8: Through-Wall Fraction vs. Time for Axial Crack on Unmitigated and Peened Component (a_0/t=1.3% [0.9 mm] and $2c_0/a_0$=4.5)

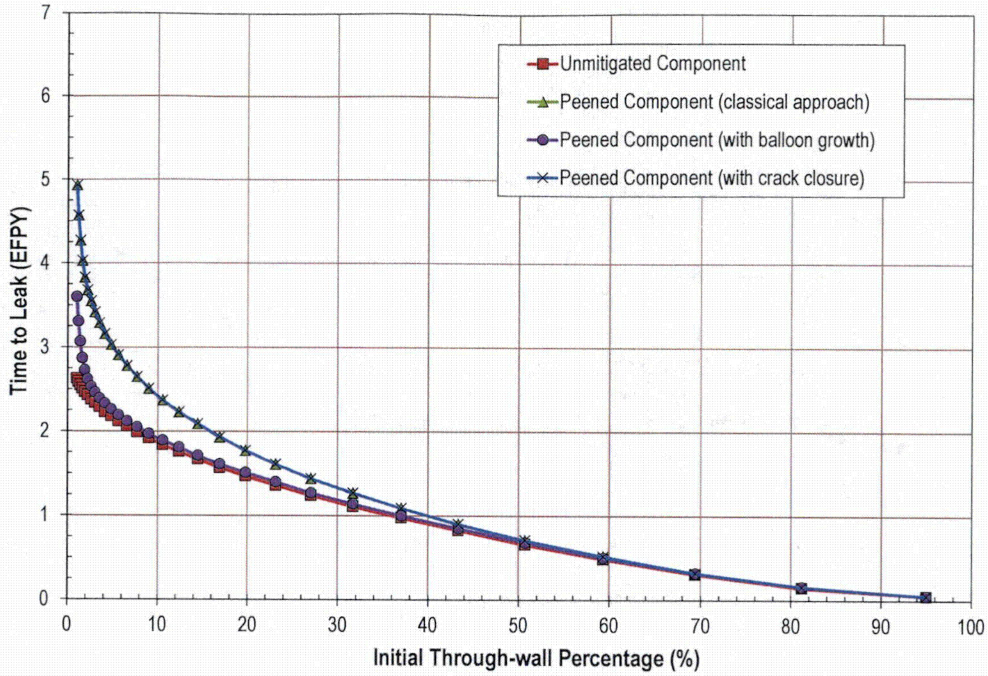

Figure 5-9
Time to Through-Wall Growth vs. Initial Crack Depth for Circumferential Cracks ($2c_0/a_0$=8.5)

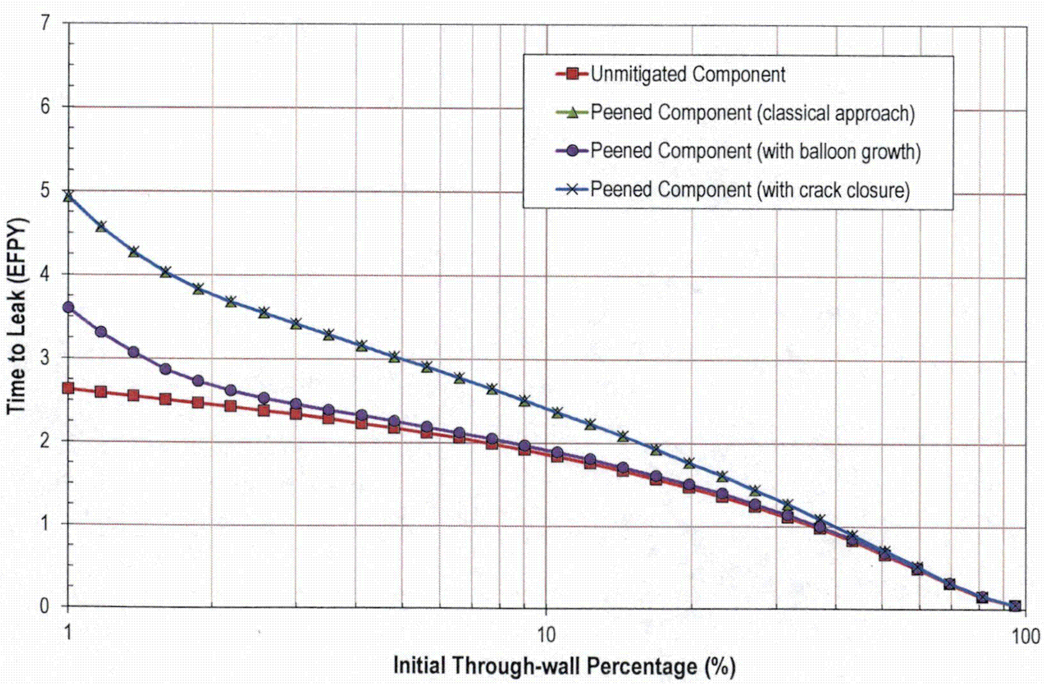

Figure 5-10
Figure 5-9 (Circumferential Cracks with $2c_0/a_0$=8.5) Replotted Using Log-Scale Abscissa

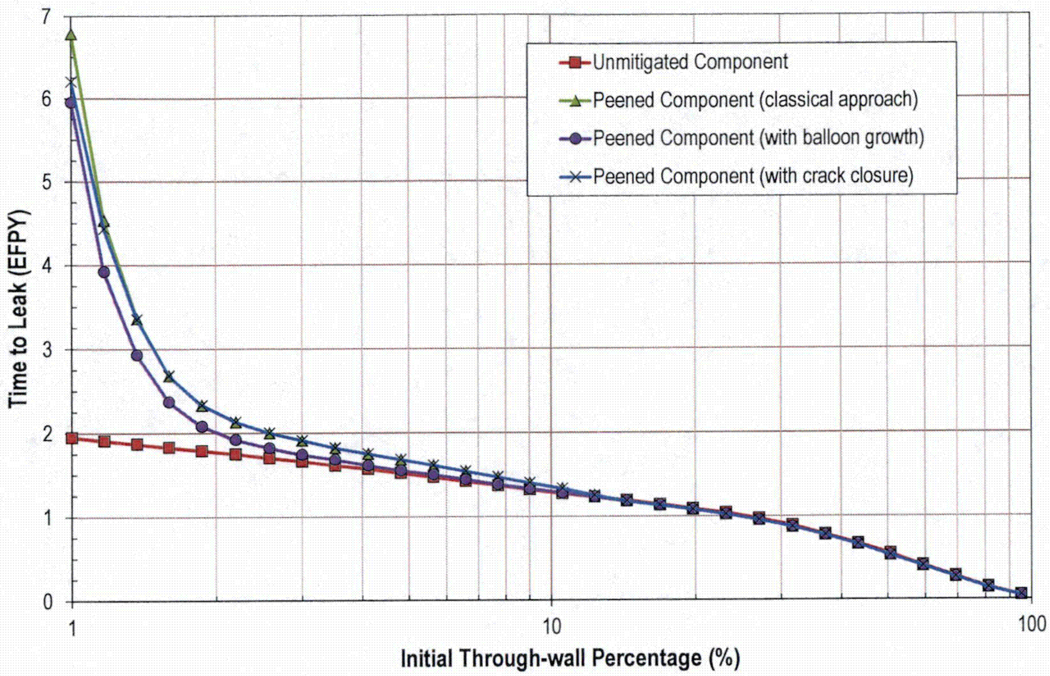

Figure 5-11
Time to Through-Wall Growth vs. Initial Crack Depth for Axial Cracks (Log-Scale Abscissa and $2c_0/a_0$=4.5)

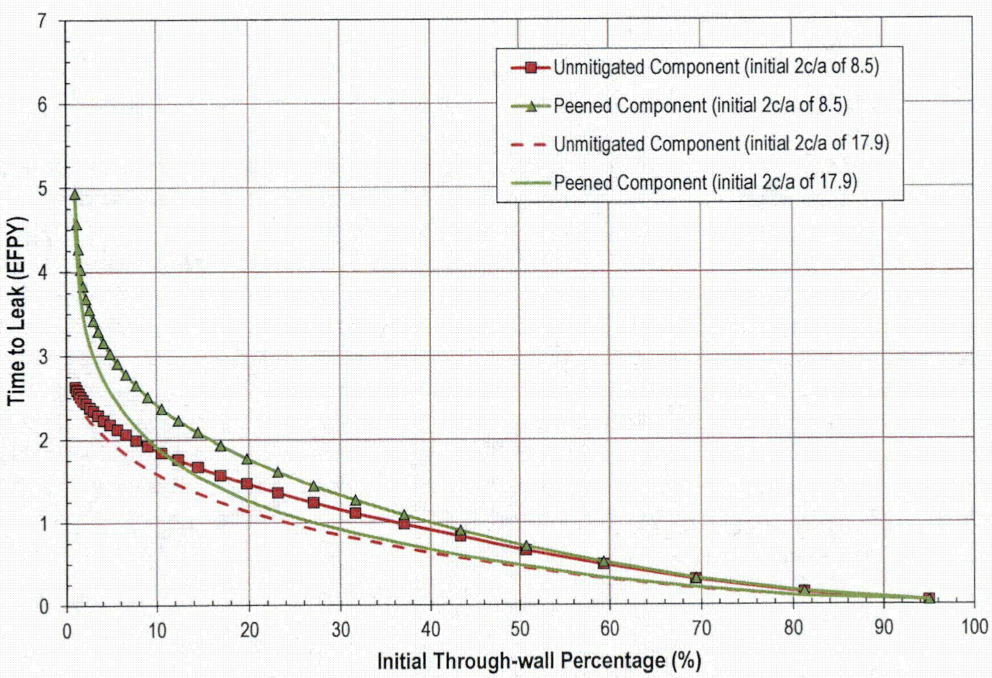

Figure 5-12
Comparing Differences due to Initial Aspect Ratio: Time to Through-Wall Growth vs. Initial Crack Depth for Circumferential Cracks

