#	Question	EPRI MRP Response
1	The letter dated October 10, 2014, and the January 21, 2015, public meeting with the NRC staff (ADAMS Accession No. ML15021A504) included changes to the requirements for a peening process to be covered by MRP-335, Revision 1, and thus the input variables for the deterministic and probabilistic calculations. Examples include significant reductions in peening penetration depths for J-groove welds and reactor upper-head penetration nozzles. In order to assure that the NRC staff is reviewing the proper input variables, please provide a complete listing of all bounding peening input variables for the deterministic and probabilistic calculations including but not limited to, area of coverage, depth of peening, compressive stresses at depth, and associated inspections. Please note that any inputs not provided here will not be considered in the NRC staff's analysis. Additionally note that when the safety evaluation resulting from the NRC staff's evaluation of this document is used as a basis for relief from inspection requirements the input values provided to this question must be achieved by the peening process for which relief would be requested.	As requested, complete listings of all bounding peening input variables for the deterministic and probabilistic calculations are included in Attachments 3 through 5. The tables of these attachments cover all analysis inputs. In addition, the full sets of performance criteria are specified in Attachment 2. As discussed in the response to RAI #2 below, Attachments 3 through 5 present revised inputs and results for all the deterministic and probabilistic analyses of MRP-335R1. The revised calculations reflect the revised performance parameters and proposed inspection requirements. The revised calculations are based on the bounding stress effect meeting the revised performance criteria. Hence, the inspection requirements presented in Attachment 2 are valid regardless of the particular peening process applied, provided that the performance criteria are met. EPRI MRP understands that the minimum performance criteria must be achieved by a peening process for which relief would be requested by a licensee. Please note that the performance criteria of Attachment 2 for Alloy 82/182 piping dissimilar metal butt welds are with limited exceptions identical to those of Appendix I of ASME Code Case N-770-4 (for peening). EPRI MRP does not request NRC review of this unapproved code case. We note for information only that EPRI MRP has adopted with limited exceptions the identical wording of the performance criteria. The limited exceptions are as follows: • Descriptive headings have been included for each individual performance criterion. These headings are for information only. • The term "benchmarked" is not used with regard to the analysis or demonstration test required to be performed to confirm the post-mitigation stress state. As used in Appendix I of N-770-4, the practical intention of including the term "benchmarked" is not clear. Regardless of the intention of including this term, it is unnecessary because, as noted in Attachment 2, peening shall be performed and qualified per requirements meeting the quality assurance criteria of 10 CFR 50 Appendix B. As such, the analysis or demonstration testing required by the performance criteria is performed in accordance with these quality assurance requirements, which provide adequate controls.

#	Question	EPRI MRP Response
		• The following phrase was deleted from the end of Performance Criterion I-2 of N-770-4: "and growth of a postulated PWSCC flaw that is at or below the demonstrated detection limit of the surface examination technique applied." The intention of this phrase is somewhat unclear, but in any case, it is not necessary to be included. The MRP analyses in Attachments 3 through 5 show that no credit for performance of surface examinations is needed to support the inspection relief of Attachment 2. As demonstrated by the analyses of Attachments 3 through 5, peening mitigation is effective because of its benefit in preventing future PWSCC initiation. The analyses are based on the minimum stress effect meeting the specific performance criteria with regard to surface stress magnitude and peening compressive residual stress depth.
2	Based on the changed peening requirements and input variables described in Question 1, the NRC staff notes that the analyses used in the report may be non-conservative. Please revise the deterministic and probabilistic analyses using bounding input data provided above or describe why such a revision of these analyses is not required.	As presented in Attachments 3 through 5, all the deterministic and probabilistic analyses of MRP-335R1 have been revised to reflect updated minimum performance criteria (documented in Attachment 2), updated inspection requirements (also documented in Attachment 2), and other inputs. In particular, the minimum stress effect parameters (surface stress and compressive residual stress depth) meeting the performance criteria for RPVHPNs have been revised to reflect the range of in-service peening processes now available for mitigation of these components. Furthermore, the main cases of the deterministic and probabilistic analyses (Attachments 3 through 5) now reflect the minimum stress conditions satisfying the performance criteria rather than the expected stress effect for example processes. In this manner, the inspection requirements presented in Attachment 2 are valid regardless of the particular peening process applied, provided that the performance criteria are met. Please note that a main purpose of the supplemental technical basis submitted as Attachment 2 to the October 2014 submittal was to address the effect of the changes in performance parameter values since MRP-335R1 was published in January 2013. A set of probabilistic sensitivity cases was used to investigate the effect of the decreased minimum peening compressive residual stress depths for RPVHPNs. However, in order to fully address this set of RAI questions, all the deterministic and probabilistic analyses of MRP-335R1 have now been revised as documented in Attachments 3 through 5.
3	The source for many of the inputs values to the probabilistic analysis provided in Tables A-4, A-9, A-10, B-7, B-11, and B-12, is described as engineering judgment. The NRC staff believes that many of these inputs could significantly affect the outcome of the analysis. Please either replace these inputs values with technically-justified values or through sensitivity analyses quantify how uncertainties in these inputs affect the outcome of the analyses.	Many of these inputs are in fact conservative assumptions, reflect plant experience, or were already investigated through sensitivity analyses. As shown in Attachments 4 and 5, the basis for each input and each input value have been revised as necessary to satisfy this comment. None of the inputs in Attachments 3 through 5 are based on engineering judgment.

#	Question	EPRI MRP Response
4	The peening penetration depth requirements described in the letter dated October 10, 2014, are only required "Unless alternative requirements are satisfied." Please describe these alternative requirements and describe who would have the responsibility to review and approve these alternative requirements. Additionally, it is unclear to the NRC staff how it would evaluate the analysis contained in MRP 335, Revision 1, without clearly defined inputs. Please delete this provision or explain why exact knowledge of input variables to the analysis is not required.	This question refers to the minimum nominal depth of the peening compressive residual stress as presented on page 2 of Attachment 1 of the October 2014 submittal. EPRI MRP agrees that this provision for alternative requirements is unnecessary, and it has been deleted from the revised performance criteria of Attachment 2. Inspection requirements for Alloy 82/182 piping butt welds and RPVHPNs are mandated by U.S. NRC, and NRC has the responsibility of considering alternatives that may satisfy NRC requirements.

#	Question	EPRI MRP Response
5	The model for post-peening residual stress profile described in Figure 5-1, which was used to perform the deterministic and probabilistic calculations, does not match the complex residual stress profiles of peened surfaces shown in MRP-267, Revision 1. See Figures 2-20, 2-21, 2-28, A-3, and A-27 in MRP-267, Revision 1, as examples. Specifically, the peened stress profile used in the calculations balances the forces over the entire thickness of the component and thus never has tensile stresses significantly higher than in the unpeened residual stress profile at any point through the depth. Peening has been shown in MRP-267, Revision 1, to often significantly increase the tensile stresses in a component in the region just beyond the initial compressive region. Considering that the included sensitivity analysis showed that the stress profile in Figure 5-18 [actually Figure 5-15] produced shorter times to leakage for small initial flaws, this effect is apparently significant. It is also unclear to the NRC staff whether it should be expected that each of the three peening methods, and any other peening methods to which the analysis contained in this report may be applied, will provide the same residual stress profile. Please: a) demonstrate that the residual stress profile is not significant to the analysis; or, b) justify the acceptability of the residual stress profile used; or, c) repeat the analysis using a residual stress profile that can be demonstrated to be bounding to all peening processes based on actual peening data; or, d) repeat the analysis using a residual stress profile for each peening method. If the last approach is chosen describe why the NRC staff should consider this review to be a generic rather than a plant/method specific review.	Peening is effective to mitigate PWSCC because it prevents initiation of new PWSCC flaws and because it arrests sufficiently shallow flaws located in areas with a surface compressive stress zone. Follow-up examinations address the possibility of growth of pre-existing PWSCC flaws that were not detected in the pre-peening examination and were too deep to be arrested by the peening. In addition to producing a surface compressive residual stress layer, peening causes deformation of the treated component. Some of the compressive stress at the peened layer is immediately relieved by deformation of the part. As the stiffness of the treated component increases, the resulting deformation decreases, and more of the initial compressive stress at the treated surface is retained. Test specimens demonstrate the magnitude and depth of the compressive residual stress (retained on the treated surface after deformation) on a conservative basis as test specimens are often not as heavy walled as actual plant components and thus often less constrained than actual plant components. As demonstrated in Attachment 6, for the components modeled by MRP-335R1, the geometry is such that the assumption of a uniform tensile stress balancing the peening compressive stress is appropriate: • The retained compressive stress at the peened surface is balanced by the through-wall residual stress profile. The residual stress profile for an unrestrained flat plate must self-balance by force and through-wall bending moment before and after peening: $$F_{net} = \int_0^t \sigma(x)dx = 0$$ $$M_{net} = \int_0^t x\sigma(x)dx = 0$$ • Thus, the peak balancing tensile stress in the post-peening through-wall profile for an unrestrained plate depends on both the force and moment imparted by the surface compressive stress layer. The peak magnitude of the tensile stress balancing the peening compressive stress zone is reduced as the component thickness increases. As the wall thickness is increased, the balancing force is spread over a greater distance. Furthermore, the difference in balancing tensile stress required to develop the balancing through-wall moment is decreased. The increase in moment arm distance means that a smaller stress difference will create the same moment.

#	Question	EPRI MRP Response
		• The peak balancing tensile stress for the case of a peened thick-wall pipe is reduced compared to an unrestrained flat plate of equivalent wall thickness. This is because the more constrained pipe geometry does not deflect as much as the plate case for equivalent peening compressive stress effect and equivalent wall thickness, corresponding to a reduced through-wall drop in the balancing stress profile. The pipe geometry does not satisfy the moment balance in the same manner as for the unrestrained flat plate as shear stresses contribute to the balance for the pipe. The result is that the balancing stress profile for a thick-wall pipe is more nearly uniform than for the case of an unrestrained flat plate of equivalent wall thickness. • Because of the thick-wall for reactor vessel outlet nozzles (RVONs) and reactor vessel inlet nozzles (RVINs), peening has a small effect on the peak tensile stress below the surface compressive zone. For the RVON geometry, the peak tensile balancing stresses are less than about 2% of the magnitude of the compressive surface stress for the case of a compressive stress layer at the pipe ID that is 1 millimeter deep. A sensitivity case in Attachment 3 (conservatively based on the type of moment balance satisfied by an unrestrained flat plate) shows a small effect on the crack growth time to leakage (less than 7%) compared to the case with a uniform balancing tensile stress. • For RPVHPNs, the effective thickness of the nozzle at the weld elevation is increased by the presence of the weld and head. Below the weld, both the OD and ID surfaces are peened, tending to balance the through-wall stress profile. In addition, the peak tensile stress tends to be dominated by weld residual stress, not tensile residual stress in response to peening. In summary, the precise form of the residual stress profile is relatively insignificant to the overall analysis, and the assumption of a uniform balancing tensile stress is appropriate for the modeled components. The example residual stress profiles of MRP-267R1 cited in this RAI question are generally for cases where the peening compressive residual stress depth is a substantial fraction of the wall thickness and where the peened component is an unrestrained flat plate, which is the reason why a more substantial peak tensile balancing stress is observed in these cases. The concern for tensile stresses generated at regions between peened and unpeened material is addressed in the third paragraph of Section 4.5 of MRP-267R1. Stress measurements show that stresses are low in transition regions and service experience indicates no problems. Please see Sections 3.2.3, 3.2.4, 3.2.5, 4.2.1, 4.2.2, and A.1.1 (including Figure A-3, Figure A-10, and Figure A 13) of MRP-267R1.

#	Question	EPRI MRP Response
6	On page A-12 it is stated that "It is noted that the peening profile data from vendors uncovered a slight trend between the residual surface stress after peening and the residual surface stress prior to peening." The NRC staff agrees that the final stress state of a peened component is influenced by the initial residual stresses in the component. Considering the presence of documented and undocumented repairs in dissimilar metal welds and J-groove welds, the NRC staff expects the deterministic and probabilistic calculations to take the high initial tensile stresses caused by a repair into account when developing the residual stress profiles. As the data available suggests that the pre-peened stresses can affect the post-peened residual stress profile, please provide a technical justification that the model post-peening residual stress profile is conservative for inner-diameter and J-groove weld repairs.	This concern for the effect of the initial residual stress condition prior to peening was discussed in detail in the October 10, 2014, submittal to NRC (e.g., in the response to NRC RAI 3-1). In summary, 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 October 2014 submittal includes stress measurements illustrating the relative insensitivity to the initial residual stress state and the largest post-peening surface compressive stress at the point of maximum tensile initial residual stress. The pre-peening through-wall stress profile does dominate the post-peening stress profile in the region beyond the peening compressive residual stress layer. In this regard, a conservative stress condition is assumed 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. In addition, the purpose of the topical report is to demonstrate appropriate inspection intervals under the assumption that the performance criteria for the peening stress improvement are satisfied. Attachments 3 through 5 present analyses that have been revised to reflect updated minimum performance parameters (documented in Attachment 2).
7	Please provide error bars to the deterministic analysis figures showing the effects of the uncertainties discussed in Sections A.8 and B.8.	The relevant uncertainties for the deterministic PWSCC crack growth calculations are those for the stress, temperature, and material variability inputs. The probabilistic calculations explicitly address these and other sources of uncertainty. The temperature and material variability inputs are modeled as a simple multiplicative factor on time. Consistent with the discussions on the April 13, 2015, conference call between NRC and EPRI MRP, the main revised deterministic crack growth calculations in Attachment 3 reflect the minimum stress effect meeting the performance criteria (documented in Attachment 2). EPRI MRP understands that this approach will be sufficient to address this RAI question. Deterministic sensitivity cases are included in Attachment 3 to investigate the effect of a post-peening stress profile representative of stress measurements documented in MRP-267R1.