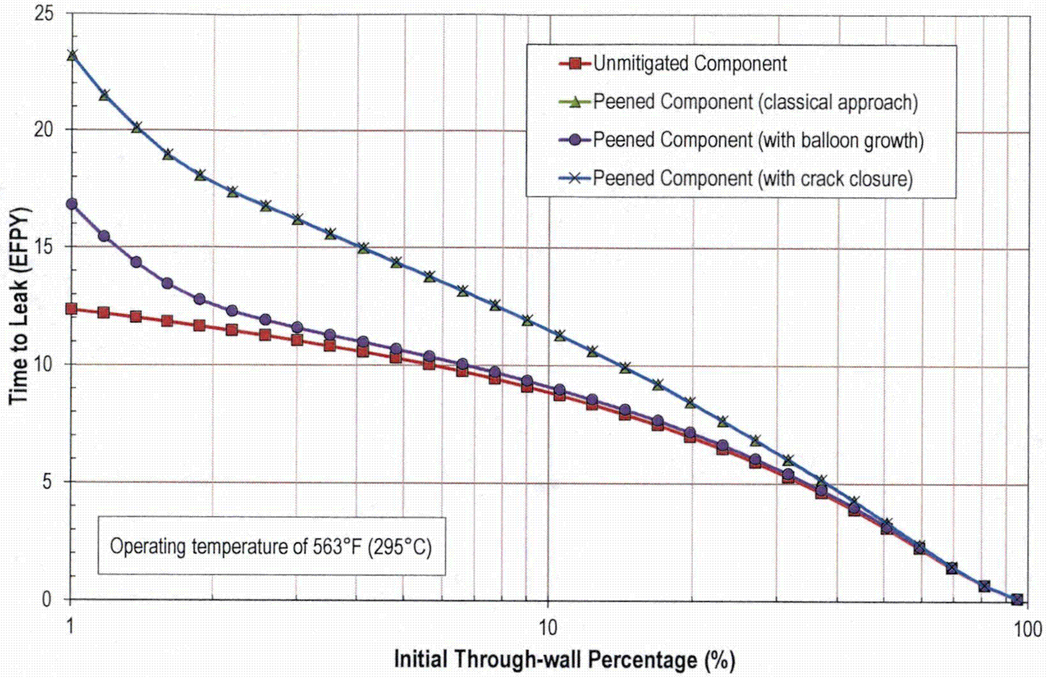

Figure 5-13
Time to Through-Weld Growth vs. Initial Crack Depth for Circumferential Crack on a RVIN ($T=563°F$ and $2c_0/a_0=8.5$)

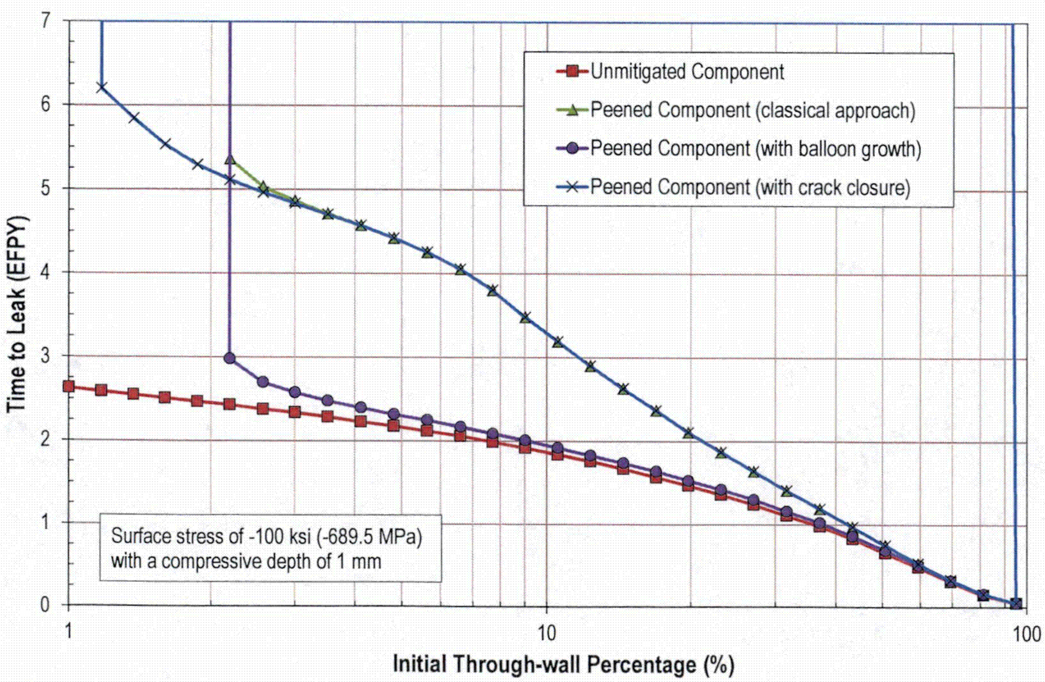

Figure 5-14
Time to Through-Weld Growth vs. Initial Crack Depth for Circumferential Crack Subject to Example Representative Peening Compressive Residual Stresses ($2c_0/a_0=8.5$)

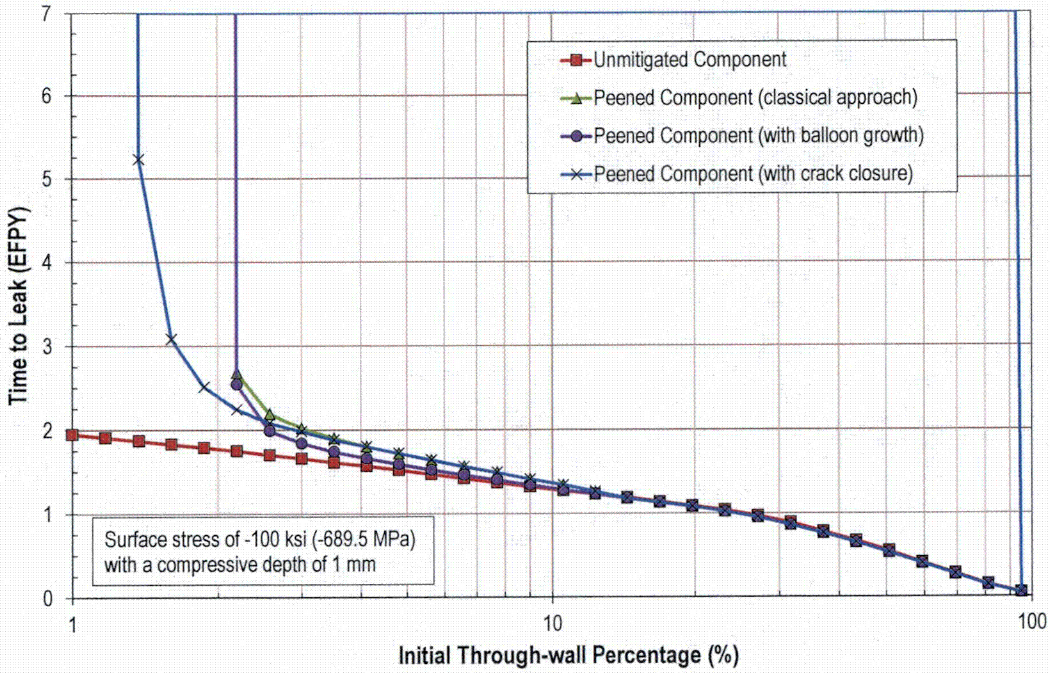

Figure 5-15
Time to Through-Weld Growth vs. Initial Crack Depth for Axial Crack Subject to Example Representative Peening Compressive Residual Stresses ($2c_0/a_0$=4.5)

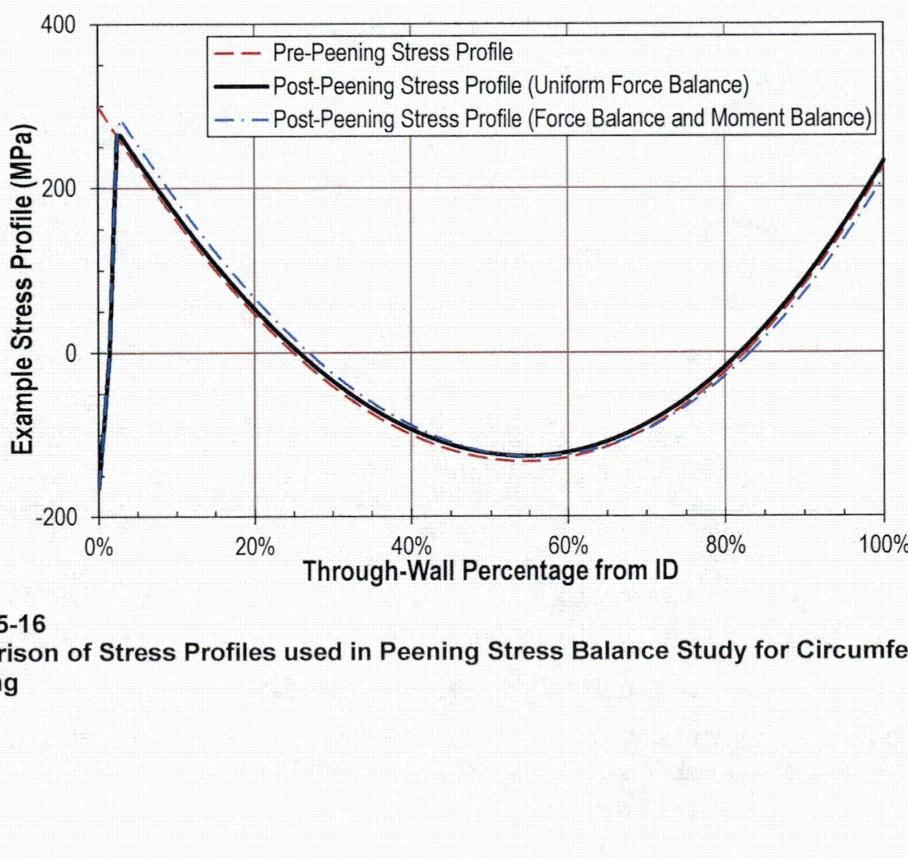

Figure 5-16
Comparison of Stress Profiles used in Peening Stress Balance Study for Circumferential Cracking

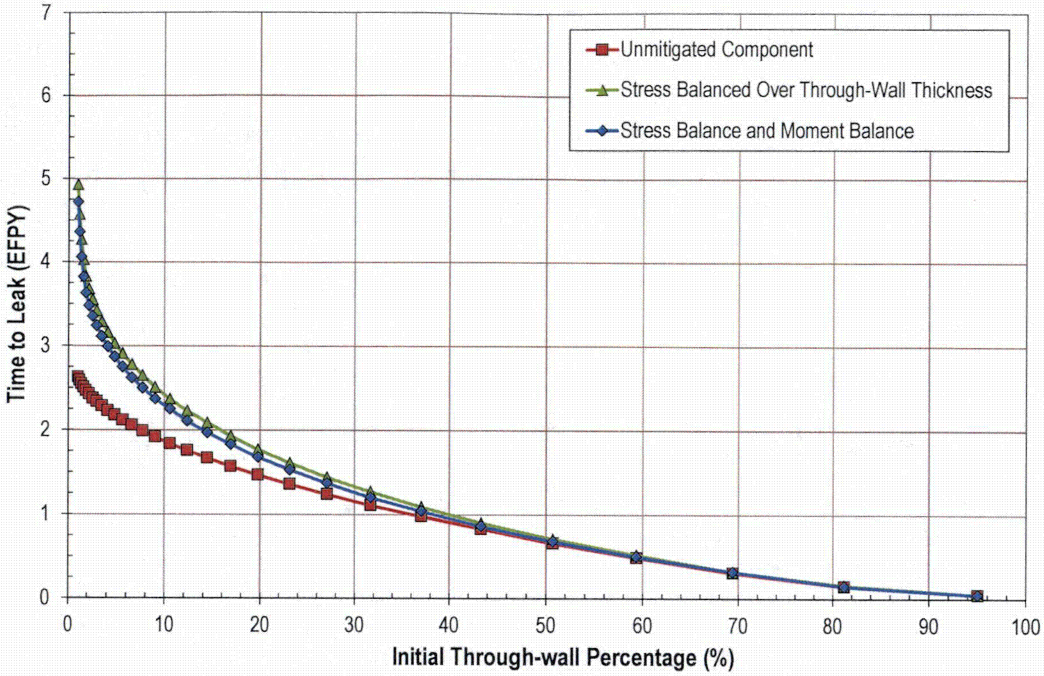

Figure 5-17
Comparing Differences due to Concentration of Force Balance: Time to Through-Wall Growth vs. Initial Crack Depth for Circumferential Cracks

5.2.2.2 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 from a part-depth flaw until the time of leakage; for the fourth crack type, growth is predicted from an initially through-wall flaw until the time of ejection.

Growth predictions for each crack type can made for the uphill and downhill locations on the penetration by 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 (1.49 and 1.98, respectively) to generate these results. The temperature of the component was set to 605°F, and cases also were run at 561°F for comparison with typical cold head operating conditions.

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 typical CRDM nozzle geometry.

<u>Crack Growth Prior to Leakage: *Bounding Peening Stress Profile*</u>

Figure 5-18 shows the growth vs. time calculation for an axial crack on the penetration nozzle ID with an initial through-wall fraction of 1% (0.16 mm). At this initial through-wall fraction, the

effect of peening is predicted to be considerable, delaying through-wall growth by approximately 5 EFPY.

Unlike ID cracks above the weld, growth of axial cracks on the penetration nozzle OD through the wall does not cause leakage. Instead, leakage occurs once an OD axial crack grows in length to reach the OD nozzle annulus beyond the weld heel. Figure 5-19 shows the calculated time history for the crack length parallel to the nozzle surface for an axial crack on the penetration nozzle OD with an initial nozzle through-wall fraction of approximately 10% (as will be demonstrated shortly, OD cracks less than approximately 4% (0.6 mm) through-wall at the time of peening are predicted to arrest). In this case the effect of peening on growth is large, delaying leakage by 1-4 EFPY for flaws up to about 30% (5 mm) through-wall at the time of peening.

Figure 5-20 shows the growth vs. time calculation for a weld crack with an initial through-wall fraction of 5% (as will be demonstrated shortly, weld cracks smaller than about 1.2%-1.9% (0.3-0.5 mm) at the time of peening are predicted to not grow through-wall in the period of operation after peening—less than 40 years). In this particular case, there is significant reduction in time to grow through-wall with peening, delaying the through-weld growth time by a factor of approximately two.

Figure 5-21 through Figure 5-26 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 downhill locations tend to grow to leak faster because of characteristically more tensile weld residual stresses.

Figure 5-25 demonstrates some initial crack depths for which the peened component results in leakage earlier than the unmitigated component. 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.

Figure 5-27 shows that the lower operating temperature of RPVHPNs in a head operating near the cold leg temperature results in a greater period of growth before a crack grows through-wall. As expected, the results scale directly with the Arrhenius factor for crack growth (changing from 605°F to 561°F scales the time to leakage by a factor of 3.1).

Crack Growth Prior to Leakage: *Example Representative Peening Stress Profile*

Figure 5-28 through Figure 5-30 present results for an example (more compressive) peening stress profile. As in the DMW deterministic analyses, peening is predicted to arrest growth for cracks less than or somewhat (up to 80%) deeper than the compressive layer depth. Peening is predicted to be beneficial for slowing the growth of cracks significantly (~80-300%) deeper than the compressive residual stress layer depth, but the potency of this effect depends on the nature of the operating stresses and residual stresses beyond the peening compressive layer (i.e. the pre-peening stresses); the effect of peening on the crack growth time rapidly fades for weld cracks deeper than the compressive layer depth. It is emphasized that the main probabilistic cases apply the bounding peening stress profile meeting the performance criteria, and thus the conclusions of this assessment regarding appropriate inspection requirements and intervals for peened components are not dependent on the benefit of these representative stress profiles in slowing growth of sufficiently shallow flaws.

Generally speaking, because penetration nozzles are thinner-walled than DMW components, the effect of peening on crack growth times is observed for cracks of greater through-wall percentages.

At the nozzle OD and weld locations, where the peening penetration depth is assumed to be 3.0 mm, cracks less than approximately 15%-35% through-wall may be arrested upon the application of peening. Figure 5-31 presents the time history for the calculated length parallel to the nozzle surface of an uphill nozzle OD flaw, demonstrating how balloon crack growth permits growth in crack length along the nozzle surface while the compressive surface stress pins the crack length using the classical and crack closure approaches to stress intensity factor calculation. In the classical approach, the compressive peening stress at the surface arrests growth of the crack surface length but the crack tip continues to grow deeper through the nozzle wall. Once the crack penetrates through-wall, growth of the crack length resumes because the effect of peening is conservatively not credited for though-wall crack growth. It is expected that the results of stress intensity factor calculations using the balloon growth approximation are the most representative of actual crack growth. Balloon crack growth is modeled in the probabilistic analysis base cases.

As with DMW components, the effect of peening on the growth of cracks that are deeper than the compressive residual stress layer depth is predicted to be small when balloon crack growth is approximated. The effect of the balloon growth approximation is not observed at weld locations, where crack surface length growth is constrained by the width of the weld.

Circumferential Through-Wall Crack Growth

Circumferential through-wall crack growth along the weld contour of penetration nozzles is a significant concern when assessing PWSCC risk in reactor vessel 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 [23]). A flaw angle of 300° is conservatively taken to be the size at which nozzle ejection occurs, per the calculations in MRP-110 [12]. 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 605°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) that are used to predict the crack growth.

Figure 5-32 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 conservatively 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 18 EFPY after initiation and uphill cracks are predicted to cause ejection approximately 23 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 9.5 EFPY after initiation.

Table 5-2
Inputs for RPVHPN Deterministic Calculations

Symbol	Description	Units	Value	Units	Value
	General Component Inputs				
t	Nozzle thickness	in	0.622	m	0.0158
D_o	Nozzle outer diameter	in	4	m	0.1016
t_{head}	Reactor head thickness	in	5.984	m	0.152
T	Operating temperature - Hot Case	°F	605.0	°C	318
	Operating temperature - Cold Case		561.0		294
P_{op}	Normal operating pressure	ksi	2.25	MPa	15.5
$f_{oper,ID}$	Penetration nozzle ID hoop stress concentration factor	Nondim	3.48	Nondim	3.48
N/A	J-groove weld geometries used to simulate crack growth of crack initiation on weld	See mean values given in Table B-3			
	Growth Rate Inputs				
Q_g	Thermal activation energy for PWSCC flaw propagation	kcal/mole	31.1	kJ/mole	130.0
f_{weld}	**Weld-to-weld factor (75th percentile value)**	**Nondim**	**1.49**	**Nondim**	**1.49**
f_{ww}	**Within weld factor (median value)**	**Nondim**	**1.00**	**Nondim**	**1.00**
f_{heat}	**Heat-to-heat factor (75th percentile value)**	**Nondim**	**1.98**	**Nondim**	**1.98**
f_{wh}	**Within heat factor (median value)**	**Nondim**	**1.00**	**Nondim**	**1.00**
α_{weld}	Flaw propagation rate equation power law constant for Alloy 182	$(in/hr)(ksi\text{-}in^{0.5})^{-1.6}$	1.62E-07	$(m/s)/(MPa\text{-}m^{0.5})^{1.6}$	9.82E-13
α_{heat}	Flaw propagation rate equation power law constant for Alloy 600	$(in/hr)(ksi\text{-}in^{0.5})^{-1.6}$	3.25E-08	$(m/s)/(MPa\text{-}m^{0.5})^{1.6}$	1.97E-13
b	Flaw propagation rate equation power law exponent	Nondim	1.6	Nondim	1.6
$K_{1,th}$	K_I Stress intensity factor threshold	$ksi\text{-}in^{0.5}$	0.0	$MPa\text{-}m^{0.5}$	0.0
$T_{ref,g}$	Absolute reference temperature to normalize PWSCC flaw propagation data	°F	617.0	°C	325
$K_{circ,mult}$	**Circumferential through-wall crack *K* curve multiplier**	**Nondim**	**1.0**	**Nondim**	**1.0**
$c_{circ,mult}$	Circumferential through-wall crack environmental factor	Nondim	2.0	Nondim	2.0
N/A	Distance below weld toe of OD crack location	in	0.13	mm	3.2
Δt	**Time step size for crack increment**	**yr**	**1/20**	**yr**	**1/20**
	Residual Stress Inputs				
N/A	Weld residual stress profile parameters	See mean values given in Table B-4			
$\sigma_{0,PPRS,ID}$	Sum of residual plus normal operating stress on nozzle ID surfaces	ksi	10.0	MPa	69.0
$x_{1,PPRS,ID}$	Penetration depth for peening performed on nozzle ID surfaces	in	0.01	mm	0.25
$\sigma_{0,PPRS,ext}$	Sum of residual plus normal operating stress on nozzle OD and weld surfaces	ksi	0.0	MPa	0.0
$x_{1,PPRS,ext}$	Penetration depth for peening performed on nozzle OD and weld surfaces	in	0.04	mm	1.0
$f_{1,PPRS}$	Ratio of minimally-affected depth to penetration depth (See Section B.3.3)	Nondim	2.0	Nondim	2.0
$f_{2,PPRS}$	Fraction of depth between penetration depth and minimally affected depth where peening results in no effect (See Section B.3.3)	Nondim	0.7	Nondim	0.7
	Stability Inputs				
$\theta_{circ,init}$	Initial angle for circumferential through-wall cracks immediately following leaks	degrees	30.0	degrees	30.0
$\theta_{circ,crit}$	Critical flaw angle for nozzle ejection	degrees	300.0	degrees	300.0