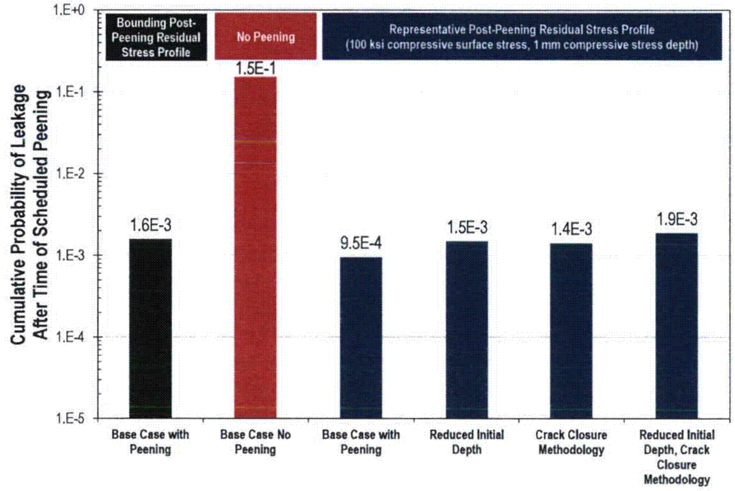
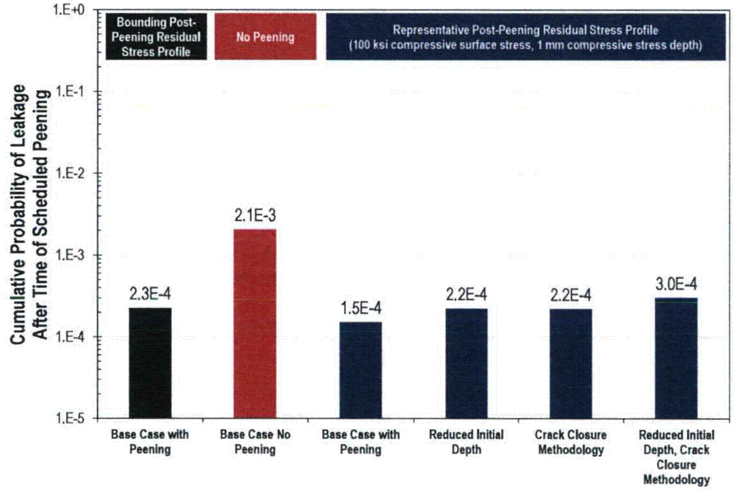
#	Question	EPRI MRP Response
8	While the NRC staff has been working with the extremely low probability of rupture (xLPR) PWSCC program and has a good understanding of the quality control processes for xLPR, Appendix A identifies several additional enhancements to the program beyond the xLPR software. Provide the differences between this probabilistic model and the xLPR Code Version 2, and the basis for the acceptability of these differences.	As a key participant in the xLPR Models Group, the authors of the probabilistic model are closely familiar with the modeling approaches of the xLPR software that are relevant to modeling PWSCC initiation, growth, and detection. Below is a list of the key differences, and the basis for the acceptability of these differences. A key distinction between MPR-335R1 and xLPR Version 2.0 is that the xLPR program does not currently address the geometry for partial-penetration (J-groove) nozzles. As such, this response focuses only on contrasting the differences with regard to modeling of the Alloy 82/182 piping butt welds. The MRP-335R1 probabilistic model takes a simplified approach in which the large risk reduction for peened Alloy 82/182 piping butt welds is demonstrated on the basis of the probability of through-wall penetration of PWSCC. *Rupture Modeling*: With regard to the modeling of the Alloy 82/182 piping butt welds, the main difference is that MRP-335R1 takes a simplified approach of modeling through-wall penetration but not pressure boundary rupture. Growth after through-wall penetration, crack opening displacement and leak rate, and component stability are not modeled explicitly. However, by demonstrating a greatly improved risk of through-wall penetration, the results demonstrate a reduced risk of large flaws that could compromise structural integrity. 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 a factor between 10 and 100 for the probabilistic base cases) supports the conclusion that rupture frequency (and boric acid wastage potential) is also reduced through the program of peening with the reduced frequency inspections. *Fatigue Growth*: The MRP-335R1 model does not treat the contribution of fatigue for initiation or growth. The cracking degradation concern, including for Alloy 82/182 piping butt welds and top head nozzles, is dominated by PWSCC initiation and growth. xLPR Version 2.0 predictions are expected to confirm the marginal effect of fatigue on leakage risks in piping butt weld components. *Accident Conditions*: xLPR Version 2.0 includes treatment for accident conditions, such as seismic loading. These accident conditions are of interest in xLPR primarily for their contribution to stability risks. As stated above, the MRP-335R1 model for Alloy 82/182 piping dissimilar metal butt welds does not consider stability risks explicitly and therefore modeling of accident loads is not critical.

#	Question	EPRI MRP Response
		PWSCC Crack Initiation Modeling: PWSCC initiation modeling is similar among the MRP-335R1 and xLPR Version 2.0 models. Both utilize semi-empirical model forms with key coefficients calibrated with field data for PWSCC detections in butt weld components in domestic plants. Both utilize circumferential discretization in order to model multiple flaw formation. Some mathematical details vary, as listed below: • *Alternative Model Forms*: Like MRP-335R1, xLPR Version 2.0 includes a Weibull model form for PWSCC crack initiation. However, xLPR includes two alternative model forms. The first alternative is the material index model, termed "Direct Model 1" in some xLPR documentation. This model is functionally similar to the Weibull model in that both include temperature and surface stress effects; however, the material index model captures uncertainty using a proportionality constant of arbitrary distribution type. So long as the two models are calibrated to equivalent data sets, their predictions will be similar. The second alternative factors in mechanical properties as surrogates for estimating cold work and strain rate and their effect on the initiation process, termed "Direct Model 2" in some xLPR documentation. It is challenging to determine the full potential for Direct Model 2 as different strength properties have not been developed for specific Alloy 82/182 piping butt welds in plants, The impact of aggressive surface conditions was studied indirectly in sensitivity cases that increased the initiation likelihood relative to the base case. Substantially accelerated crack initiation times relative to the Weibull model fit to domestic plant experience were assumed in these sensitivity cases. • *Temporal Variation*: The xLPR initiation model factors in temporal variation using a Miner's rule approximation for damage accumulation. This approach enables the treatment of changing surface stresses or temperature. The MRP-335R1 initiation model treats one key temporal change—the change in surface stresses at the time of peening—but otherwise cannot treat temporal variation. Studies with temporal variation were not of primary importance for MRP-335R1 objectives.

#	Question	EPRI MRP Response
		Weld Residual Stress Form: MRP-335R1 utilized the weld residual stress profile model form from the xLPR Pilot Study—third or fourth order polynomials fit to a set of constraints on the value of stress at various through-wall positions. In Version 2.0 of xLPR, the weld residual stress profile progressed to a piecewise linear model with stress defined at up to 26 points through the component thickness. While the Version 2.0 xLPR model affords more flexibility in the definition of weld residual stress, the primary characteristics of weld residual stress (i.e., ID surface stress, OD surface stress, tensile-compressive crossover point, force balance in the case of axial stresses) are well-captured in the MRP-335R1 model. *Peening Modeling*: Given the charter of MRP-335R1 to investigate peening, the MRP-335R1 model includes more detail for modeling peening stress profiles. This includes explicit definition of the peening stress profile with ID compressive stress and penetration characteristics, treatment of stress redistribution, and implementation of a partial crack closure methodology. Current xLPR modeling permits the specification of a surface stress component with the capability to mimic the effect of peening on PWSCC initiation, but profiles have not been developed to mimic the penetration of the peening stress effect into the component thickness. *Inspection Options*: Given the charter of MRP-335R1 to investigate different inspection options, the MRP-335R1 modeling framework includes more flexibility with regard to in-service examination scheduling.

#	Question	EPRI MRP Response
9	One input variable in probabilistic calculations that has high sensitivity and high uncertainty is the probability of crack initiation. In the probabilistic analysis, the report states on page 5-30, "the predicted likelihood of cracks existing after the pre-peening inspection was very low; less than 3E-04." Given operational experience with primary water stress corrosion cracking and the low probability of detection (POD) using ultrasonic inspection for flaws on the order of 0.25 mm to 1 mm, provide the basis for this assumed crack initiation probability.	For clarification, the statistic is the predicted likelihood of an initiated crack existing *on a given weld* after the pre-peening inspection. The reported statistic is calculated by summing the number of welds that have at least one crack in service during the cycle following peening (no new flaws are modeled to initiate following the cycle in which peening occurs) divided by the number of active realizations at the time of peening (realizations that leak prior to peening are excluded). The statistic reflects the likelihood that a flaw greater than an assumed minimum depth (i.e., the flaw depth at initiation) exists at the time of peening and is not detected by the pre-peening inspection. The relatively high stresses that result in PWSCC crack initiation tend to grow flaws to greater depths in relatively short time periods, making them more detectable. It is noted that the value of this statistic reported in Section 5.3.1 of Attachment 3 using the latest inputs and assumptions (less than 3×10^{-3}) is a factor of 10 greater than that in MRP-335R1. While the flaw depth assumed upon PWSCC initiation is a factor, sensitivity cases are used to address this assumption (M18 and M19 of Attachment 4; and cases in response to RAI #10) and to investigate the effects of a highly conservative initiation model (M13 of Attachment 4). For all sensitivity cases, the predicted likelihood of an initiated crack existing on a given weld after the pre-peening inspection remains below 1.1×10^{-2}. The reported statistic is specific to RVONs and RVINs, and plant experience has shown a relatively low frequency of PWSCC at these locations for the unmitigated condition. This experience includes ET examinations of the ID surface of the subset of RVONs and RVINs that are volumetrically examined from inside the piping. Such ET examinations are sensitive to relatively small and shallow flaws. Conservatively, the initiation Weibull model used in Attachment 4 includes all Alloy 82/182 dissimilar metal butt weld locations in primary system piping of U.S. PWRs.

#	Question	EPRI MRP Response
10	The deterministic analysis found that the crack growth rates are sensitive to the use of the crack closure model (see Figure 5-13). Shallow initial flaws subjected to partial closure constitute a limiting, but realistic, condition. Section A.9.3 mentions a sensitivity case aimed at addressing crack closure effects, which have been shown to be important in deterministic studies. The NRC staff notes that it is necessary to include both updated K solutions and sample shallow initial flaw sizes to truly account for crack closure. What was the initial flaw size distribution included in the Crack Closure Methodology sensitivity case (Case 13)?	In terms of through-wall fraction, the initial flaw size used was a log-normal distribution with a log-μ parameter of -3 and a log-σ parameter of 0.35. For the Alloy 82/182 piping dissimilar metal butt weld (DMW) example cases (i.e., 70 mm thickness), this equates to a 5th percentile of roughly 2 mm, a median of 3.5 mm, and a 95th percentile of roughly 6 mm. This distribution generally exceeds the 1 mm compressive residual stress depth used for DMW IDs. For the RPVHPN example cases (i.e., 16 mm thickness), this equates to a 5th percentile of roughly 0.4 mm, a median of roughly 0.8 mm, and a 95th percentile of roughly 1.4 mm. This distribution generally exceeds the 0.25 mm compressive residual stress depth used for nozzle IDs and straddles the 1 mm depth used for nozzle exteriors. Given that the initial flaw depth distributions used in the sensitivity cases employing the partial crack closure methodology generally exceeded the modeled compressive depth of residual stresses, it is informative to repeat the DMW cases with an initial flaw depth distribution shifted to lower values. For the purpose of this sensitivity investigation, it is appropriate to assume a peening stress effect representative of stress measurements documented in MRP-267R1 (as documented in Section 5.2.1 of Attachment 3) rather than the minimum stress effect meeting the performance criteria. The crack closure effect clearly has a greater potential influence for the "representative" case. The DMW example cases were repeated using an initial depth distribution with a 5th percentile of roughly 0.2 mm, a median of 0.35 mm, and a 95th percentile of roughly 0.6 mm. This distribution is consistently below the 1 mm compressive residual stress depth used for DMW IDs and is generally below the compressive depth even after superimposing operational stresses for the peening effect assumed here. The results are shown in the figures below: • The reduction in initial depth results in increased leakage likelihood for DMWs (by a factor of about 1.5). This increased likelihood is due to the greater possibility of shallow flaws being present that are not reliably detectable at the pre-peening examination. Nonetheless, the leakage likelihood for peened DMWs with a relaxed in-service inspection schedule remains well below that predicted for unpeened components inspected in accordance with the applicable requirements for unmitigated DMWs. • The application of the partial crack closure methodology with the reduction in initial depth has a rather small effect on the leakage predictions. This is because flaws generally reside in one of two states at the time of peening: i) shallower than compressive stress layer resulting from peening and therefore fully closed and arrested or ii) appreciably deeper (e.g., two times or more) than the compressive stress layer and therefore largely unaffected. The fraction of flaws between these states — i.e., the fraction of flaws for which partial crack closure may be important — is small for peening. Partial crack closure has been found to be more important for deeper stress improvement methods like mechanical stress improvement.

#	Question	EPRI MRP Response
		 

#	Question	EPRI MRP Response
11	Table A-2 lists operating load inputs for the reactor pressure hot leg nozzle probabilistic analysis. The loading input includes operating pressure and a thermal expansion bending load of MNTEy = 4519.4 kN-m [3333.5 ft-kips]. All deadweight and axial loads are assumed to be zero. A memorandum from Aladar Csontos to Timothy R. Lupold (ADAMS Accession No. ML112160169) contains example loading inputs for hot-leg nozzles. These loads show similar magnitude bending loads (~103 ft-kips [MRP understands that this figure of 103 ft-kips is incorrect]) and nonzero axial loads. Please provide further justification of assumed loading input for the probabilistic analyses. What is the effect on the recommended inspection intervals of including axial loads in the probabilistic calculation loading input?	For convenience, the resultant moment due to normal thermal pipe expansion and deadweight bending was input as single value. For the RVON base cases, the MRP crack growth calculations assume a resultant bending moment of 40,000 in-kips (3333 ft-kips). This value exceeds the highest normal operating bending load in ML112160169, i.e., 2648.3 ft-kips. Model Sensitivity case M9 in Attachment 4 bounds the effect of bending load by assuming the lowest value in ML112160169, i.e., 348.3 ft-kips. Regarding the axial loads, the end cap pressure load dominates the other sources of axial load during normal operation for the RVON/RVIN location, so these other sources were neglected in the original calculations. For the revised probabilistic calculations of Attachment 4, a tensile axial load of 100 kips was assumed (in addition to the axial pressure stress). This axial load exceeds that for the cases documented in ML112160169. As explicitly shown in the results of Attachment 4, the recommended inspection intervals remain valid considering the variability in the different bending and axial load components under normal operation.

#	Question	EPRI MRP Response
12	Appendix A of MRP-335, Revision 1 describes equations for calculating both pre-peened and post-peened residual stress profiles. Equation A-18, in particular, includes force balance terms (Aa and Ah) that are used to maintain the same effective residual through-wall force before and after peening. Please provide the derivation of Aa in Equation A-18 to the NRC staff for review. Also, please provide the following so that NRC staff can perform deterministic confirmatory calculations for a dissimilar metal butt weld: a. An example pre-peened axial residual stress profile, calculated according to Section A.3.2. b. An example post-peened axial residual stress profile, calculated according to Section A.3.3. c. Pipe geometry inputs associated with a. and b.	The derivation of the axial residual stress profile after peening will be done in several steps. First, the equations for the stress profile in each region of the curve are posed in terms of *x*, the absolute through-wall distance. Second, the integrated stress—accounting for the pipe wall curvature—is evaluated for each region. Then the adjustment factor used to ensure force balance is calculated. The adjustment factor represents the uniform tensile balancing stress produced in response to the peening compressive stress layer. Finally, the resulting profile is generated. Summarizing Section A.3.3 of MRP-335R1, the through-wall residual stress profile after peening is: $\sigma(x)=\begin{cases} \sigma_p-\left(\frac{\sigma_p}{x_1}\right)x & 0\le x\le x_1 \quad [1a] \\ \left(\frac{x-x_1}{x_2-x_1}\right)\cdot\sigma_{WRS}\left(\frac{x_2}{t}\right) & x_1<x\le x_2 \quad [1b] \\ \left(\frac{x-x_2}{x_3-x_2}\right)\left(\sigma_{WRS}\left(\frac{x_3}{t}\right)+A-\sigma_{WRS}\left(\frac{x_2}{t}\right)\right)+\sigma_{WRS}\left(\frac{x_2}{t}\right) & x_2<x\le x_3 \quad [1c] \\ \sigma_{WRS}\left(\frac{x}{t}\right)+A & x_3<x\le t \quad [1d] \end{cases}$ where *t* is the component thickness and σ_p, x_1, x_2, and x_3 are pre-established properties of the peening profile. The function σ_{WRS} is the third-order polynomial residual stress profile before peening: $\sigma_{WRS}\left(\frac{x}{t}\right)=\sigma_0+\sigma_1\left(\frac{x}{t}\right)+\sigma_2\left(\frac{x}{t}\right)^2+\sigma_3\left(\frac{x}{t}\right)^3 \quad [2]$ The adjustment factor, *A*, is derived to preserve through-wall stress balance: $\int_0^t \sigma(x)(R_i+x)\cdot dx=0 \quad [3]$ where R_i is the component inner radius. The integral of each piecewise region is evaluated in Eqs. 4a through 4d below:

#	Question	EPRI MRP Response
		$$\int_0^{x_1}\left(\sigma_p-\left(\frac{\sigma_p}{x_1}\right)x\right)(R_i+x)\cdot dx$$ $$\Rightarrow\int_0^{x_1}\sigma_p\left(-\frac{x^2}{x_1}+\left(1-\frac{R_i}{x_1}\right)x+R_i\right)\cdot dx$$ $$\Rightarrow\left[\sigma_p\left(-\frac{x^3}{3x_1}+\left(1-\frac{R_i}{x_1}\right)\frac{x^2}{2}+R_i x\right)\right]_0^{x_1}$$ $$\Rightarrow\sigma_p\left(\frac{x_1^2}{6}+\frac{R_i x_1}{2}\right)$$ [4a]
		$$\int_{x_1}^{x_2}\left(\left(\frac{x-x_1}{x_2-x_1}\right)\cdot\sigma_{WRS}\left(\frac{x_2}{t}\right)\right)(R_i+x)\cdot dx$$ $$\Rightarrow\frac{1}{x_2-x_1}\sigma_{WRS}\left(\frac{x_2}{t}\right)\int_{x_1}^{x_2}\left(x^2+(R_i-x_1)x-R_i x_1\right)\cdot dx$$ $$\Rightarrow\frac{1}{x_2-x_1}\sigma_{WRS}\left(\frac{x_2}{t}\right)\left[\frac{x^3}{3}+(R_i-x_1)\frac{x^2}{2}-R_i x_1 x\right]_{x_1}^{x_2}$$ $$\Rightarrow\frac{1}{x_2-x_1}\sigma_{WRS}\left(\frac{x_2}{t}\right)\left(\frac{x_2^3-x_1^3}{3}+(R_i-x_1)\frac{x_2^2-x_1^2}{2}-R_i x_1(x_2-x_1)\right)$$ [4b]

#	Question	EPRI MRP Response
		$$\begin{aligned} &\int_{x_2}^{x_3}\left(\left(\frac{x-x_2}{x_3-x_2}\right)\left(\sigma_{WRS}\left(\frac{x_3}{t}\right)+A-\sigma_{WRS}\left(\frac{x_2}{t}\right)\right)+\sigma_{WRS}\left(\frac{x_2}{t}\right)\right)(R_i+x)\cdot dx \\ &\Rightarrow \frac{1}{x_3-x_2}\left(\sigma_{WRS}\left(\frac{x_3}{t}\right)+A-\sigma_{WRS}\left(\frac{x_2}{t}\right)\right)\int_{x_2}^{x_3}\left(x^2+(R_i-x_2)x-R_i x_2\right)dx \\ &\qquad +\sigma_{WRS}\left(\frac{x_2}{t}\right)\int_{x_2}^{x_3}(R_i+x)dx \\ &\Rightarrow \frac{1}{x_3-x_2}\left(\sigma_{WRS}\left(\frac{x_3}{t}\right)+A-\sigma_{WRS}\left(\frac{x_2}{t}\right)\right)\left[\frac{x^3}{3}+(R_i-x_2)\frac{x^2}{2}-R_i x_2 x\right]_{x_2}^{x_3} \\ &\qquad +\sigma_{WRS}\left(\frac{x_2}{t}\right)\left[R_i x+\frac{x^2}{2}\right]_{x_2}^{x_1} \qquad [4c] \\ &\Rightarrow \frac{1}{x_3-x_2}\left(\sigma_{WRS}\left(\frac{x_3}{t}\right)+A-\sigma_{WRS}\left(\frac{x_2}{t}\right)\right)\left(\frac{x_3^3-x_2^3}{3}+(R_i-x_2)\frac{x_3^2-x_2^2}{2}-R_i x_2(x_3-x_2)\right) \\ &\qquad +\sigma_{WRS}\left(\frac{x_2}{t}\right)\left(\frac{x_3^2-x_2^2}{2}+R_i(x_3-x_2)\right) \\ &\Rightarrow \frac{1}{x_3-x_2}\left(\sigma_{WRS}\left(\frac{x_1}{t}\right)-\sigma_{WRS}\left(\frac{x_2}{t}\right)\right)\left(\frac{x_1^3-x_2^3}{3}+(R_i-x_2)\frac{x_1^2-x_2^2}{2}-R_i x_2(x_3-x_2)\right) \\ &\quad +\frac{A}{x_3-x_2}\left(\frac{x_3^3-x_2^3}{3}+(R_i-x_2)\frac{x_3^2-x_2^2}{2}-R_i x_2(x_3-x_2)\right)+\sigma_{WRS}\left(\frac{x_2}{t}\right)\left(\frac{x_3^2-x_2^2}{2}+R_i(x_3-x_2)\right) \end{aligned}$$ $$\begin{aligned} &\int_{x_3}^{t}\left(\sigma_0+\sigma_1\left(\frac{x}{t}\right)+\sigma_2\left(\frac{x}{t}\right)^2+\sigma_3\left(\frac{x}{t}\right)^3+A\right)(R_i+x)dx \\ &\Rightarrow \int_{x_3}^{t}\left(\sum_{n=0}^{3}\left(\frac{\sigma_n}{t^n}x^n\right)+A\right)(R_i+x)dx \\ &\Rightarrow \int_{x_3}^{t}\left(\sum_{n=0}^{3}\left(\frac{\sigma_n}{t^n}x^n R_i+\frac{\sigma_n}{t^n}x^{n+1}\right)+A(R_i+x)\right)dx \qquad [4d] \\ &\Rightarrow \left[\sum_{n=0}^{3}\left(\frac{\sigma_n}{(n+1)t^n}x^{n+1}R_i+\frac{\sigma_n}{(n+2)t^n}x^{n+2}\right)+A\left(R_i x+\frac{x^2}{2}\right)\right]_{x_3}^{t} \\ &\Rightarrow \sum_{n=0}^{3}\left(\frac{\sigma_n}{(n+1)t^n}\left(t^{n+1}-x_3^{n+1}\right)R_i+\frac{\sigma_n}{(n+2)t^n}\left(t^{n+2}-x_3^{n+2}\right)\right)+A\left(R_i(t-x_3)+\frac{(t^2-x_3^2)}{2}\right) \end{aligned}$$

#	Question	EPRI MRP Response
		The four expressions should sum to zero. The *A* term was separated from other terms above to facilitate solution. To wit: $\begin{aligned}&\sigma_p\left(\frac{x_1^2}{6}+\frac{R_i x_1}{2}\right)+\\ &\frac{1}{x_2-x_1}\sigma_{WRS}\left(\frac{x_2}{t}\right)\left(\frac{x_2^3-x_1^3}{3}+(R_i-x_1)\frac{x_2^2-x_1^2}{2}-R_i x_1(x_2-x_1)\right)+\\ &\frac{1}{x_3-x_2}\left(\sigma_{WRS}\left(\frac{x_3}{t}\right)-\sigma_{WRS}\left(\frac{x_2}{t}\right)\right)\left(\frac{x_3^3-x_2^3}{3}+(R_i-x_2)\frac{x_3^2-x_2^2}{2}-R_i x_2(x_3-x_2)\right)+\\ &\sigma_{WRS}\left(\frac{x_2}{t}\right)\left(\frac{x_3^2-x_2^2}{2}+R_i(x_3-x_2)\right)+\\ &\sum_{n=0}^{3}\left(\frac{\sigma_n}{(n+1)t^n}\left(t^{n+1}-x_3^{n+1}\right)R_i+\frac{\sigma_n}{(n+2)t^n}\left(t^{n+2}-x_3^{n+2}\right)\right)=\\ &-\left(\frac{1}{x_3-x_2}\left(\frac{x_3^3-x_2^3}{3}+(R_i-x_2)\frac{x_3^2-x_2^2}{2}-R_i x_2(x_3-x_2)\right)+\left(R_i(t-x_3)+\frac{(t^2-x_3^2)}{2}\right)\right)A\end{aligned}$ [5] Figure 5-1 and Figure 5-2 of Attachment 3 show the axial residual stress profile before and after peening given the following inputs, which are representative of a RVON Alloy 82/182 piping dissimilar metal butt weld: t = thickness: 69.9 mm R_i = inner radius: 381 mm $[\sigma_0, \sigma_1, \sigma_2, \sigma_3]$ = WRS profile coefficients: [300, -1510, 1169, 266] MPa σ_p = ID compressive stress after peening: 165 MPa (compressive) $[x_1, x_2, x_3]$ = peening penetration parameters: [1, 1.7, 2] mm The resulting adjustment factor *A* is 6.3 MPa, which represents 3.8% of the inner surface compressive stress after peening.

#	Question	EPRI MRP Response
13-A	The ultrasonic testing (UT) and eddy current testing (ET) POD curves supplied in Section V show that reasonable assurance for the detection of flaws on the order of 1 mm for welds and outer diameter examinations of reactor pressure vessel head and 0.25 mm for ID examinations does not exist. The assumed POD curves for UT and ET appear to show that one should expect pre-peening inspections to be ineffective. a. Please provide justification that ultrasonic testing is an adequate approach given the very low PODs for 0.25 mm and 1 mm deep flaws.	The Topical Report does not take credit for detection of all flaws prior to peening. Instead, in a similar manner as for the case for unmitigated heads, a robust program of ongoing examinations addresses the possibility of pre-existing stress corrosion cracks that were not detected by the pre-peening examination and that were too deep to be arrested by the peening application. 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. None of the analysis cases of the revised set of calculations in Attachments 3 through 5 take credit for any eddy current examinations. The improved condition of peened RPVHPNs and ongoing UT prescribed in Attachment 2 result in a reduced concern for pressure boundary leakage and degradation of structural integrity.
13-B	The ultrasonic testing (UT) and eddy current testing (ET) POD curves supplied in Section V show that reasonable assurance for the detection of flaws on the order of 1 mm for welds and outer diameter examinations of reactor pressure vessel head and 0.25 mm for ID examinations does not exist. The assumed POD curves for UT and ET appear to show that one should expect pre-peening inspections to be ineffective. b. Given that the American Society of Mechanical Engineers (ASME) Code requirement does not allow flaws greater than 75 percent through-wall, how does the deterministic analysis provided in the report support the extension of the inspection requirements identified in Table 4-1 given the small improvements in times to leakage shown for flaws with low PODs?	The deterministic calculations demonstrate that flaws significantly deeper than the peening compressive residual stress layer grow largely unaffected by peening, and they are implemented within the structure of the probabilistic models to evaluate the potential safety and leakage effects of PWSCC degradation. The inspection requirements identified in Attachment 2 are supported by the full set of analyses in Attachments 3 through 5. Peening is effective to mitigate PWSCC because it prevents initiation of new PWSCC flaws and because it arrests sufficiently shallow flaws located in areas with a surface compressive stress zone. The small improvements in times to leakage shown in the deterministic calculations are a minor factor. Follow-up examinations and ongoing ISI examinations address the potential for growth of pre-existing flaws not detected in the pre-peening examination. It is noted that this ASME requirement refers to the limit for leaving flaws detected via NDE and located on the piping butt weld ID (axial or circumferential flaws) or on the RPVHPN tube ID (axial flaws only) in service for additional operation. PWSCC flaws detected in the J-groove weld are not acceptable for future operation regardless of size.

#	Question	EPRI MRP Response
14	Figures 5-32 and B-31 show that the nozzle-ejection probability is very sensitive to, and increases with, the length of the in-service inspection interval. The results of the probabilistic evaluations show either a small decrease in the nozzle ejection probability with peening to an increase in the nozzle ejection probability coupled with the inspection frequency change. Given that peening the upper head can increase the nozzle ejection frequency and the sensitivity of the nozzle ejection frequency to the inspection interval, please explain how the probabilistic results support the requested increased Inspection intervals.	As calculated, frequencies of pressure boundary rupture often vary over multiple orders of magnitude, and the absolute acceptance criterion for the time-averaged nozzle ejection frequency (per head) may be taken as 5×10^{-5} per year. (An initiating event frequency of 5×10^{-5} per year results in a core damage frequency of no more than about 1×10^{-6} per reactor year considering the range of conditional core damage probabilities applicable to piping breaks of relevant size. The 1×10^{-6} per reactor year criterion is consistent with the change in core damage frequency criterion of U.S. NRC Regulatory Guide 1.174 for permanent changes in plant design parameters, technical specifications, etc.) On that basis, the results are only modestly sensitive to the inspection interval. The original probabilistic results in MRP-335R1 support the proposed inspection intervals proposed in MRP-335R1 on the basis that: • the absolute acceptance criterion for nozzle ejection frequency is satisfied, and • the nozzle ejection frequency for the peened head with extended intervals is close to that for the unmitigated head examined per the N-729-1 intervals (i.e., every cycle for a hot head) (risk neutral). The revised probabilistic results in Attachment 5, which reflects the revised inspection intervals and performance criteria in Attachment 2, satisfy these same acceptance criteria. As shown in Figure 5-36 (hot head) of Attachment 3 and Figure B-3 (cold head) of Attachment 5, the risk neutral condition is clearly satisfied.

#	Question	EPRI MRP Response
15-A	On page 2-4, the report states, in part, "The reasons for not using ET at the J-groove welds are (1) flaws that are located exclusively in the J-groove weld are not a direct concern for the structural integrity of the head (i.e., do not credibly pose a direct concern for pressure boundary rupture)." a. Was this position used in the development of the safety basis in Appendix B?	To clarify this statement, this position applies to the nozzle ejection safety concern only. PWSCC flaws located exclusively in the J-groove weld do not present a credible direct concern for pressure boundary rupture, where by "direct concern" we mean distinct from the leakage concern due to through-wall penetration. As also discussed on page 2-4 of MRP-335R1, the safety concerns for RPVHPNs are nozzle ejection due to a very large circumferential flaw in the nozzle tube located at or above the top of the J-groove weld and structurally significant boric acid corrosion of the low-alloy steel head material due to significant pressure boundary leakage. The probabilistic calculations in Appendix B for RPVHPNs demonstrate that the examinations developed for use with peening, including direct visual examinations for evidence of pressure boundary leakage, are sufficient to address these concerns, resulting in a sufficiently small effect on nuclear safety. Note that 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 exams to characterize ET indications. This imposes unnecessary and unwarranted radiation dose to NDE inspection and repair personnel who prepare surfaces for examination and implement repairs.
15-B	On page 2-4, the report states, in part, "The reasons for not using ET at the J-groove welds are (1) flaws that are located exclusively in the J-groove weld are not a direct concern for the structural integrity of the head (i.e., do not credibly pose a direct concern for pressure boundary rupture)." b. Was reactor coolant pressure boundary leakage and corresponding boric acid corrosion of the upper head considered in the safety analysis?	Yes, the concern for reactor coolant pressure boundary leakage and corresponding boric acid corrosion of the upper head is considered. The concern is conservatively addressed through ongoing visual examinations for evidence of leakage after peening. In addition, peening acts to reduce the probability of leakage during future operation, further reducing the concern. For the case of RPVHPNs, the inspection requirements of Attachment 2 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. For example, for heads with EDY ≥ 8 at the time of peening, a VE interval of every refueling outage is maintained. 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.