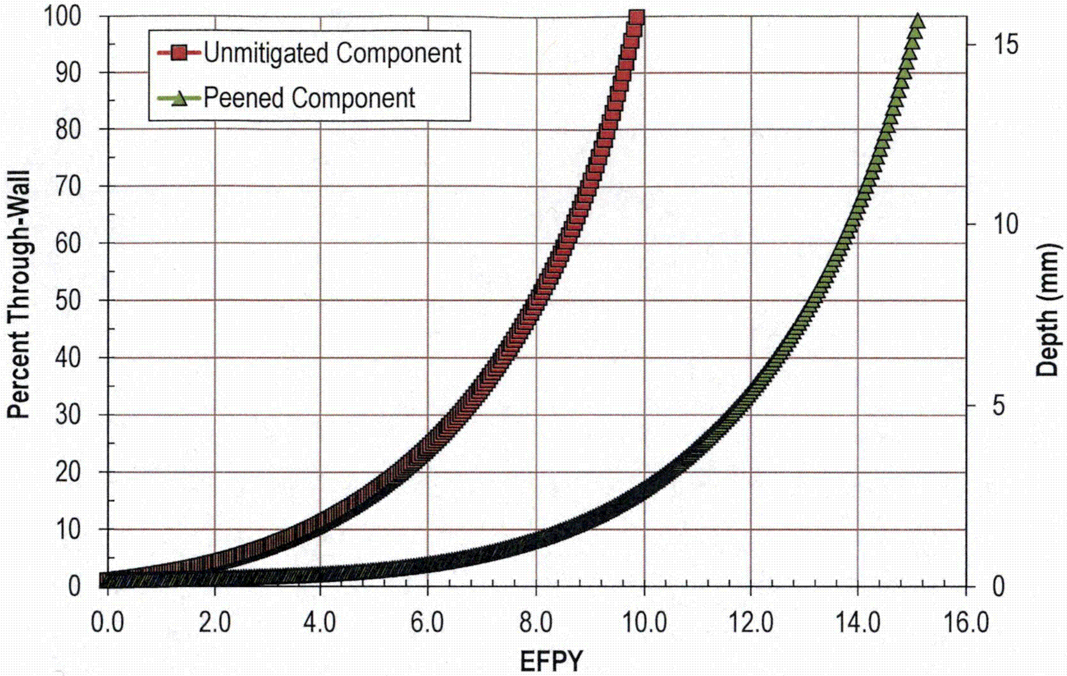

Figure 5-18
Through-Wall Percentage vs. Time for Uphill ID Axial Crack on Unmitigated and Peened Component (a_0/t=1% [0.16 mm] and $2c_0/a_0$=4.5)

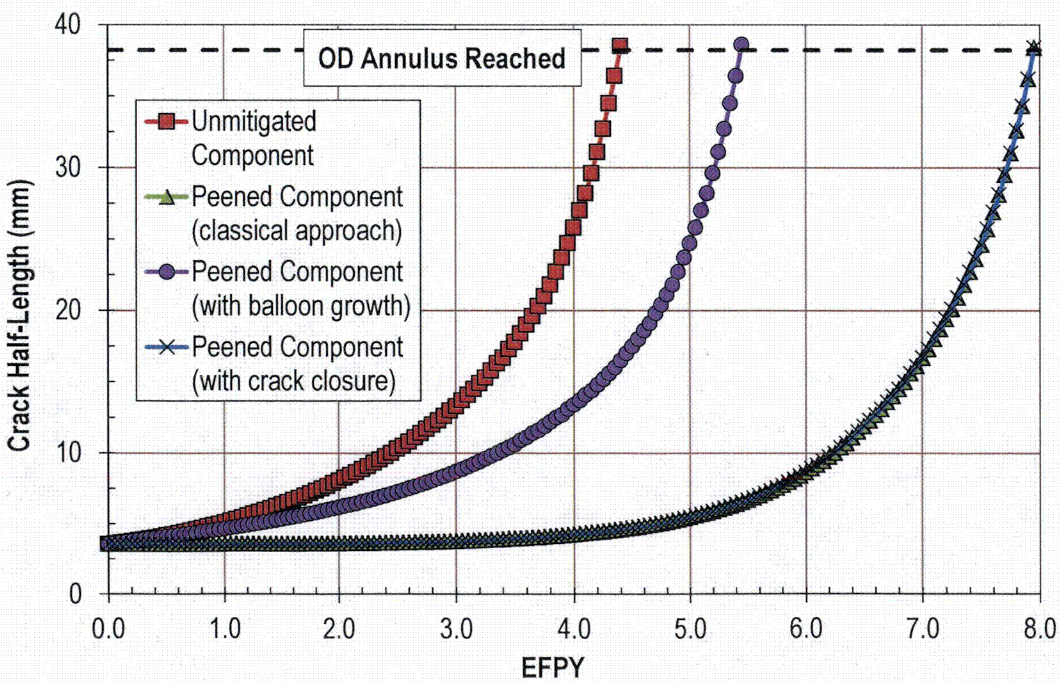

Figure 5-19
Half-Length along Nozzle Surface vs. Time for Uphill OD Axial Crack on Unmitigated and Peened Component (a_0/t=10% [1.6 mm] and $2c_0/a_0$=4.5)

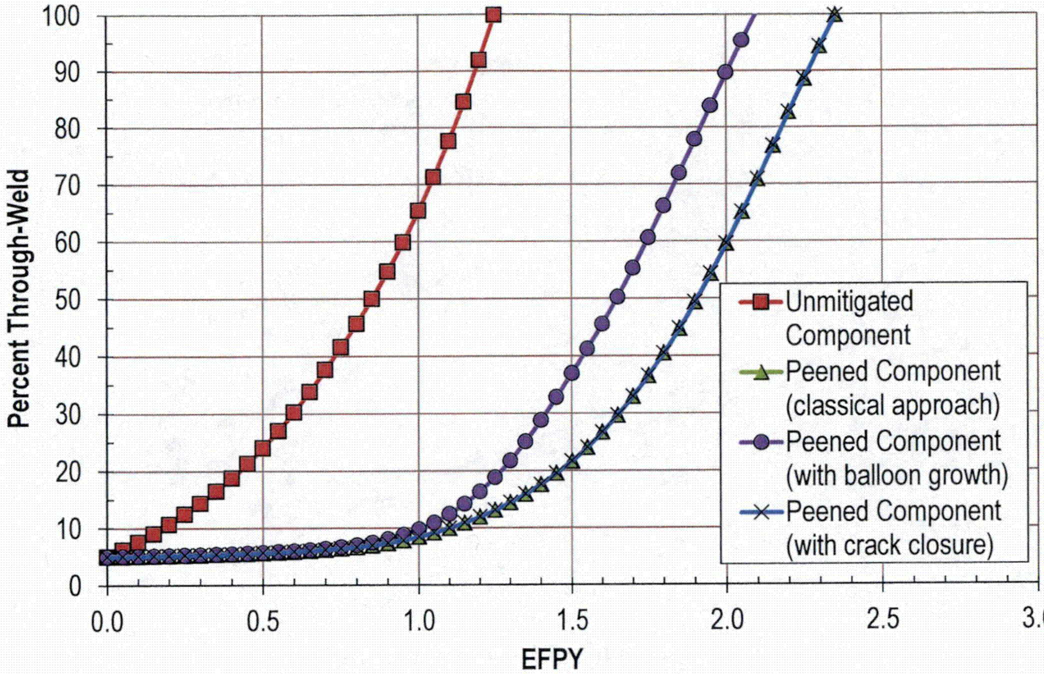

Figure 5-20
Through-Weld Percentage vs. Time for Downhill Weld Radial Crack on Unmitigated and Peened Component (a_0/t=5% [1.2 mm] and $2c_0/a_0$=4.5)

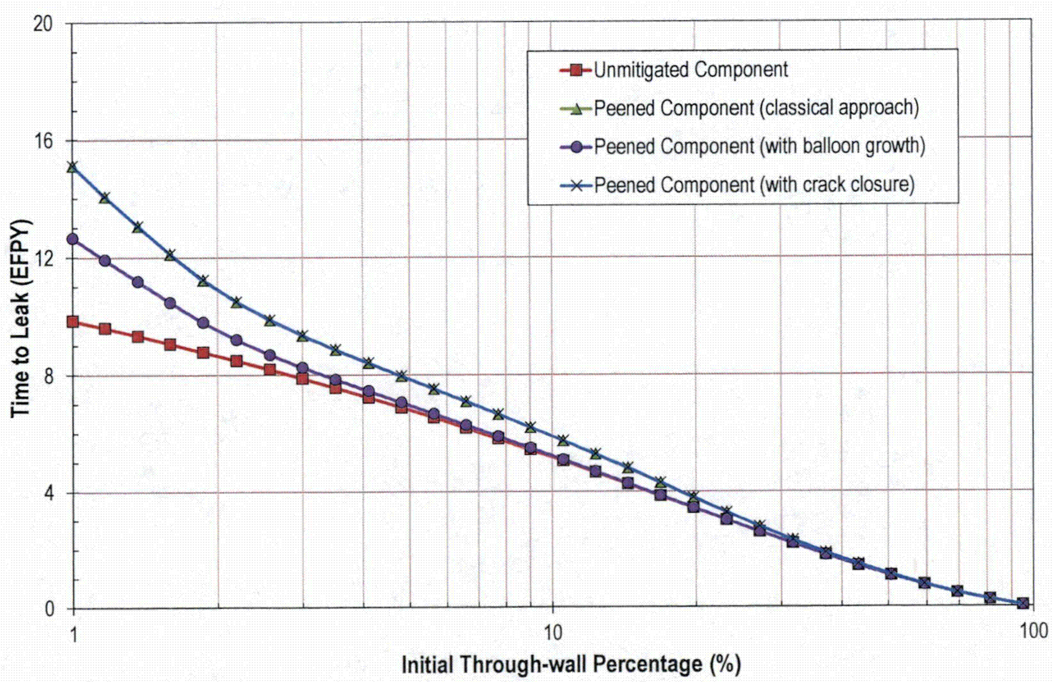

Figure 5-21
Time to Through-Wall Growth vs. Initial Crack Depth for Axial Crack on Uphill Penetration Nozzle ID (Log-Scale Abscissa, $2c_0/a_0$=4.5)