#	Question	EPRI MRP Response
15-C	On page 2-4, the report states, in part, "The reasons for not using ET at the J-groove welds are (1) flaws that are located exclusively in the J-groove weld are not a direct concern for the structural integrity of the head (i.e., do not credibly pose a direct concern for pressure boundary rupture)." c. Do the calculations assume that a flaw in the weld will stay in the weld material and not grow into the nozzle material?	The calculations make conservative assumptions in this regard: • It is assumed that cracks may initiate at up to six locations for each penetration: on nozzle tube ID, on the nozzle tube OD below the weld, and on the weld wetted surface, both on the uphill and downhill sides of the nozzle. • Once a crack that is modeled to initiate on the weld wetted surface reaches the nozzle annulus, it is conservatively assumed that a 30° through-wall circumferential flaw is immediately produced in the nozzle tube above the weld elevation. This represents immediate initiation of a new flaw (or immediate branching to a flaw) on the nozzle OD of the type of flaw that could cause nozzle ejection were it to grow to encompass a very large proportion of the nozzle tube cross section. • For the purpose of modeling crack detection via UT from the nozzle ID, it is conservatively assumed that a flaw that initiated on the weld wetted surface never becomes detectable by growing into the nozzle tube until leakage is modeled to occur and the 30° circumferential flaw is produced. On the other hand, plant experience has shown that in many cases weld flaws initiate near the toe of the weld on the tube, readily grow into the nozzle tube wall, and become detectable via UT from the nozzle ID.
15-D	On page 2-4, the report states, in part, "The reasons for not using ET at the J-groove welds are (1) flaws that are located exclusively in the J-groove weld are not a direct concern for the structural integrity of the head (i.e., do not credibly pose a direct concern for pressure boundary rupture)." d. Provide a basis for why 1 mm of depth of compression is sufficient to address any potential fabrication defects.	The purpose of peening is to mitigate the potential for PWSCC service-related degradation. Follow-up examinations and ongoing ISI examinations are designed to address the potential for growth of pre-existing flaws deeper than the peening depth of compression that were not detected in the pre-peening examination.
16 Part 1	In the letter dated October 10, 2014, the Response to Question 4-14 states that References (a), (b), and (c) are available for viewing at the EPRI Nondestructive Examination Center in Charlotte. Submit References (a), (b), and (c) for the NRC review or justify why these references cannot be submitted.	As discussed on the April 13, 2015, conference call between NRC and EPRI MRP, these proprietary EPRI documents are available for review by NRC at the EPRI offices in Charlotte, NC. EPRI NDE experts in Charlotte are available to provide access to the documents and discuss their contents. Note that none of the analysis cases of the revised set of calculations in Attachments 3 through 5 take credit for any eddy current examinations. These Eddy Current Examination Technique Specification Sheet documents will not be referenced in the revised version of MRP-335R1.

#	Question	EPRI MRP Response
16 Part 2	In addition, MRP-335, Revision 1, Chapter 5, presents POD curves from MRP-262, Revision 1, which are used to model the inspection. EPRI 1008007 is referenced in MRP-262, Revision 1, and provides the technical basis for the PDI qualification program. As the NRC staff has many questions regarding the validity of the POD curves used in MRP-335, Revision 1, and thus their applicability to the pending application, the NRC staff would like to review this technical basis document. Please submit reference (f) or provide justification for why EPRI 1008007 cannot be submitted.	As discussed on the April 13, 2015, conference call between NRC and EPRI MRP, the proprietary EPRI report 1008007 is available for review by NRC at the EPRI offices in Charlotte, NC. EPRI NDE experts in Charlotte are available to provide access to the report and discuss its contents. Note that the probabilistic analyses in Attachment 4 include sensitivity cases examining the effect of uncertainty in the POD inputs for UT of piping butt welds. This includes Model Sensitivity Case #6, which assumes a 20% reduction in POD below the base case POD curves for circumferential and axial flaws.
17	The goal of MRP-335, Revision 1, is to provide a technical basis to justify alternate inspections intervals given that the peening process involved achieves the coverage area, compression magnitude, and compression depth are achieved. MRP-335, Revision 1 is currently limited to three peening processes: underwater laser peening, water-jet peening, and air-laser peening. Given that the calculations in MRP-335, Revision 1, are not process specific, please describe whether it is necessary to limit the document to these three processes.	No, the revised version of MRP-335R1 will make clear that the inspection requirements are valid for any process that meets the performance criteria. The revised calculations presented in Attachments 3 through 5 assume a peening stress effect corresponding to the minimum values of the peening performance parameters (compression magnitude and compression depth) meeting the performance criteria. Therefore, the inspection requirements of Attachment 2 are applicable to any process meeting the performance criteria. It is emphasized that peening is effective if the intended stress change is achieved, regardless of the details of the peening process itself.
18	The response to Question 4-6(f) states that MRP-335, Revision 1 will follow appropriate actions to disposition a flaw in the pre-peening examination in accordance with Code Case N-770-4. However, the NRC has not approved N-770-4. Using ASME Code Case N-770-4 would require NRC review and approval of this code case, which would delay the usefulness of this document. Please include the required actions in the revised documents as opposed to referencing unapproved ASME code cases.	In accordance with the question, the revised version of MRP-335R1 will not reference any ASME code case not approved by U.S. NRC. Attachment 2 is a completely revised version of Section 4 of MRP-335R1 that defines the inspection requirements and performance criteria. The required actions for components mitigated via peening are included in Attachment 2.

#	Question	EPRI MRP Response
19	Many of the RAI responses in the letter dated October 10, 2014, require revisions to MRP-335, Revision 1. a. The response to Question 4-1A, last paragraph, states that "...EPRI MRP agrees to remove the subject footnotes regarding this option from a revised version of MRP-335R1." b. The response to Question 4-6(c) states that "...To resolve this comment, MRP will revise MRP-335R1 to cite Figure 1 of Code Case N-770-4 as the appropriate definition for the examination volume and surface. As necessary, the revised topical report will define minimum distances for overlap of adjacent non-susceptible material..." c. The response to Question 4-7A states that "...MRP concurs with ASME that Appendix IV is an appropriate set of requirements for demonstration of ET to be applied to Alloy 82/182piping butt welds mitigated by peening and will revise MRP-335R1 to include this requirement in lieu of 'demonstrated by the inspection vendor per current practices.'" d. The response to Questions 4-12(a) and 4-12(b) states that EPRI agrees with the NRC staff's suggestions of adding additional information regarding Code Cases N-729-1 and N-770-1 (N-770-4) to the footnotes of Table 4-1. e. The response to Question 4-12(c) states that "...a discussion of N-722-1 can be added to Section 4 and Table 4-1..." The NRC staff suggests that the response to Question 4-12(c) be added to Section 4 and Table 4-1 verbatim. Please provide the revised text for MRP-335, Revision 1, that will address these changes.	All these items have been addressed in Attachment 2, which is a completely revised version of Section 4 of MRP-335R1 that defines the inspection requirements and performance criteria.

4
EXAMINATION REQUIREMENTS

Section XI of the ASME Boiler and Pressure Vessel Code specifies periodic in-service inspections of safety-significant LWR components including primary system pressure boundary components. Because of the concern for PWSCC of Alloy 600/82/182 pressure boundary components in PWRs, augmented inspection requirements have been developed for such locations. These augmented inspection requirements are currently defined in ASME Code Cases that are made mandatory with conditions by 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[1] 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 nor sufficiently shallow to have been arrested by the peening process. The required timing of the follow-up inspection(s) was established on the basis of the detailed probabilistic calculations and is supported by the deterministic analyses.

[1] 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].

- Finally, in-service inspections (ISIs) are required to be performed regularly at the intervals prescribed in Table 4-1 for DMWs and Table 4-2 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 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.[2] 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 [4].

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 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

[2] 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.

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 [5], the top-level safety assessment report MRP-110 [6], and lower-level safety assessment reports MRP-103 [7], MRP-104 [8], and MRP-105 [9]. In the fall of 2014, the technical basis for inspections of unmitigated heads with Alloy 600 nozzles was updated by MRP [10] 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 [10] 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.[3] 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 Alloy 600 nozzles is typically every four or five 18-month fuel cycles, or three or four 24-month fuel cycles. More frequent volumetric/surface examinations may be required if PWSCC has previously been detected in the subject head.

[3] 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.

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

Item L of Table 4-1 defines alternative inspection requirements for Alloy 82/182 dissimilar metal piping 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 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).

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 nominal compressive residual stress field extends to a minimum depth of 0.04 in. (1.0mm) on the susceptible material along the wetted surface unless the alternative performance criterion is used.

Sustainability of Effect

The mitigation process is permanent or at least effective for the remaining service life of the component: the stress state after any relaxation must still meet the performance criteria.

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 demonstrated by analysis or testing, the mitigation process shall not have degraded the component 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 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:

- 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

<u>Examination Coverage</u>

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).

<u>Acceptance Criteria for Item L of Table 4-1</u>

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 4-1, 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 4-1 during the outage in which the flaw was identified. If corrected by a mitigation technique in Table 4-1, 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 Table 4-1, Note (5).

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 4-1.

Eddy current examinations shall be performed in accordance with IWA-2223 and the performance criteria in Section 4.2.8.

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 purposes 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 Peening

It is noted that Section 3.5 of MRP-335 Rev. 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 or demonstration testing required below is 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 susceptible 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 shall be included in the evaluation.

An analysis or demonstration test shall be performed to confirm the post-mitigation stress state. The analysis or testing shall show that the steady-state operating axial and hoop direction stresses combined with residual stresses are compressive at the inside surface. A pre-stress improvement residual stress condition resulting from a construction weld repair from the inside surface to a depth of 50% of the weld thickness and extending for 360° shall be assumed. The analysis or

testing shall identify the critical process parameters and define acceptable ranges of the parameters needed to ensure that the compressive stress field has been developed.

4.2.8.1.1 Nominal Depth of Compressive Residual Stress

For peening, demonstration testing shall confirm the nominal depth of the compressive residual stress produced by the peening technique is at least 0.04 in. (1.0 mm), unless the alternative of Section 4.2.8.1.2 is used.

4.2.8.1.2 Alternative Requirement

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 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.

4.2.8.2 Sustainability

The effect produced by the mitigation process shall be permanent.

An analysis or demonstration test shall be performed to confirm that the mitigation process is permanent. The analysis and 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

Testing shall be performed to verify that the peening process maintains the compressive surface stress condition for the remaining service life of the component.

4.2.8.3 UT Inspectability

The capability to perform ultrasonic examinations of the relevant volume of the component shall not have been adversely affected.

Mockup testing and nondestructive examination qualified to Section XI, Mandatory Appendix VIII, performance demonstration requirements shall have been performed to demonstrate that a qualified examination of the relevant volume of the mitigated component can be accomplished subsequent to the mitigation including changes to component geometry, material properties, or other factors.

4.2.8.4 Lack of Adverse Effects

The mitigation process shall not have degraded the component or adversely affected other components in the system.

Analysis or testing shall have been performed to verify that peening does not cause undesirable hardness at the peened surface, 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 Considerations for Pre-Existing Flaws

Existing flaws, if any, shall be addressed as part of the mitigation.

4.2.8.6.1 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.

4.2.8.6.2 Assessment of Potential Fatigue Flaw Growth

An analysis meeting the requirements of IWB-3640 shall be performed to assess growth by fatigue of a shallow postulated planar surface flaw [either half the nominal compressive depth or 0.02 in. (0.5 mm)] in the peened compressive residual stress zone. The fatigue assessment shall include the applied stress cycles that occur at the specific location, in combination with the levels of compressive stress expected from the applied peening method, adjusted for temperature and load-cycling-induced relaxation.

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.

(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 weld inlay, onlay, overlay, peening, or stress improvement, as follows:

(1) Not applicable.

(2) The first examinations following weld inlay, onlay, overlay, peening, or stress improvement for Inspection Items D through 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 Items D through L may be performed coincident with the vessel nozzle examinations required by Category B-D.

(3) For successive inspection intervals following weld inlay, onlay, overlay, peening, or stress improvement, 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 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 Table 4-1 (5). 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) and Table 4-1, 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 4-1 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)]. Alternatively, the flaw may be made acceptable by a repair/replacement activity or other mitigation techniques in accordance with -3132.2(e).

(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)]. Alternatively, the flaw may be made acceptable by a repair/replacement activity or other mitigation techniques in accordance with -3132.2(e).

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

Items B4.50 and B4.60 of Table 4-2 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 4.3.7. The inspection requirements in Table 4-2 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).

4.3.1 Summary of Performance Criteria of Section 4.3.7

The performance criteria of Section 4.3.7 shall be satisfied. For information only, brief summaries of the requirements of Section 4.3.7 are provided below.

<u>Peening Coverage</u>

The required coverage is the full 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 [11]. This includes the entire wetted surface of the Alloy 82/182 J-groove weld and butter material, as well as the surface of the Alloy 600 tube material in the region of high weld residual stress on the nozzle outside surface and nozzle inside surface.

<u>Stress Magnitude</u>

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.

<u>Depth of Effect</u>

The nominal compressive residual stress field extends a 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

<u>Sustainability of Effect</u>

The mitigation process is permanent or at least effective for the remaining service life of the component: the stress state after any relaxation must still meet the performance criteria.

<u>Inspectability</u>

The capability to perform ultrasonic examination 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 (including vibration effects during application) is not to have detrimental effects on the peened surfaces or surrounding transition areas.

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 4-2:

- A volumetric examination of the nozzle tube is to be performed as the baseline inspection.
- Additionally, a documented leak path assessment through all J-groove welds is to be performed.

As an alternative to the above bullets, 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.

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. It is emphasized that 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 4-2, 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 ≥ 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 for peened penetrations are shown in Table 4-2 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.

- 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.

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.

Surface or Volumetric 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 is 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/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 4-2 requires prior NRC approval.

Acceptance Criteria for Item B4.50 of Table 4-2

The visual examination acceptance standards for Item B4.50 of Table 4-2 are in accordance with Subsubarticle -3140 of N-729-1 with the addition of the following to Paragraph -3141:

(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.

(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 4-2

The surface and volumetric examination acceptance standards for Item B4.60 of Table 4-2 are in accordance with Subsubarticle -3130 of N-729-1 with the addition of the following to Paragraph -3131:

(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.

(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 4.3.7 and Section XI IWA-2200.

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

It is noted that Section 3.5 of MRP-335 Rev. 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 or demonstration testing required below is performed in accordance with these quality assurance requirements, which provide adequate controls.

4.3.7.1 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 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). Susceptible material locations include 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 peened surfaces shall be included in the evaluation and shall not exceed +10 ksi (+70 MPa) in the area of interest.

4.3.7.1.1 Demonstration of Nominal Surface Stress

An analysis and demonstration test shall be performed to demonstrate the required capability of the peening method to produce the required stress state. The testing shall quantify the post-mitigation stress state exclusive of normal operating 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 operating stresses) has been produced on the mitigated surface. The analysis shall combine the normal operating stresses with residual stresses obtained from the testing. The combined stress shall not exceed +10 ksi (+70MPa) on the application surface.

4.3.7.1.2 Nominal Depth of Compressive Residual Stress

The nominal compressive surface residual stress field shall be demonstrated by testing.

a) The nominal compressive residual stress field shall extend to a minimum depth of 0.04 in. (1.0 mm) on the outside surface of the nozzle and attachment weld surface area susceptible to PWSCC initiation as defined in Section 4.3.7.1.

b) The nominal compressive residual stress field on the nozzle inside surface shall extend to a minimum depth of 0.01 in. (0.25 mm) on surfaces susceptible to PWSCC initiation as defined in Section 4.3.7.1.

4.3.7.2 Sustainability

The effect produced by the mitigation process shall result in a peened surface with a stress state no greater than +10 ksi (+70 MPa) including residual and operating stresses.

An analysis or demonstration test shall be performed to confirm that the mitigation process is permanent or at least effective for 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 and (b) any material properties related to stress relaxation over time.

4.3.7.3 UT Inspectability

The capability to perform ultrasonic examination 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. 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.

4.3.7.4 Lack of Adverse Effects

The mitigation process, including vibration effects during application shall not degrade the component or adversely affect other components in the system.

4.3.7.4.1 Component Geometry

An analysis or testing shall be performed to verify that the mitigation process does not result in changes to the component geometry.

4.3.7.4.2 Other Effects

Analysis or testing shall be performed to verify that peening does not cause undesirable hardness at the peened surface, erosion of surfaces, undesirable surface roughening, or detrimental effects in the transition regions adjacent to the peened regions.

4.3.7.5 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.

Table 4-2
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 4.3.7	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 4.3.7	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. 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, 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. 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 4.3.7 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 4.3.7.
(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-weld and penetration tubing (outside and inside) susceptible to PWSCC initiation and growth.

4.4 References

1. ASME Code Case N-770-1, "Alternative Examination Requirements and Acceptance Standards for Class 1 PWR Piping and Vessel Nozzle Butt Welds Fabricated With UNS N06082 or UNS W86182 Weld Filler Material With or Without Application of Listed Mitigation Activities," Section XI, Division 1, American Society of Mechanical Engineers, New York, Approval Date: December 25, 2009.
2. ASME Code Case N-729-1, "Alternative Examination Requirements for PWR Reactor Vessel Upper Heads With Nozzles Having Pressure-Retaining Partial-Penetration Welds," Section XI, Division 1, American Society of Mechanical Engineers, New York, Approval Date: March 28, 2006.
3. ASME Code Case N-722-1, "Additional Examinations for PWR Pressure Retaining Welds in Class 1 Components Fabricated with Alloy 600/182/82 Materials," Section XI, Division 1, American Society of Mechanical Engineers, New York, Approval Date: January 26, 2009.
4. *Materials Reliability Program: Primary System Piping Butt Weld Inspection and Evaluation Guidelines (MRP-139, Revision 1)*, EPRI, Palo Alto, CA: 2008. 1015009. [Freely Available at www.epri.com]
5. *Materials Reliability Program: Inspection Plan for Reactor Vessel Closure Head Penetrations in U.S. PWR Plants (MRP-117)*, EPRI, Palo Alto, CA: 2004. 1007830. [Freely Available at www.epri.com]
6. *Materials Reliability Program: Reactor Vessel Closure Head Penetration Safety Assessment for U.S. PWR Plants (MRP-110NP): Evaluations Supporting the MRP Inspection Plan*, EPRI, Palo Alto, CA: 2004. 1009807-NP. [NRC ADAMS Accession No.: ML041680506]
7. *Materials Reliability Program: Reactor Vessel Head Nozzle and Weld Safety Assessment (MRP-103NP)*, EPRI, Palo Alto, CA: 2004. 1009402. [NRC ADAMS Accession No.: ML041680477]
8. *Materials Reliability Program: RV Head Nozzle and Weld Safety Assessment for Westinghouse and Combustion Engineering Plants (MRP-104NP)*, EPRI, Palo Alto, CA: 2004. 1009403. [NRC ADAMS Accession No.: ML041680483]
9. *Materials Reliability Program: Probabilistic Fracture Mechanics Analysis of PWR Reactor Pressure Vessel Top Head Nozzle Cracking (MRP-105NP)*, EPRI, Palo Alto, CA: 2004. 1007834. [NRC ADAMS Accession No.: ML041680489]
10. *Materials Reliability Program: Reevaluation of Technical Basis for Inspection of Alloy 600 PWR Reactor Vessel Top Head Nozzles (MRP-395)*. EPRI, Palo Alto, CA: 2014. 3002003099. [Freely Available at www.epri.com]
11. *Materials Reliability Program: Generic Evaluation of Examination Coverage Requirements for Reactor Pressure Vessel Head Penetration Nozzles, Revision 1 (MRP-95R1NP)*, EPRI, Palo Alto, CA: 2004. 1011225. [NRC ADAMS Accession No.: ML043200602]

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 (Attachment 2).

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 (Attachment 2), 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 [1].

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.

<u>Bounding Peening Stress Profile</u>

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[1]), 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 +69 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 tress of 69 MPa (10 ksi) in the direction of maximum operating stress for flaws on the nozzle ID surface, and a residual stress value 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 negligible.

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[1] 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.

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 RPVH penetration, 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 minimum 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 [1]:

- 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 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 RPVH penetration, the compressive residual stress depth is assumed to be approximately 3.0 mm (0.12 inch).

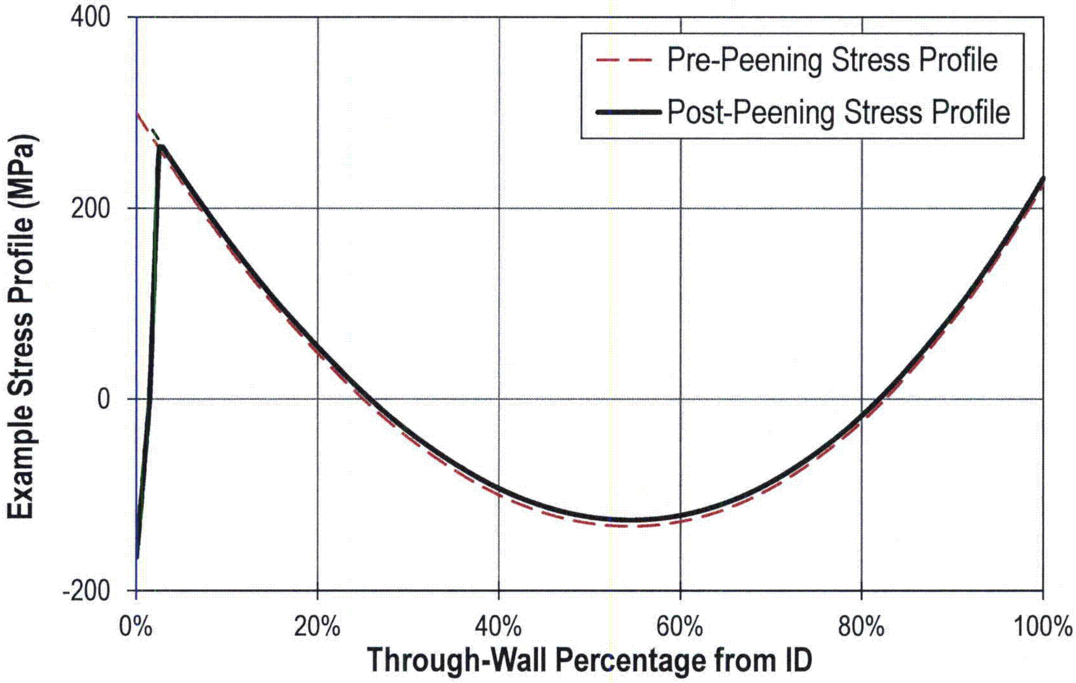

Figure 5-1
Example Post-Peening Residual Stress Profile for Circumferential Crack

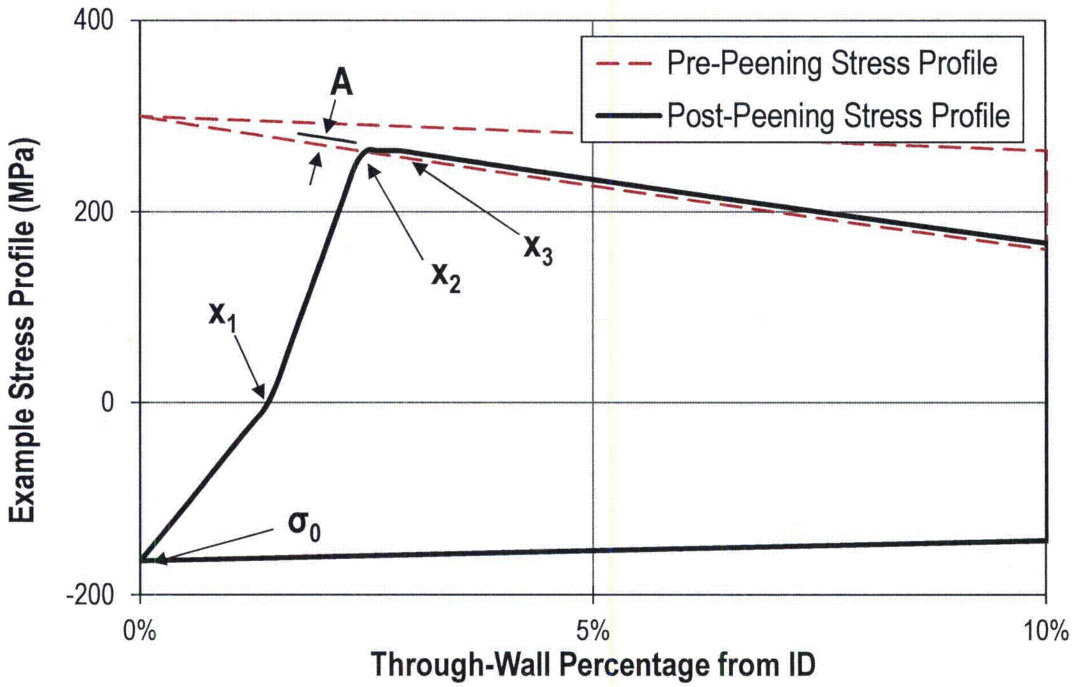

Figure 5-2
Example Post-Peening Residual Stress Profile near Surface of Circumferential Crack

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 DM weld components (Section 5.2.2.1) and at various locations on reactor 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 [2] and MRP-115 [3]. 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.

Bounding Peening Stress Profile

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).

Example Representative Peening Stress Profile

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 MRP-335R1 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 MRP-335R1 Section A.3.3)	Nondim	0.7	Nondim	0.7

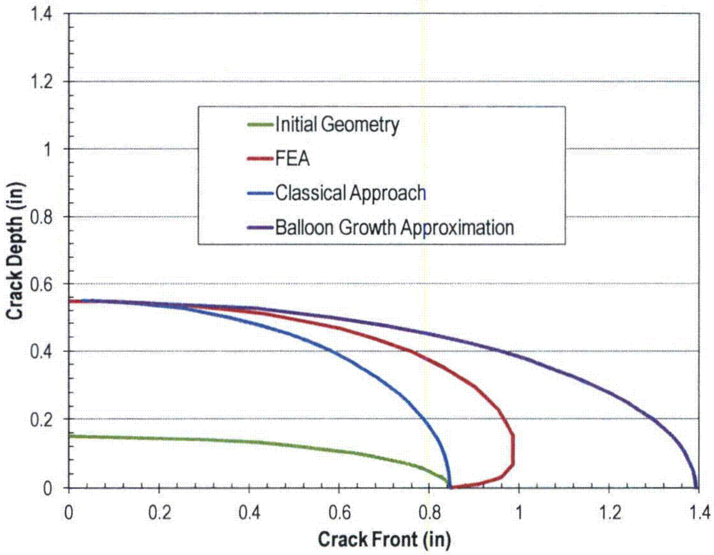

Figure 5-3
Example of Crack Front Shapes Predicted in a Peened Component with: a) FEA, b) Classical Analytical Methods, or c) the Balloon Growth Approximation

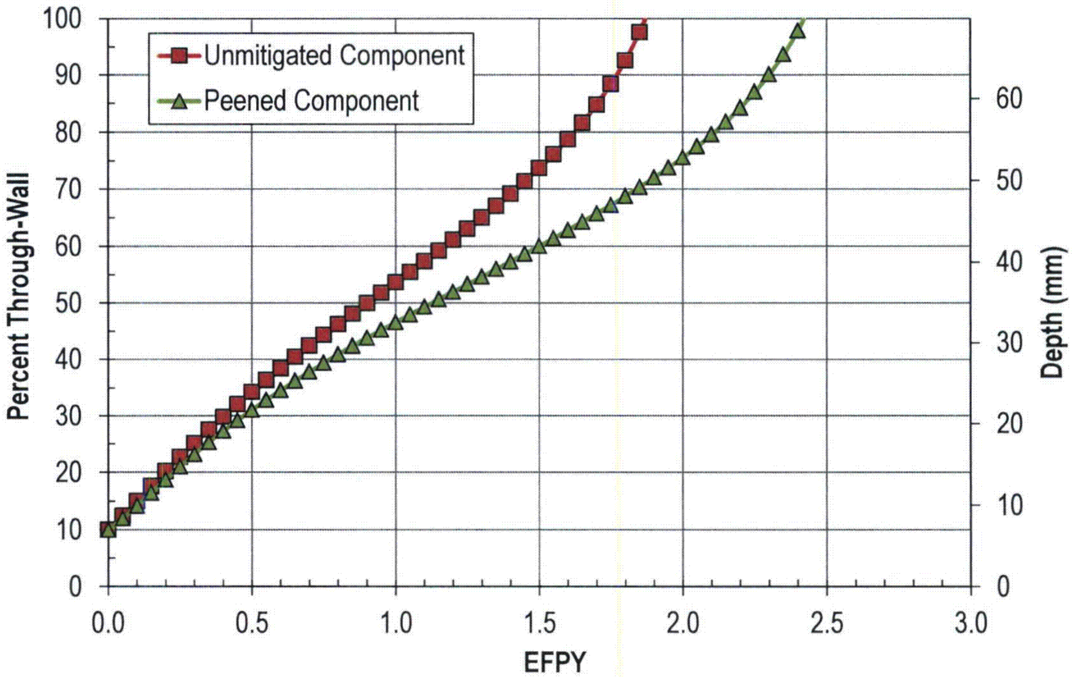

Figure 5-4
Through-Wall Fraction vs. Time for Circumferential Crack on Unmitigated and Peened Component (a_0/t=10% [7.0 mm] and $2c_0/a_0$=8.5)

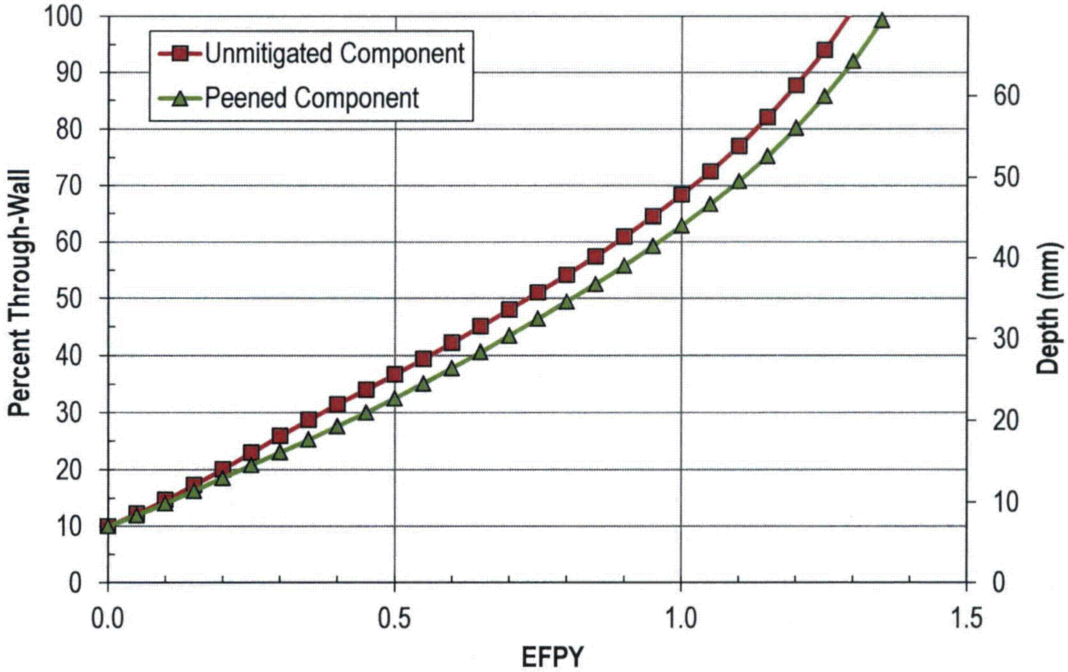

Figure 5-5: Through-Wall Fraction vs. Time for Axial Crack on Unmitigated and Peened Component (a_0/t=10% [7.0 mm] and $2c_0/a_0$=4.5)