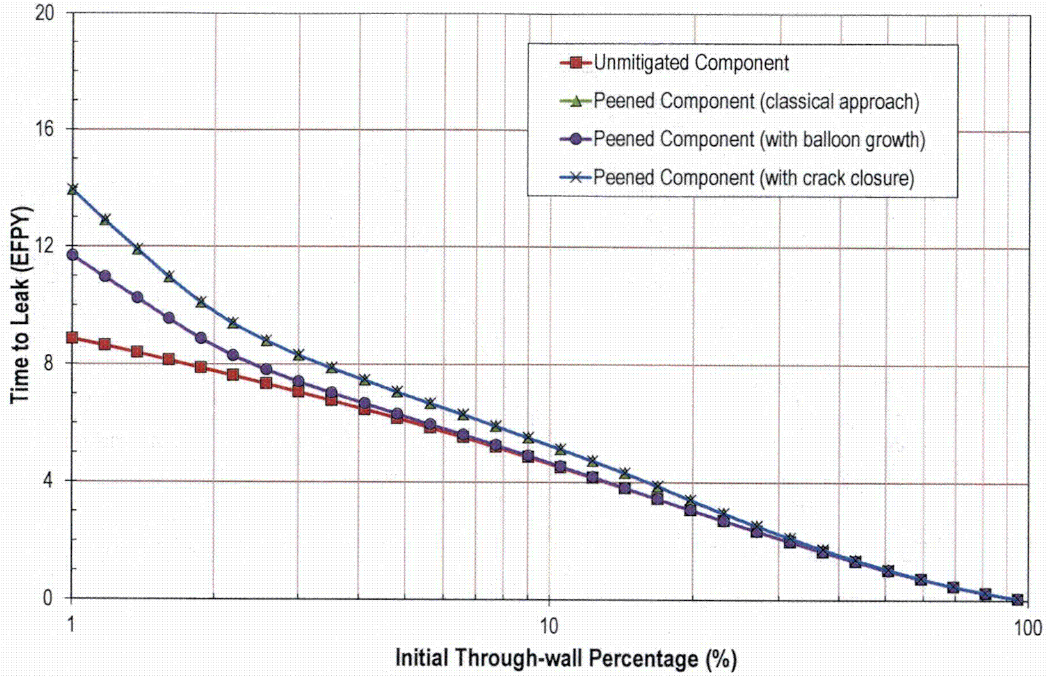

Figure 5-22
Time to Through-Wall Growth vs. Initial Crack Depth for Axial Crack on Downhill Penetration Nozzle ID (Log-Scale Abscissa, $2c_0/a_0$=4.5)

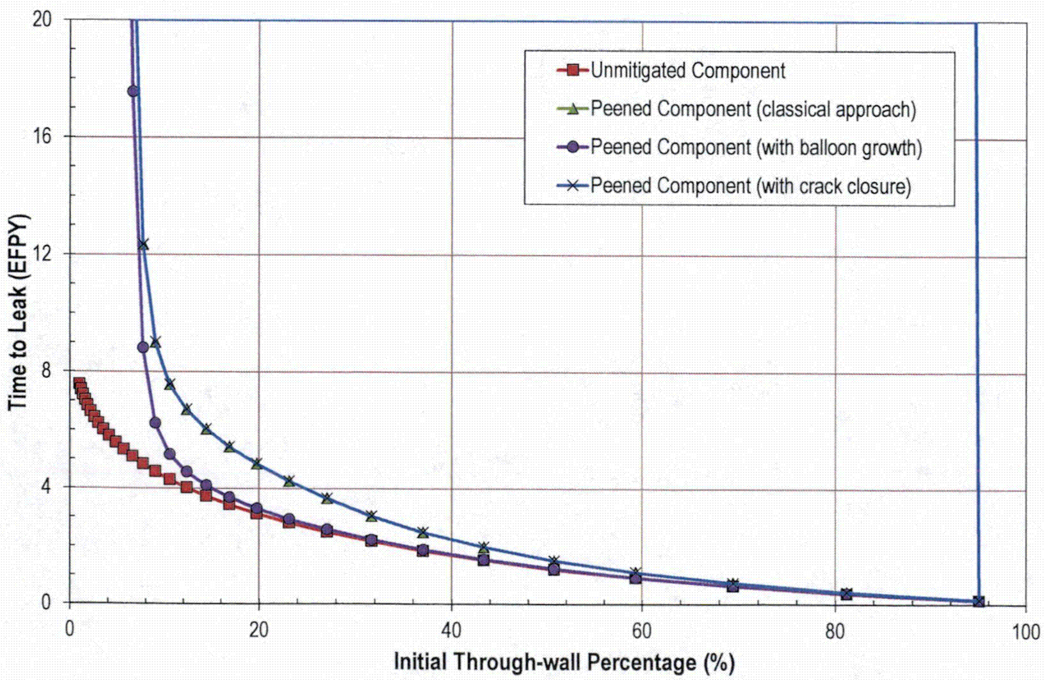

Figure 5-23
Time to OD Nozzle Annulus vs. Initial Crack Depth for Axial Crack on Uphill Penetration Nozzle OD ($2c_0/a_0$=4.5)

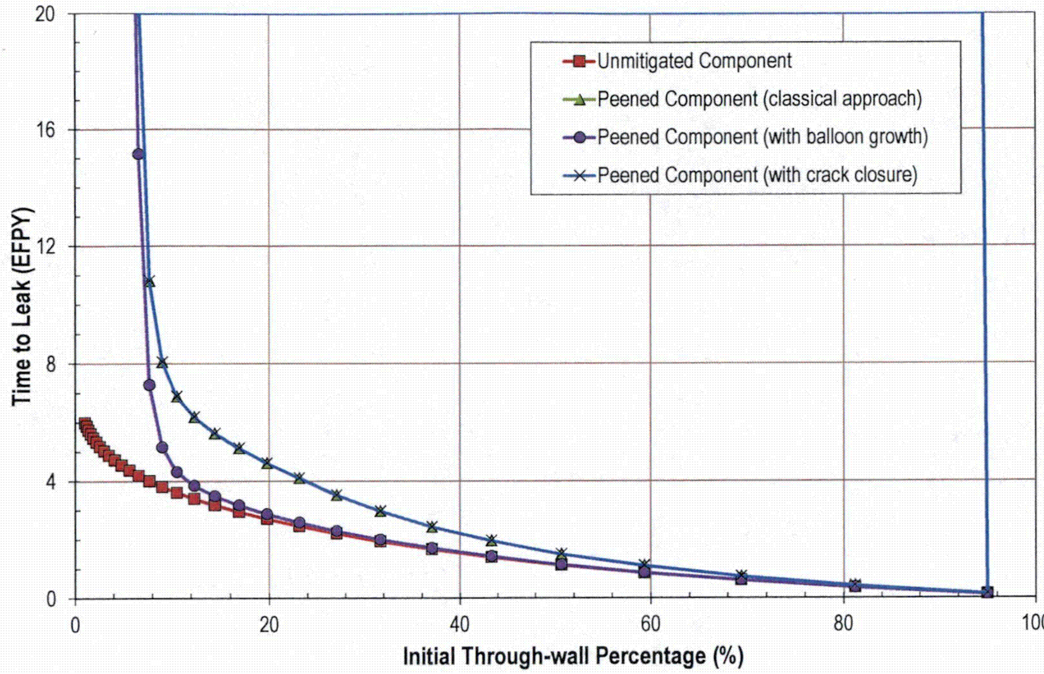

Figure 5-24
Time to OD Nozzle Annulus vs. Initial Crack Depth for Axial Crack on Downhill Penetration Nozzle OD ($2c_0/a_0$=4.5)

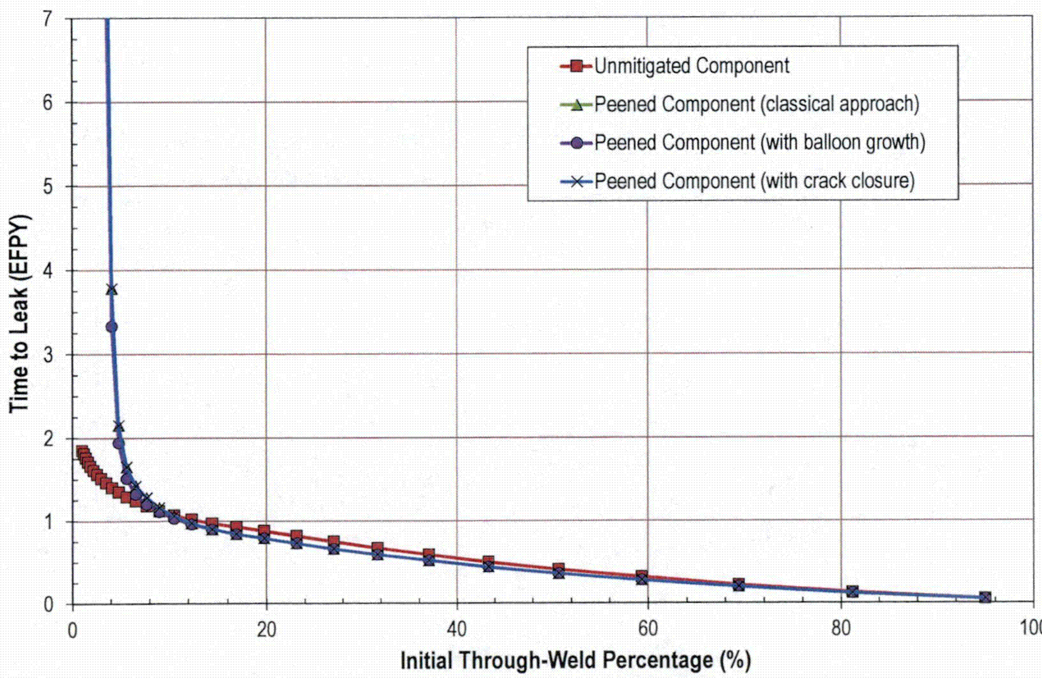

Figure 5-25
Time to Through-Weld Growth vs. Initial Crack Depth for Weld Radial Crack on Uphill J-Groove Weld ($2c_0/a_0$=4.5)

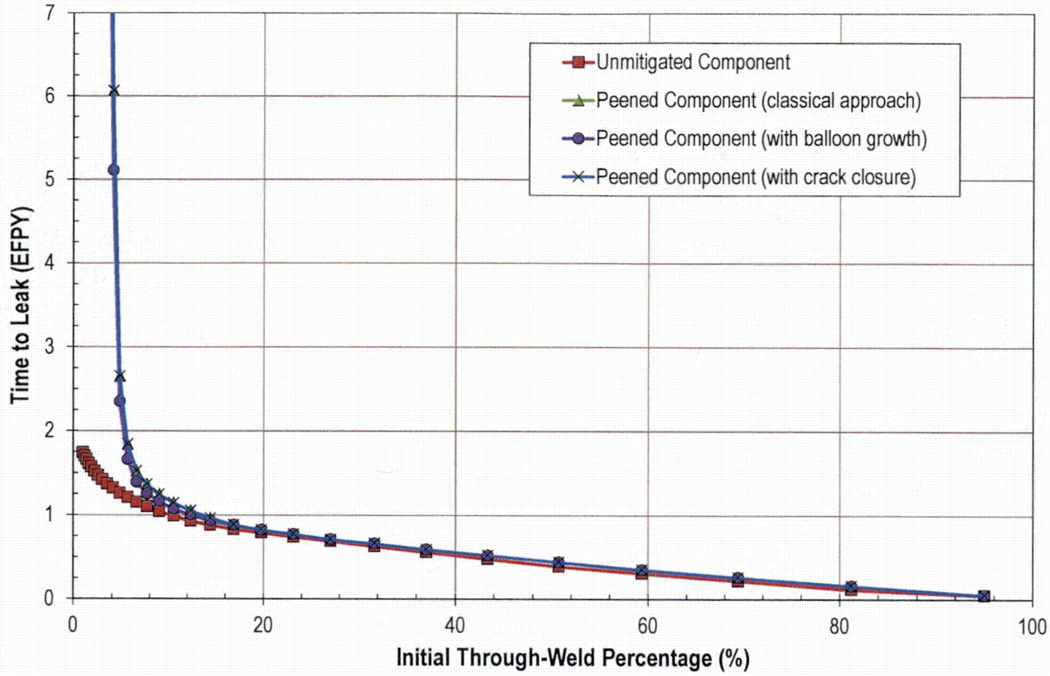

Figure 5-26
Time to Through-Weld Growth vs. Initial Crack Depth for Weld Radial Crack on Downhill J-Groove Weld ($2c_0/a_0$=4.5)

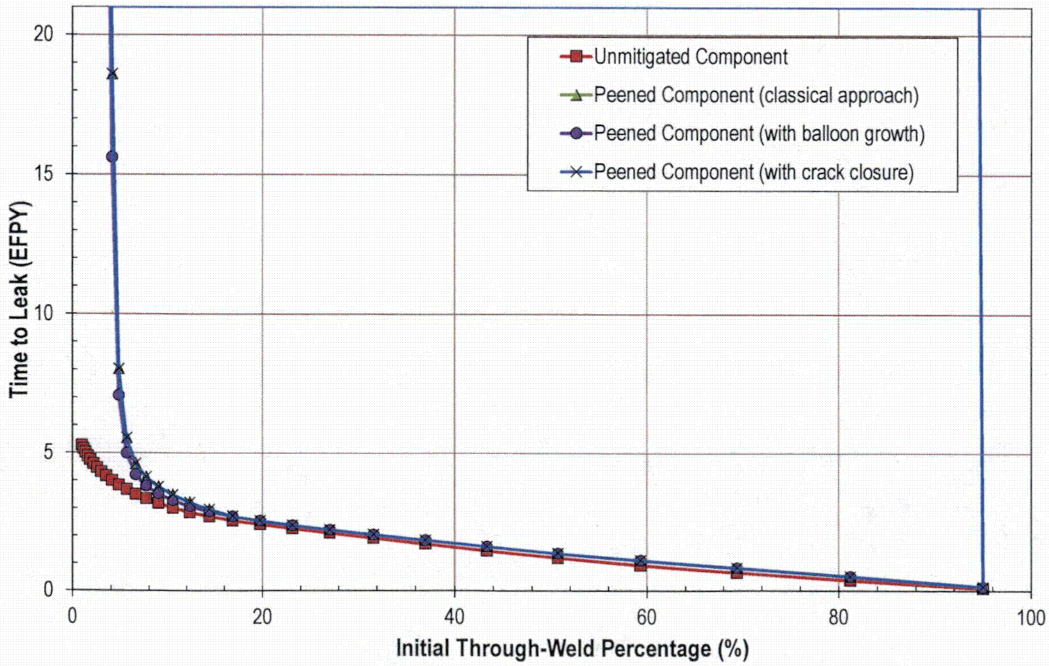

Figure 5-27
Time to Through-Weld Growth vs. Initial Crack Depth for Weld Crack on Downhill J-Groove Weld on a Cold Head RPVHPN ($2c_0/a_0$=4.5)

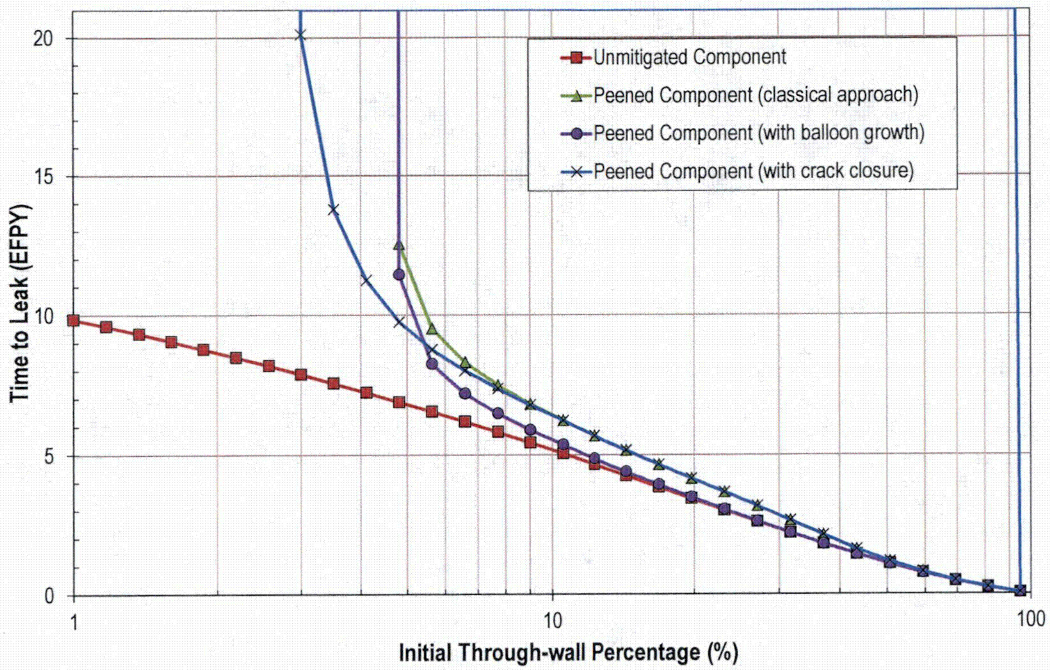

Figure 5-28
Time to Through-Weld Growth vs. Initial Crack Depth for Axial Crack on Uphill Penetration Nozzle ID Subject to More Compressive Peening Residual Stress Profile ($2c_0/a_0$=4.5)

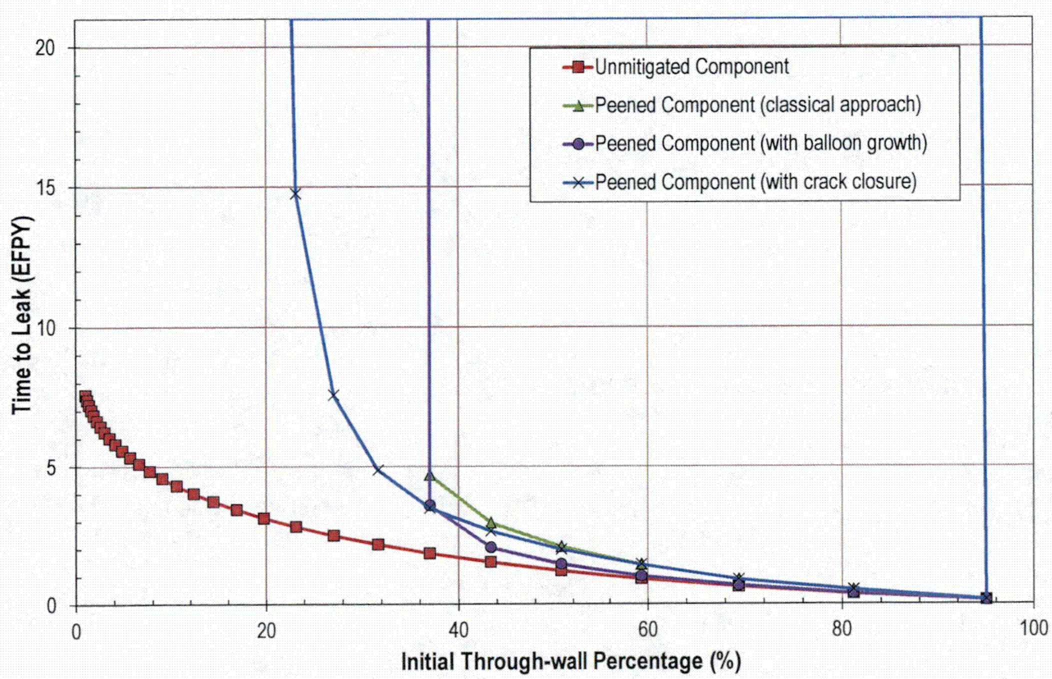

Figure 5-29
Time to Through-Weld Growth vs. Initial Crack Depth for Weld Crack on Uphill Penetration Nozzle OD Subject to More Compressive Peening Residual Stress Profile ($2c_0/a_0$=4.5)

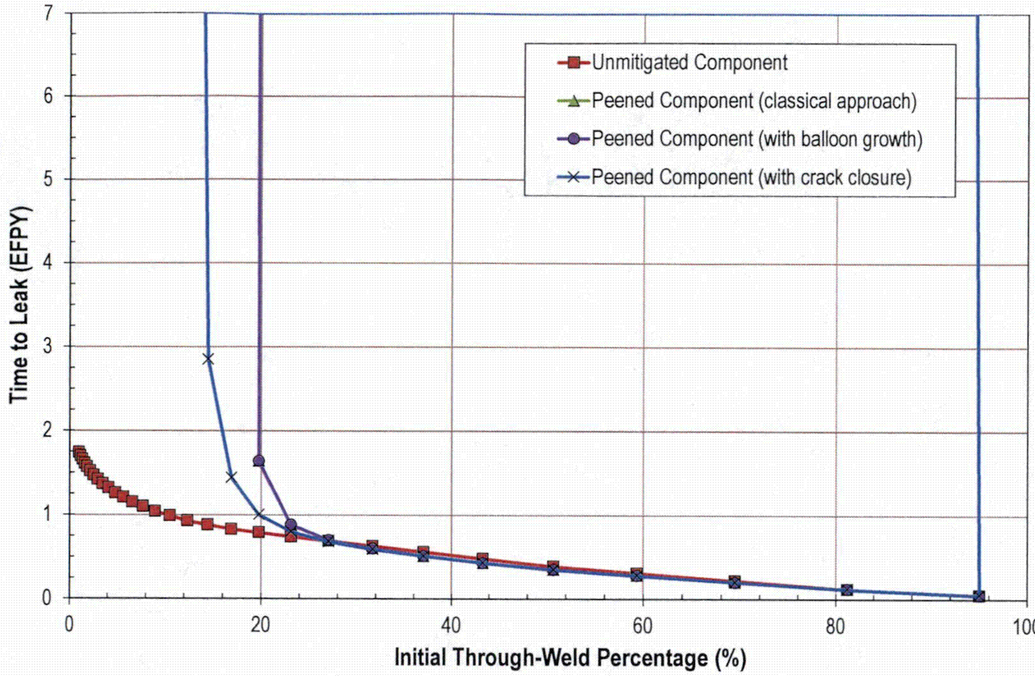

Figure 5-30
Time to Through-Weld Growth vs. Initial Crack Depth for Weld Crack on Downhill J-Groove Weld Subject to More Compressive Peening Residual Stress Profile ($2c_0/a_0$=4.5)