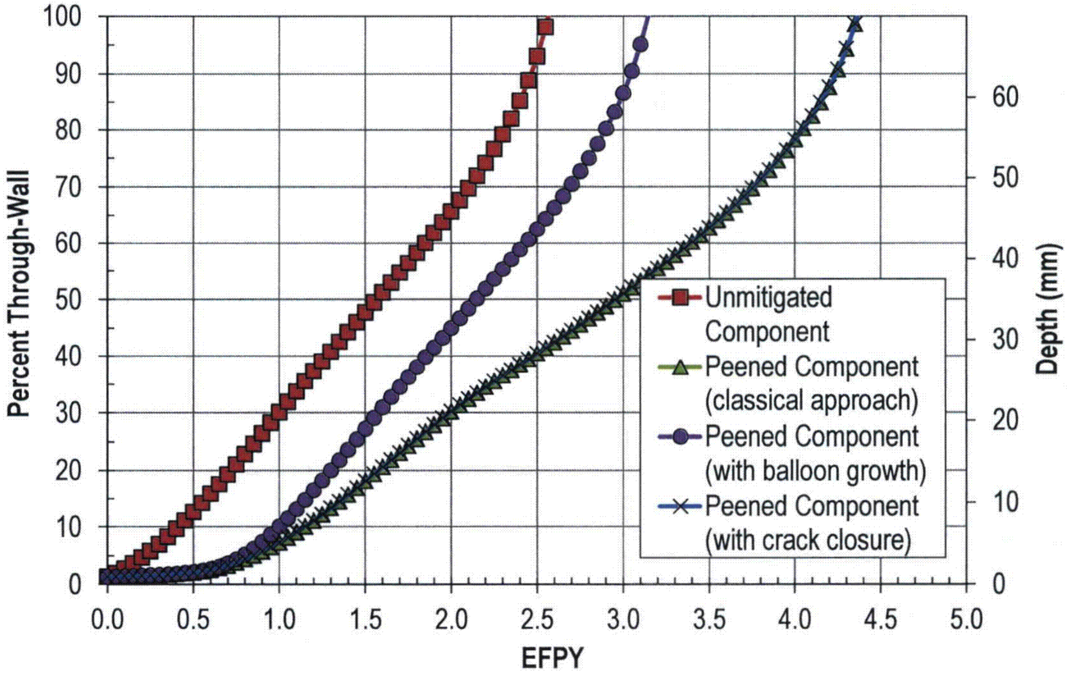

Figure 5-6
Through-Wall Fraction vs. Time for Circumferential Crack on Unmitigated and Peened Component (a_0/t=1.3% [0.9 mm] and $2c_0/a_0$=8.5)

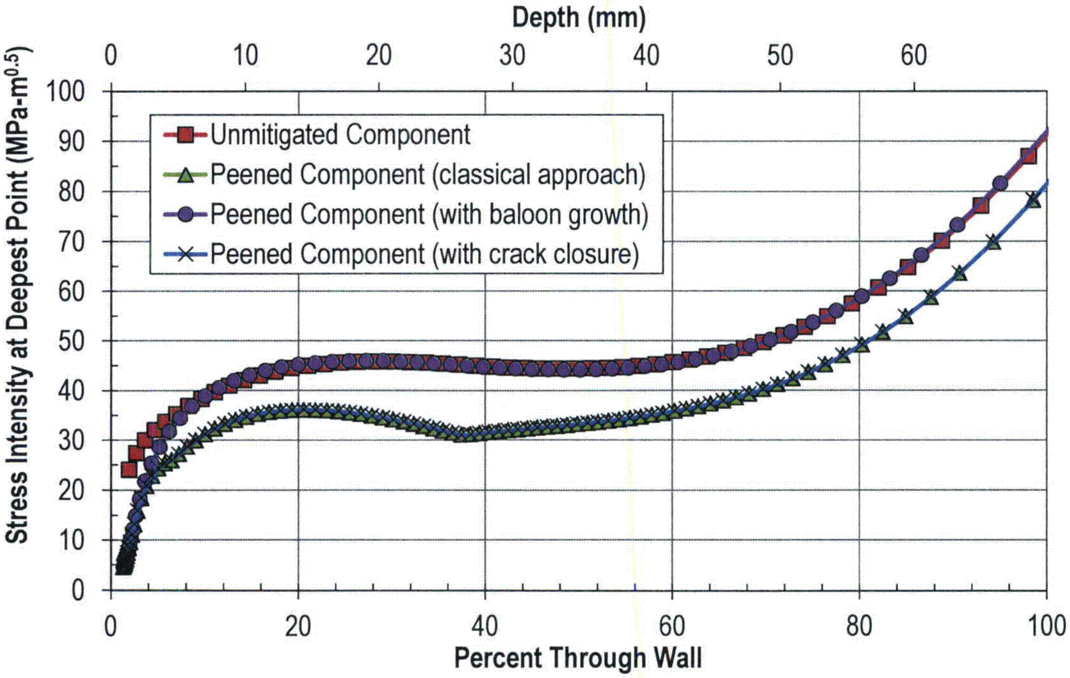

Figure 5-7
Stress Intensity Factor vs. Through-Wall Fraction for Circumferential Crack on Unmitigated and Peened Component (a_0/t=1.3% [0.9 mm] and $2c_0/a_0$=8.5)

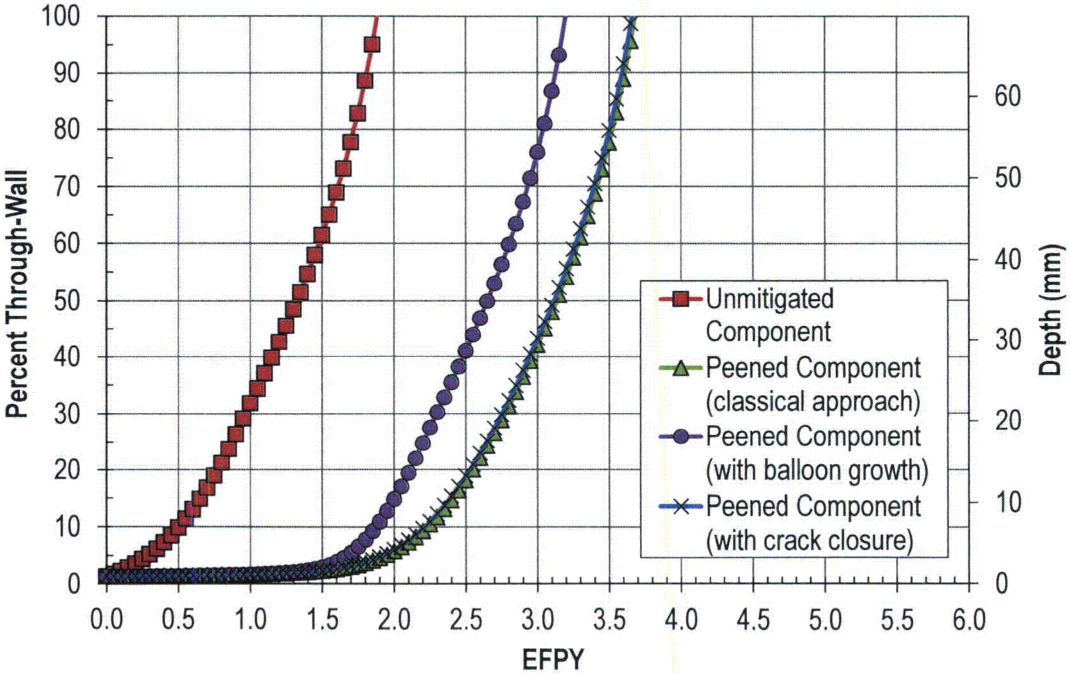

Figure 5-8: Through-Wall Fraction vs. Time for Axial Crack on Unmitigated and Peened Component (a_0/t=1.3% [0.9 mm] and $2c_0/a_0$=4.5)

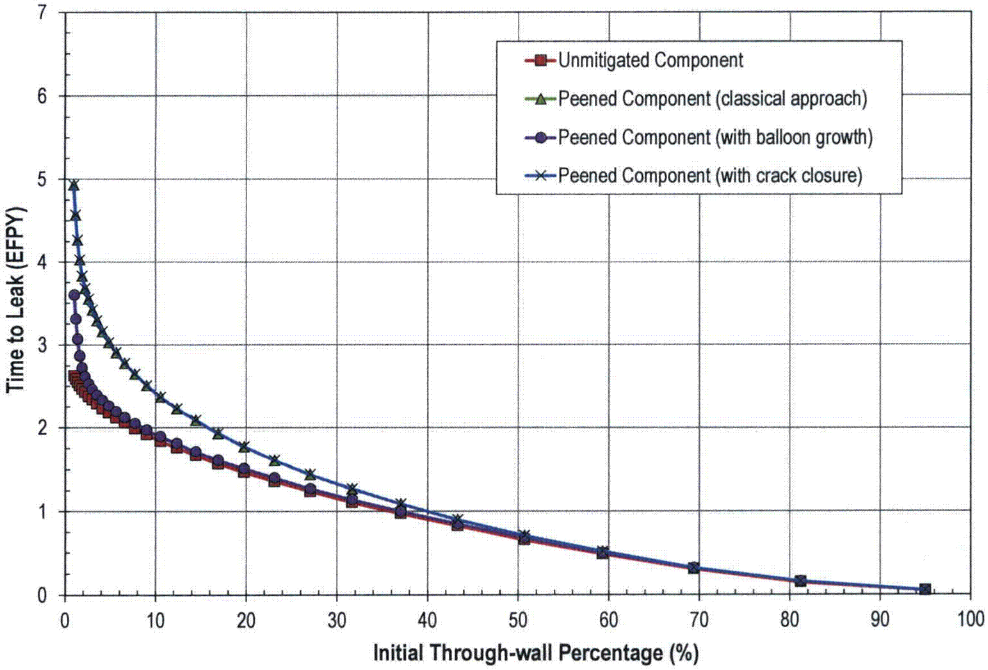

Figure 5-9
Time to Through-Wall Growth vs. Initial Crack Depth for Circumferential Cracks ($2c_0/a_0$=8.5)

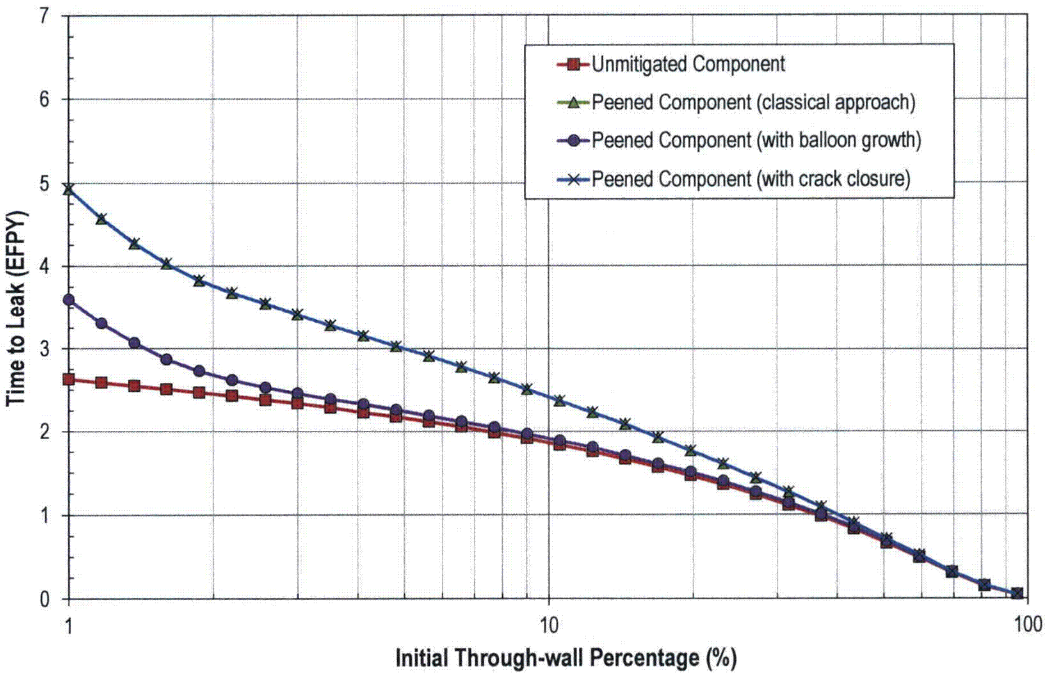

Figure 5-10
Figure 5-9 (Circumferential Cracks with $2c_0/a_0$=8.5) Replotted Using Log-Scale Abscissa

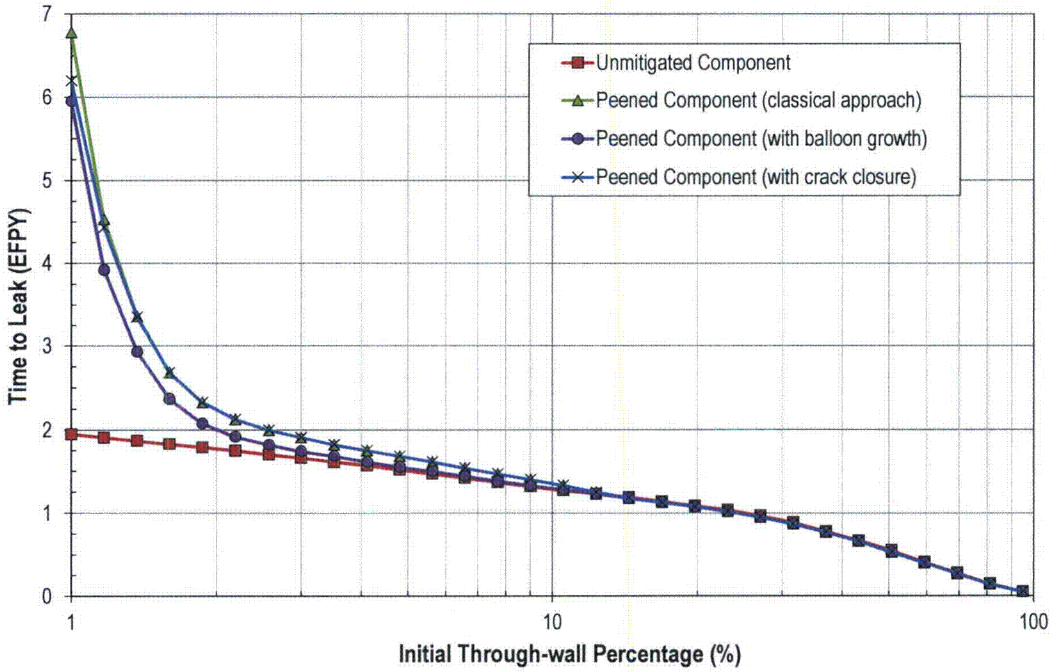

Figure 5-11
Time to Through-Wall Growth vs. Initial Crack Depth for Axial Cracks (Log-Scale Abscissa and $2c_0/a_0=4.5$)