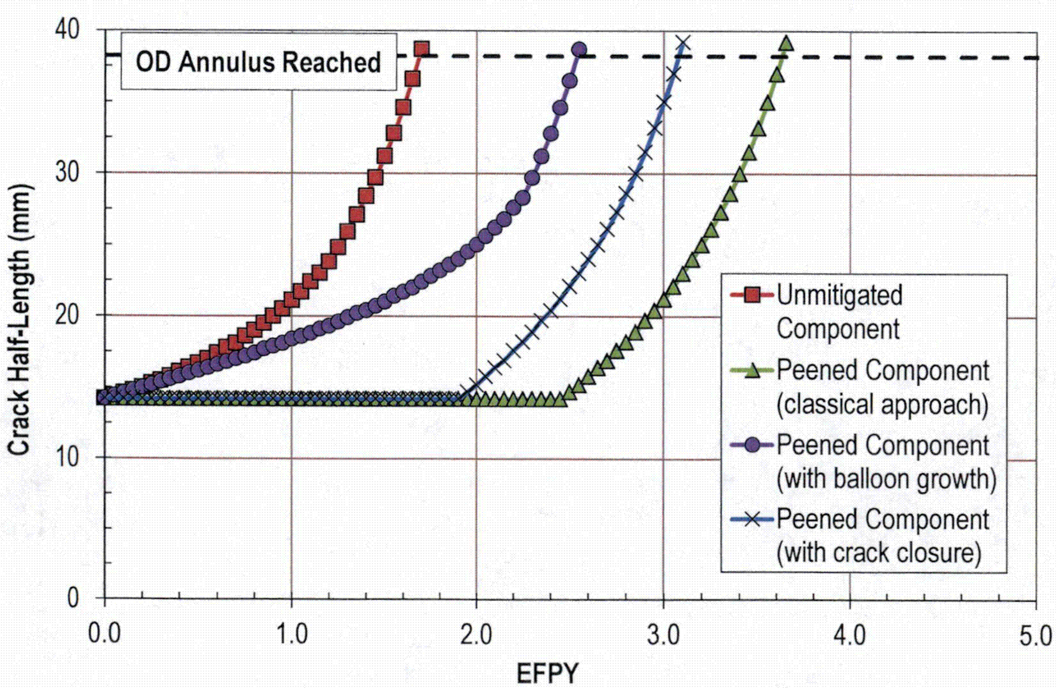

Figure 5-31
Half-Length along Nozzle Surface vs. Time for Uphill OD Axial Crack on Unmitigated and Peened Component Subject to More Compressive Peening Residual Stress Profile (a_0/t=40% [6.3 mm] and $2c_0/a_0$=4.5)

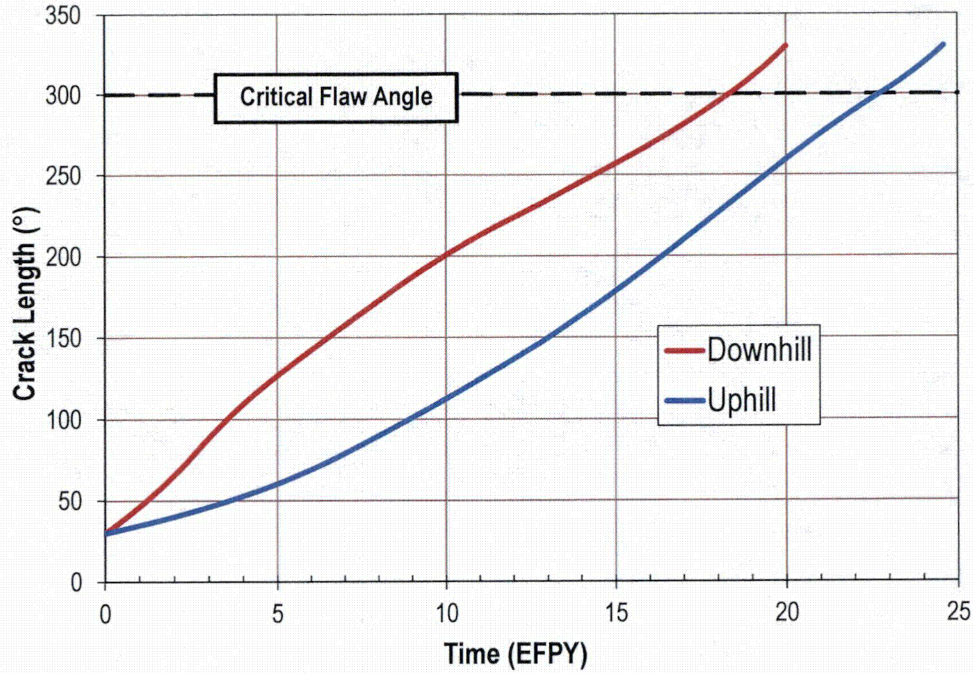

Figure 5-32
Circumferential Crack Length vs. Time for Through-Wall Cracks Along the Weld Contour

5.2.3 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 [26] solutions for identical cracks in the presence of identical stress profiles. The results of this validation study are depicted in Figure 5-33.

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.

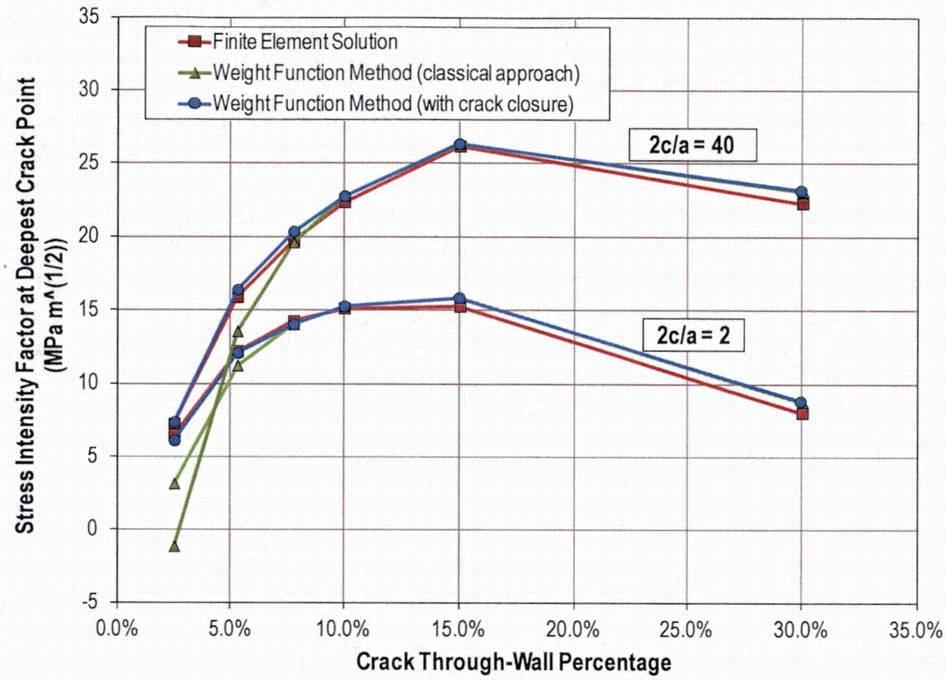

Figure 5-33
Results of Stress Intensity Factor Calculation Method Validation Study

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 ejection).

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 probabilistic model.

Figure 5-34 provides an important example result depicting cumulative probability of leakage 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 (RVON). When calculating the cumulative probability of leakage after the

hypothetical time of peening, realizations in which leakage occurs prior to the time of peening are discarded and not included in the reported statistic.

For both the hot and cold DMW components, the predicted likelihood of cracks existing on a given weld after the pre-peening inspection was low; less than 3×10^{-3} for the base cases. The cumulative probability of leakage after the follow-up inspection was predicted to be lower; less than 1.6×10^{-4} per year for the base cases. This result predicted that the vast majority (>90%) of the leakage risk would be incurred between the application of peening and the follow-up inspection.

For the RVON, it was predicted that the cumulative probability of leakage after peening would be reduced by a factor between 60 and 150 (compared to cumulative probabilities of leakage on the same span of time for an unmitigated RVON), depending on the post-peening follow-up and ISI scheduling. 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 RVIN, it was predicted that the cumulative probability of leakage after peening would be reduced by a factor between 8 and 24 (compared to cumulative leakage probabilities on the same span of time for an unmitigated RVIN), depending on the post-peening follow-up and ISI scheduling. 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 RPVHPN probabilistic model.

Figure 5-35 provides an important example result depicting average ejection frequency (AEF) 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 vessel head. Figure 5-36 provides an important example result depicting cumulative leakage probability versus post-peening inspection schedule characteristics for a hot reactor vessel head.

The RPVHPN results demonstrated a larger trend with respect to the ISI frequency than the DMW results. This is due in large part to the higher likelihood of cracks existing after the pre-peening inspection. It was predicted that, on average, approximately two nozzles in each hot head and one nozzle in approximately two cold heads would have unrepaired cracks after the pre-peening inspection.

For both the hot and cold heads, the cumulative probability of leakage after peening was predicted to be reduced by a factor between 3.5 and 6.0 times, depending on the post-peening examination schedule. For example, using a 10-year (one interval) UT inspection frequency, the cumulative probability of leakage after peening was predicted to decrease by a factor of

approximately five for both hot and cold heads. It is emphasized that the leakage probability as calculated is greatly influenced by the conservative assumptions that one third of the crack initiations occur on the wetted surface of the weld metal and that the weld flaws grow to cause leakage with no chance of becoming detectable via UT performed from the nozzle inside surface. In the probabilistic modeling, 75% to 90% or more of leaks that occur after peening occur due to weld-initiated cracks. On the contrary, plant experience shows that most CRDM nozzles leaks have been accompanied by cracking of the nozzle tube base metal detectable via UT from the nozzle inside surface. The assumptions made in the modeling conservatively increase the chance of developing circumferential cracks in the nozzle tube above the weld elevation since a 30° through-wall circumferential crack is assumed to be produced immediately upon leakage. The probability of leakage due to base metal cracking is also a more relevant measure to assess the benefit of periodic UT examinations because such examinations are not qualified to detect weld flaws.

For the hot head, using a post-peening ISI interval of 10 years (one interval), combined with a follow-up examination either one or two cycles after peening resulted in somewhat higher ejection risks compared to the unmitigated case: 182% and 147% of the unmitigated reactor vessel head risk, respectively. However, the same interval with a follow-up inspection both one and two cycles after peening resulted in an ejection risk lower than (83% of) the unmitigated case.