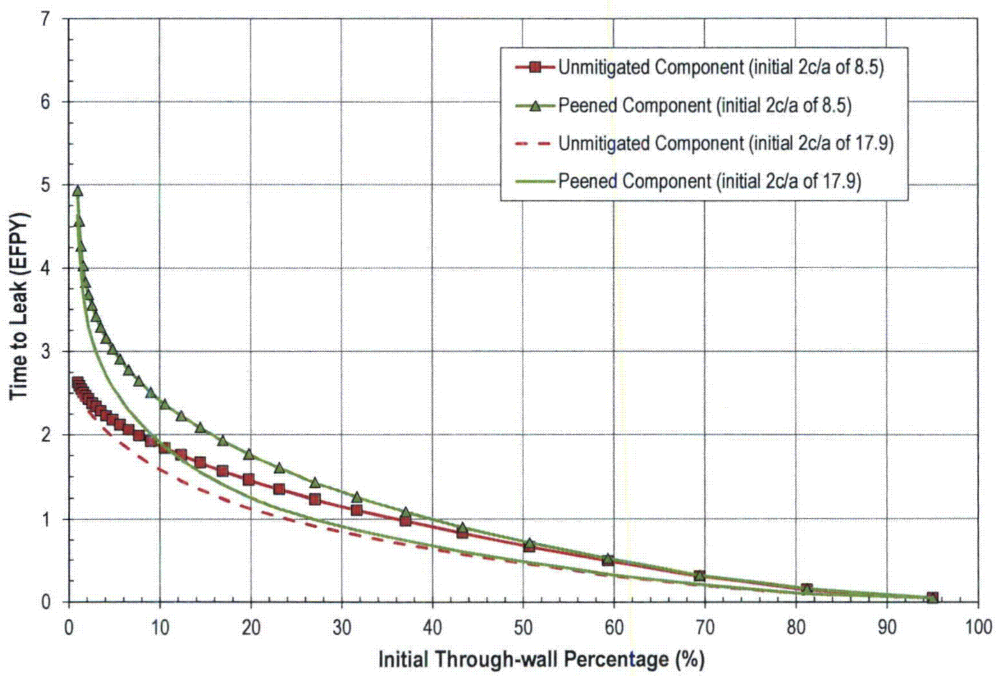

Figure 5-12
Comparing Differences due to Initial Aspect Ratio: Time to Through-Wall Growth vs. Initial Crack Depth for Circumferential Cracks

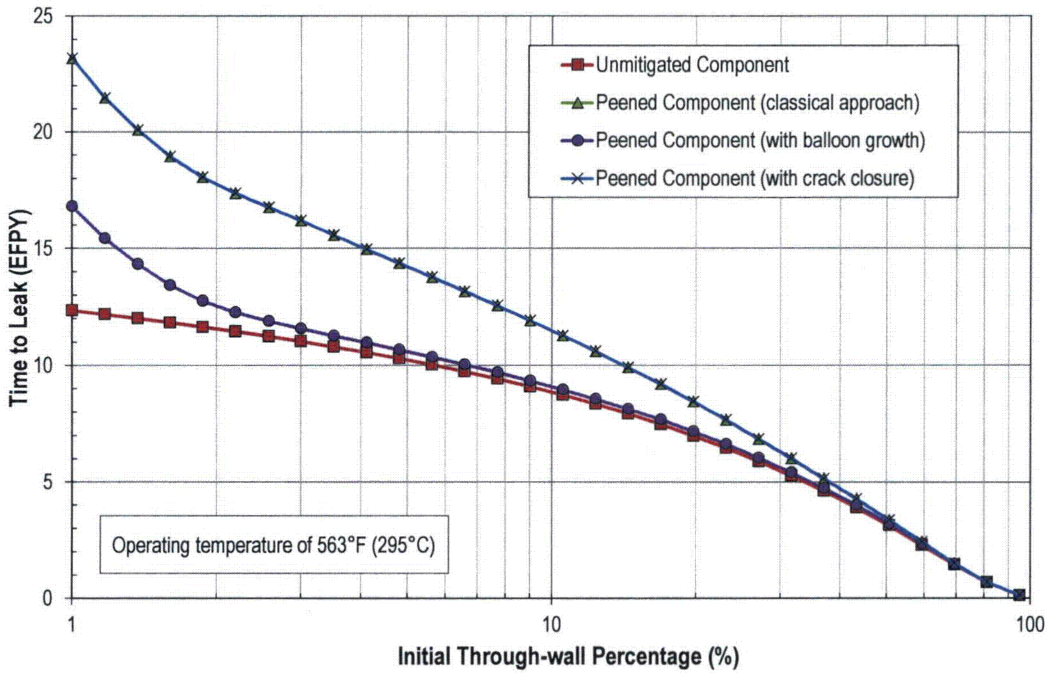

Figure 5-13
Time to Through-Weld Growth vs. Initial Crack Depth for Circumferential Crack on a RVIN ($T=563°F$ and $2c_0/a_0=8.5$)

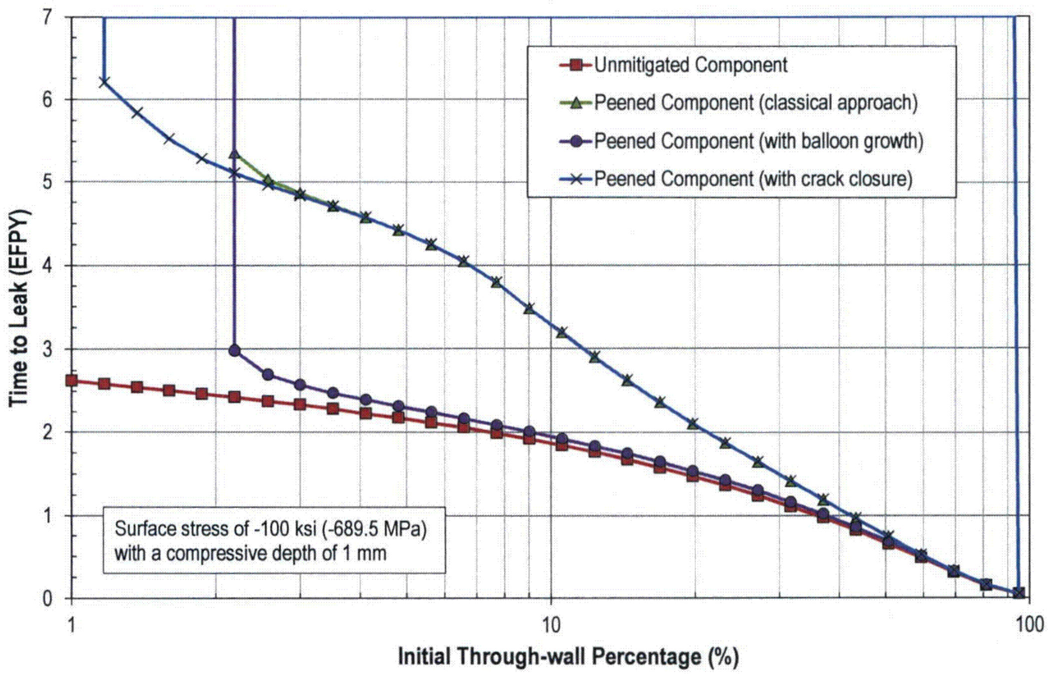

Figure 5-14
Time to Through-Weld Growth vs. Initial Crack Depth for Circumferential Crack Subject to Example Representative Peening Compressive Residual Stresses ($2c_0/a_0=8.5$)

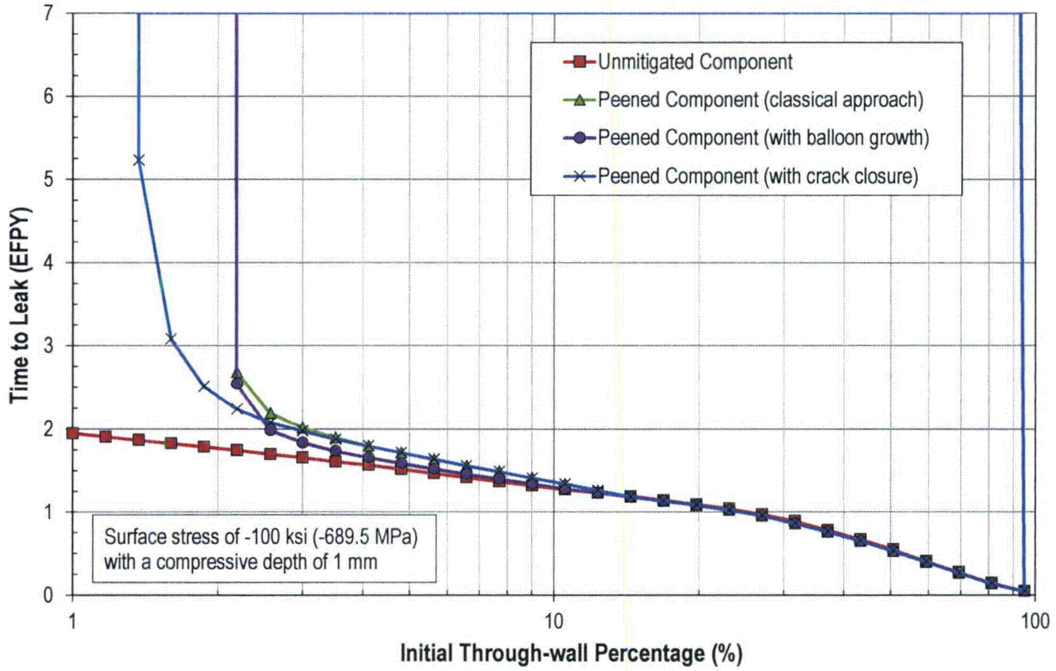

Figure 5-15
Time to Through-Weld Growth vs. Initial Crack Depth for Axial Crack Subject to Example Representative Peening Compressive Residual Stresses ($2c_0/a_0$=4.5)

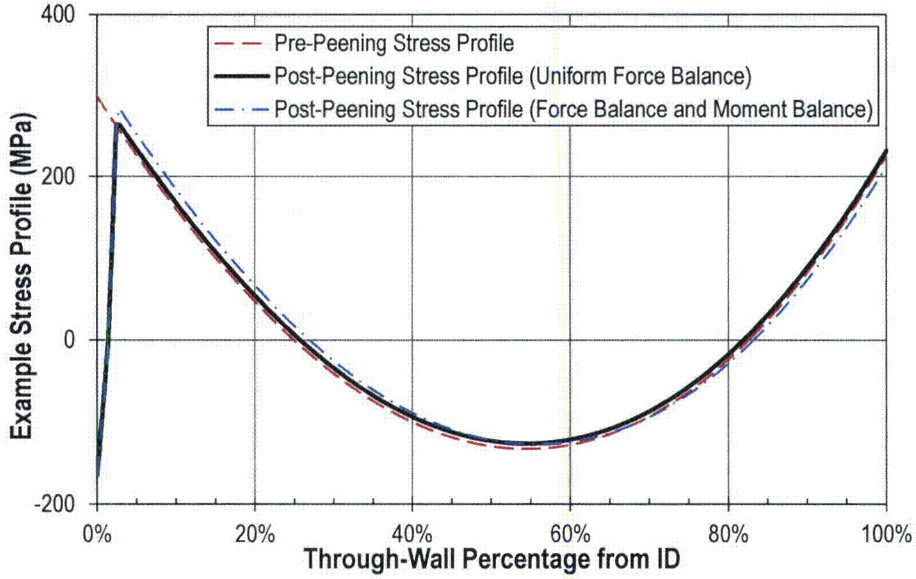

Figure 5-16
Comparison of Stress Profiles used in Peening Stress Balance Study for Circumferential Cracking

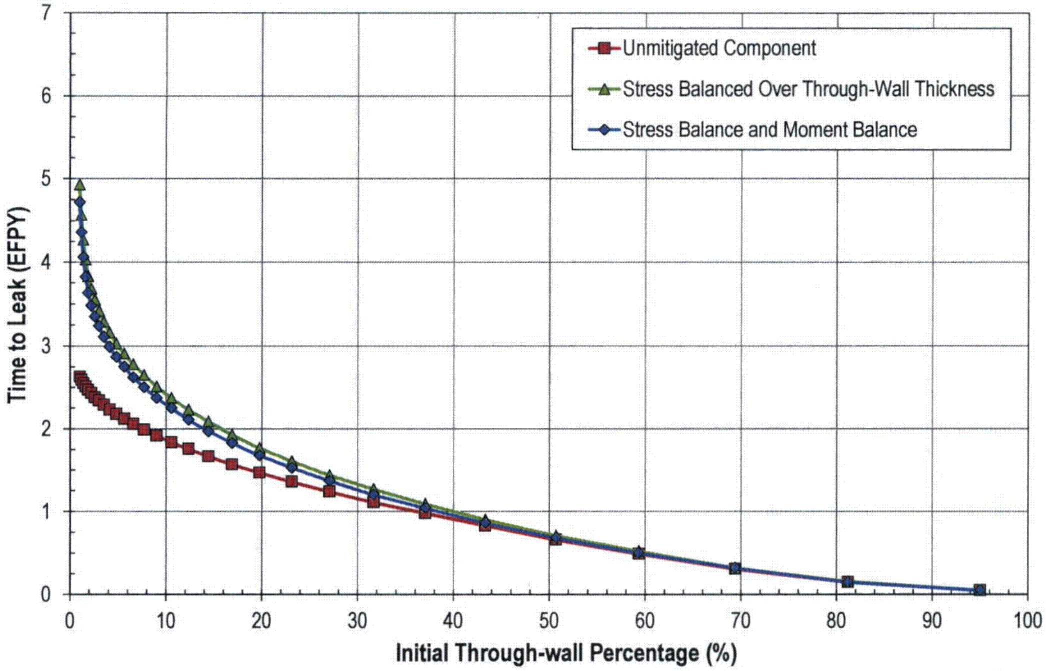

Figure 5-17
Comparing Differences due to Concentration of Force Balance: Time to Through-Wall Growth vs. Initial Crack Depth for Circumferential Cracks

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 RVHPNs 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).

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

Figure 5-28 through Figure 5-30 present results for an example (more compressive) peening stress profile. As in the DM weld 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 benefit of peening rapidly fades for weld cracks deeper than the compressive layer depth.

Generally speaking, because penetration nozzles are thinner-walled than components with a DM weld, 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 DM weld 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 penetration nozzle and weld butter material interfaces.

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 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 [4]). A flaw angle of 300° is conservatively taken to be the size at which nozzle ejection occurs, per the calculations in MRP-110 [5].