For the cold head, the AEF after peening was predicted to improve compared to the unmitigated case when a post-peening ISI frequency of every 10 years (one interval) was used. A post-peening ISI of one interval resulted in somewhat lower ejection risks compared to the unmitigated case: 79%, 45%, and 66% 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 the second cycle after peening 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.

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 hot head (with a follow-up inspection the first and second cycle after peening and an ISI interval of 5 cycles), the ratio of maximum IEF to AEF was 3.12. The same ratio for the unmitigated hot head was 1.42. For a peened cold 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 4.00. The same ratio for the unmitigated cold head was 3.60. The risk concentration was not substantially worse for the peened case than for the unmitigated case. Moreover, these ratios are considered modest in absolute terms.

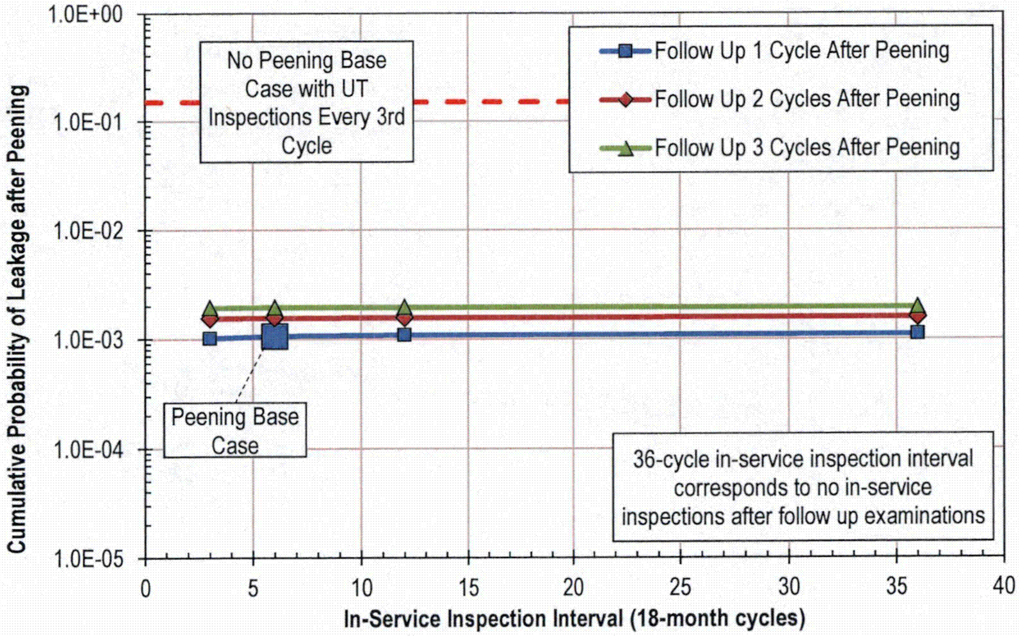

Figure 5-34
Cumulative Probability of Leakage after Hypothetical Time of Peening vs. ISI Frequency for a RVON

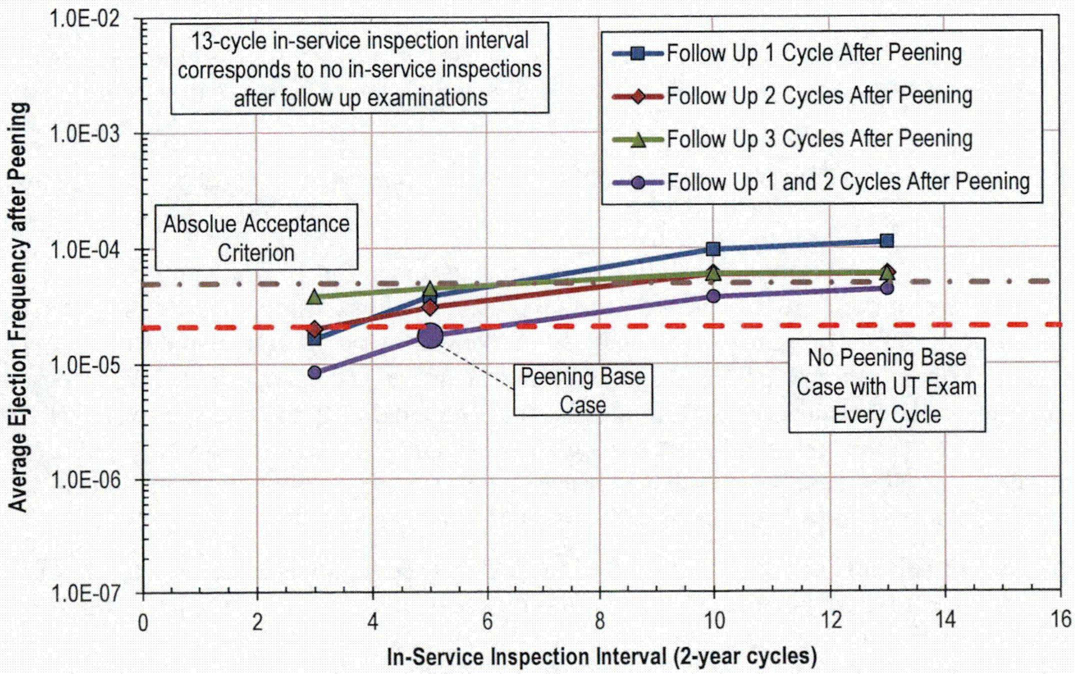

Figure 5-35
Average Ejection Frequency after Hypothetical Time of Peening vs. ISI Frequency for Hot Reactor Vessel Head

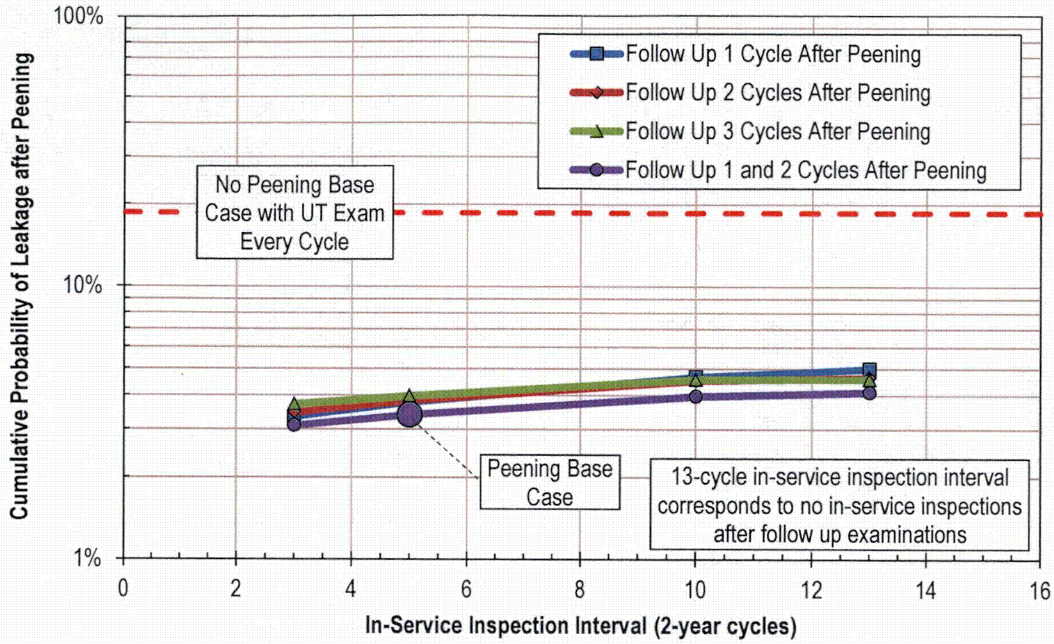

Figure 5-36
Cumulative Probability of Leakage after Hypothetical Time of Peening vs. ISI Frequency for Hot Reactor Vessel Head

5.4 Conclusions

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

The effect of peening on PWSCC of 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. Per the performance criteria of Section 4, the residual plus normal operating stress at the peened surface during future operation of the peened component is no greater than +10 ksi (+70 MPa) (tensile) for RPVHPNs and no greater than 0 ksi (0 MPa) for DMWs. These bounding stress levels are conservatively less than the tensile stress required for PWSCC initiation of an engineering scale flaw to occur over plant time scales. Laboratory testing demonstrates that a tensile stress that is at least a large fraction of the yield stress is necessary for PWSCC initiation [8]. A tensile stress of +10 ksi is clearly below the threshold.

  The deterministic and probabilistic calculations of this report investigate the growth of flaws on a component where peening has the bounding stress effect meeting the performance criteria in Section 4.

- Cracks present at the time of peening and located within a surface compressive stress layer resulting from peening are assumed to be arrested as they are not acted on by tensile stresses under normal operating conditions.

- Cracks present at the time of peening that have depths greater than the compressive stress layer after peening continue to grow.
- The integrated probabilistic modeling framework is used to investigate the appropriate degree of relaxation in the inspection interval following peening.

The deterministic analyses presented in this chapter investigate the effect of the surface stress improvement on PWSCC crack growth versus time. The deterministic results show that peening slows the growth of cracks with depths just beyond the compressive stress layer and that flaws significantly deeper than the compressive stress layer tend to grow in depth at a rate similar to that for the unmitigated case.

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 peened 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 (approximately between a factor of 10 and 100 for the probabilistic base cases per Section 4) 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 1.7×10^{-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 ratio of the maximum incremental nozzle ejection frequency to the time average nozzle ejection frequency calculated in Appendix B is of an acceptable magnitude (only a factor of 3-4). 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 5 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 is addressed by, and defense-in-depth is supported by, the required program of peening

mitigation and inspections defined in Section 4, which maintains the same basic intervals for periodic direct visual examinations for evidence of leakage as prior to peening.

The probabilistic modeling generally reflects a best-estimate approach with uncertainties treated using statistical distributions. However, with regard to some detailed aspects of the modeling, conservative simplifications were necessary to make the simulation tractable. The following modeling simplifications include conservatisms that tend to make the analysis results and the above conclusions conservative:

- For deterministic analyses of DMWs, circumferential flaws are assumed to be centered at the location of maximum bending tensile stress.
- For RPVHPNs, no credit is given to peening for slowing the growth of through-wall circumferential cracks along the weld contour.
- For 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 [23] 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 [12].
- For RPVHPNs, 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.
- For both DMWs and RPVHPNs in the probabilistic analysis, 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 DMWs in the probabilistic analysis, realizations in which leakage occurs prior to the time of peening are not credited in the reported statistics. In other words, the statistics reflect cases in which leakage has not occurred by the time of peening.
- The RVON analysis cases conservatively enter the relaxed ISI schedule immediately while a second follow-up examination within 10 years is specified by the inspection requirements.
- For both the deterministic and probabilistic analyses, cracks up to 10% of the through-wall extent are assumed to have a POD of zero via UT.