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 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-4 of MRP-335R1			
	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
$K_{I,th}$	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-5 of MRP-335R1			
$\sigma_{0,PPRS,ID}$	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 MRP-335R1 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 MRP-335R1 Section A.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

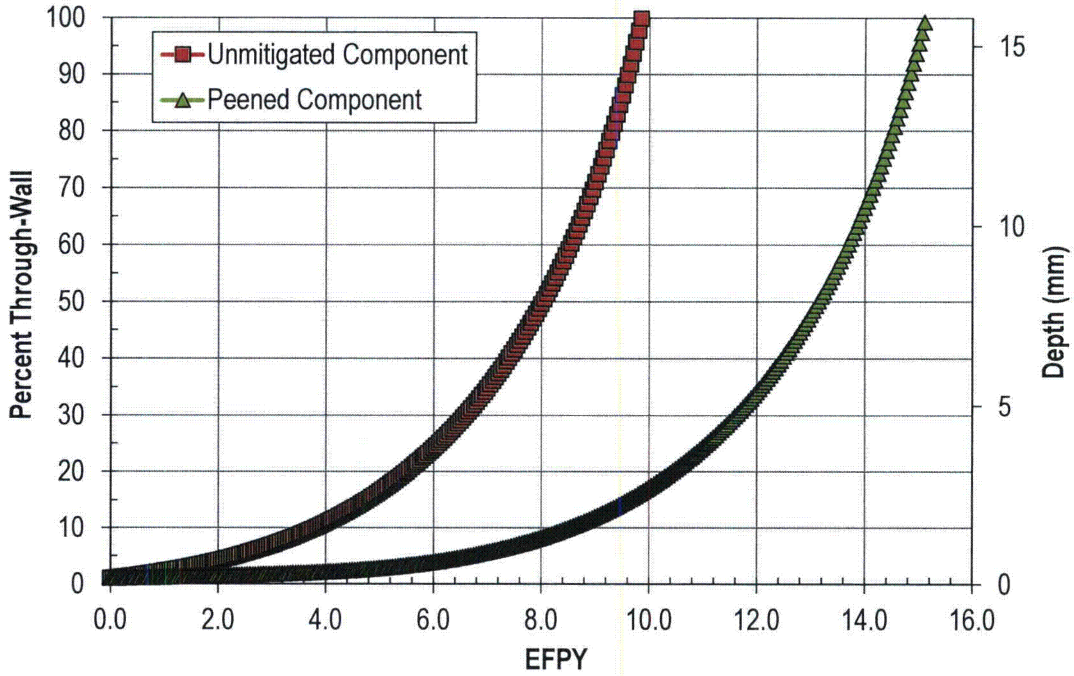

Figure 5-18
Through-Wall Percentage vs. Time for Uphill ID Axial Crack on Unmitigated and Peened Component (a_0/t=1% [0.16 mm] and $2c_0/a_0$=4.5)

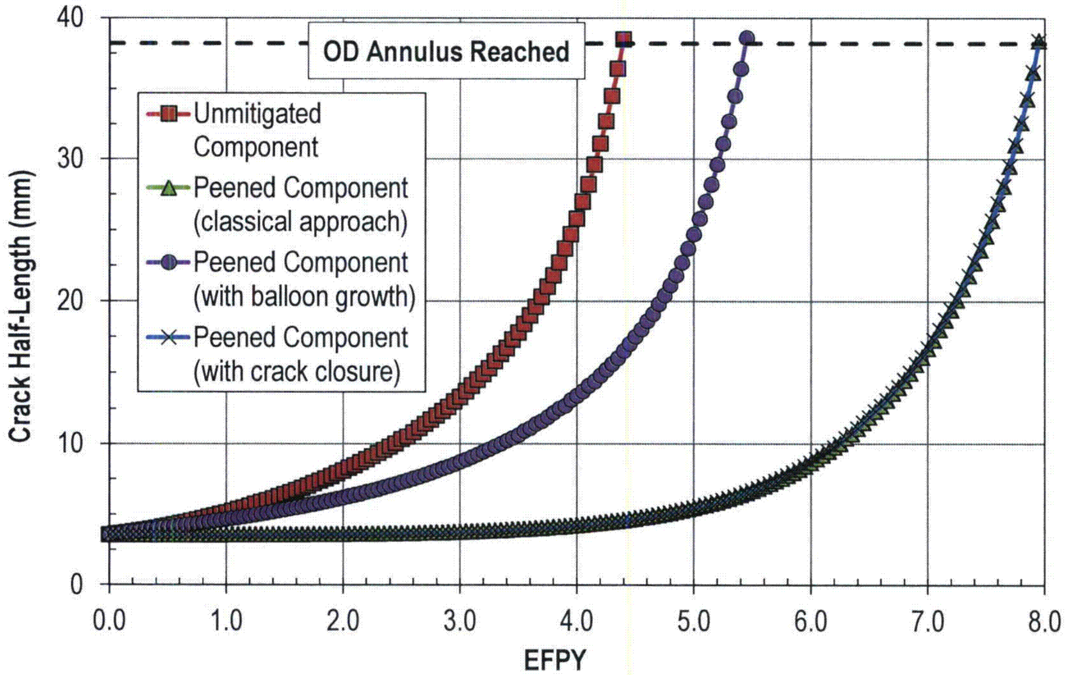

Figure 5-19
Half-Length along Nozzle Surface vs. Time for Uphill OD Axial Crack on Unmitigated and Peened Component (a_0/t=10% [1.6 mm] and $2c_0/a_0$=4.5)

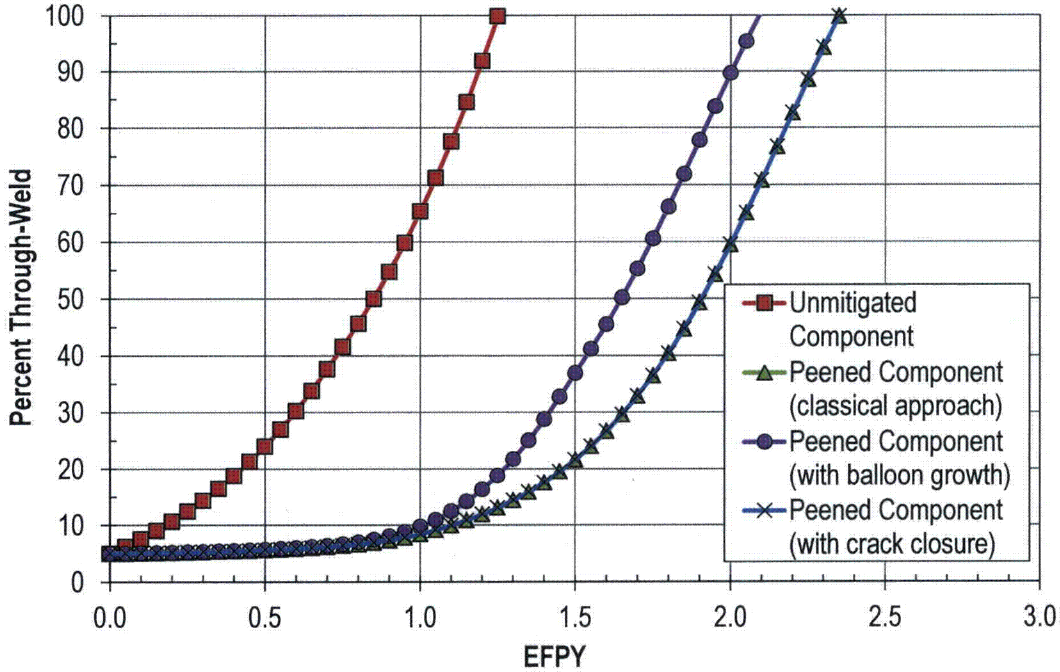

Figure 5-20
Through-Weld Percentage vs. Time for Downhill Weld Radial Crack on Unmitigated and Peened Component (a_0/t=5% [1.2 mm] and $2c_0/a_0$=4.5)

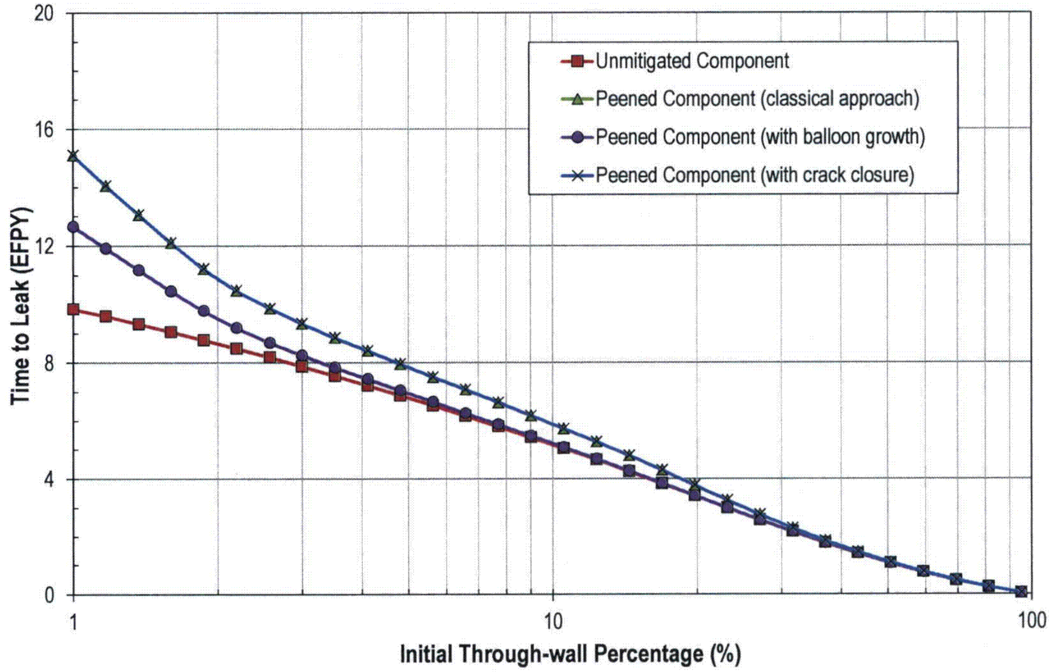

Figure 5-21
Time to Through-Wall Growth vs. Initial Crack Depth for Axial Crack on Uphill Penetration Nozzle ID (Log-Scale Abscissa, $2c_0/a_0$=4.5)

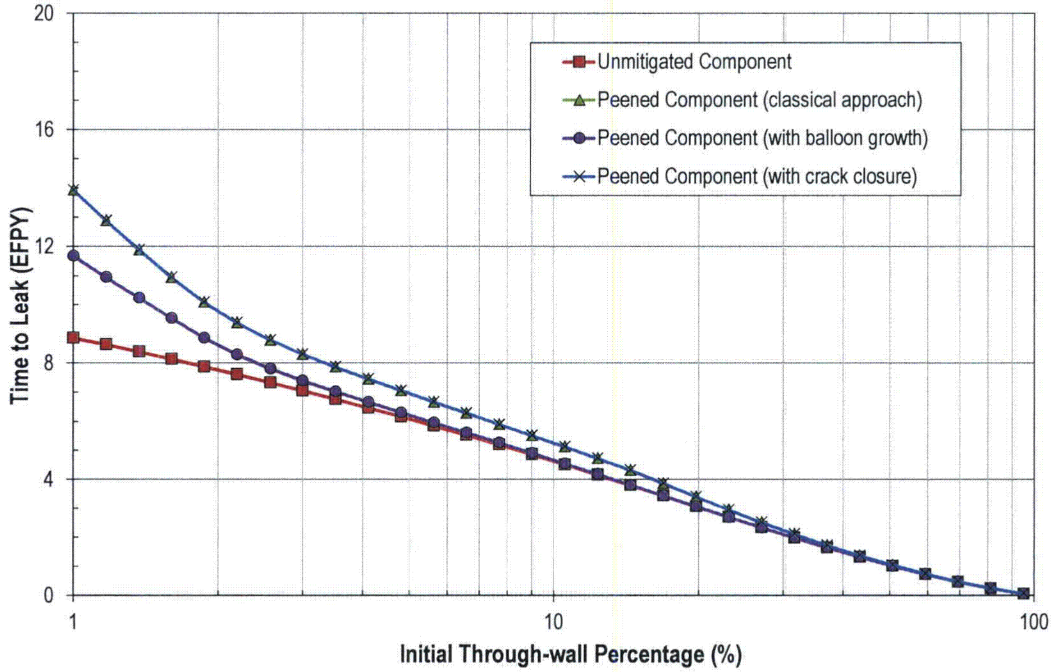

Figure 5-22
Time to Through-Wall Growth vs. Initial Crack Depth for Axial Crack on Downhill Penetration Nozzle ID (Log-Scale Abscissa, $2c_0/a_0$=4.5)

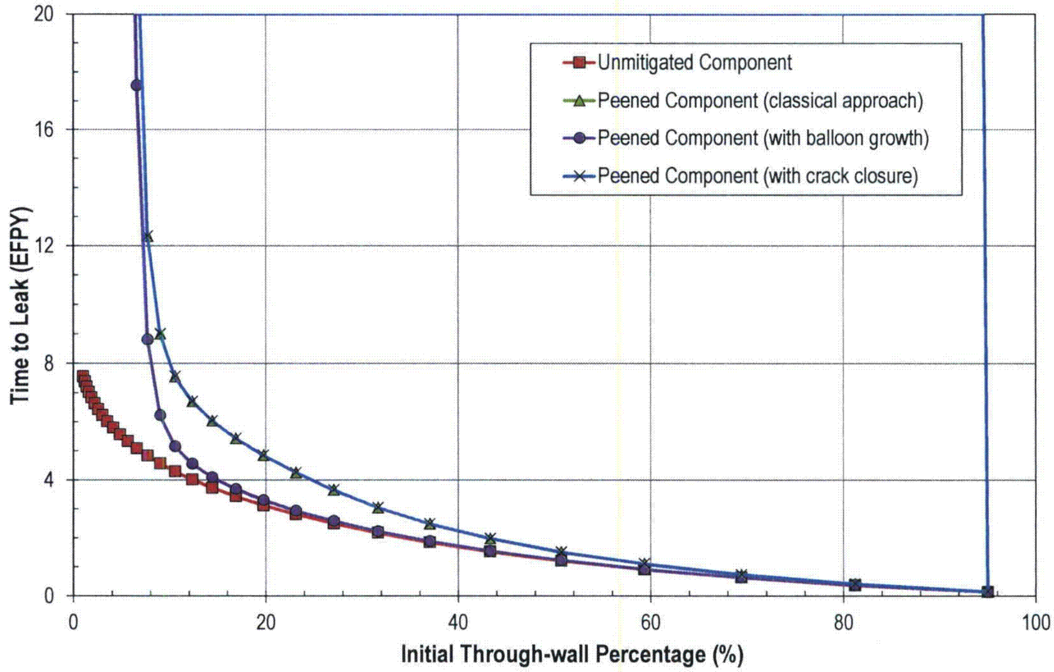

Figure 5-23
Time to OD Nozzle Annulus vs. Initial Crack Depth for Axial Crack on Uphill Penetration Nozzle OD ($2c_0/a_0$=4.5)

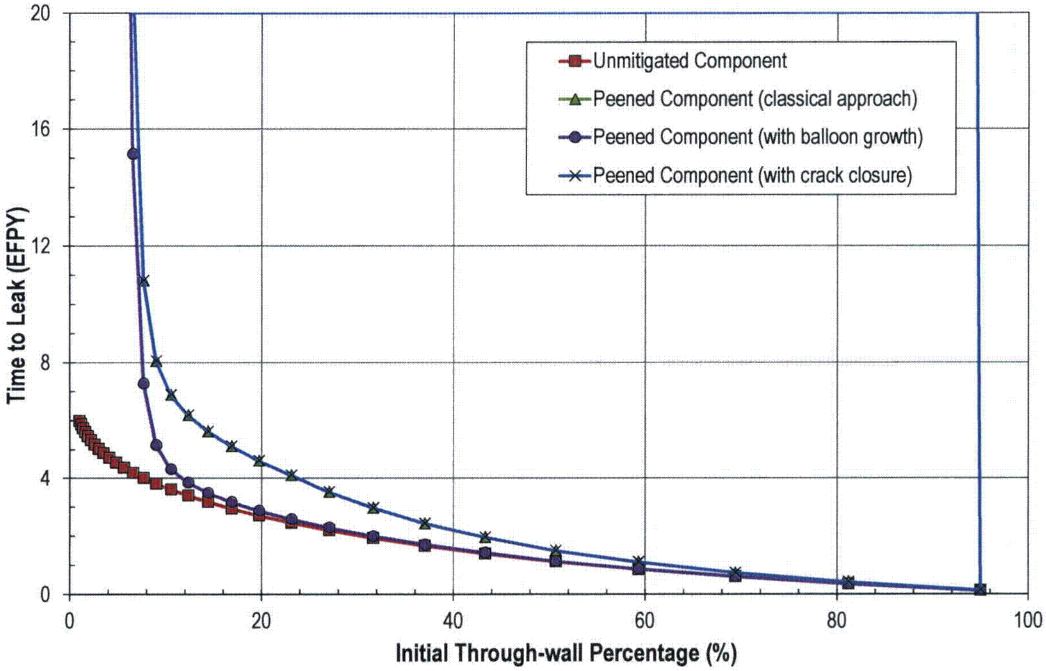

Figure 5-24
Time to OD Nozzle Annulus vs. Initial Crack Depth for Axial Crack on Downhill Penetration Nozzle OD ($2c_0/a_0=4.5$)

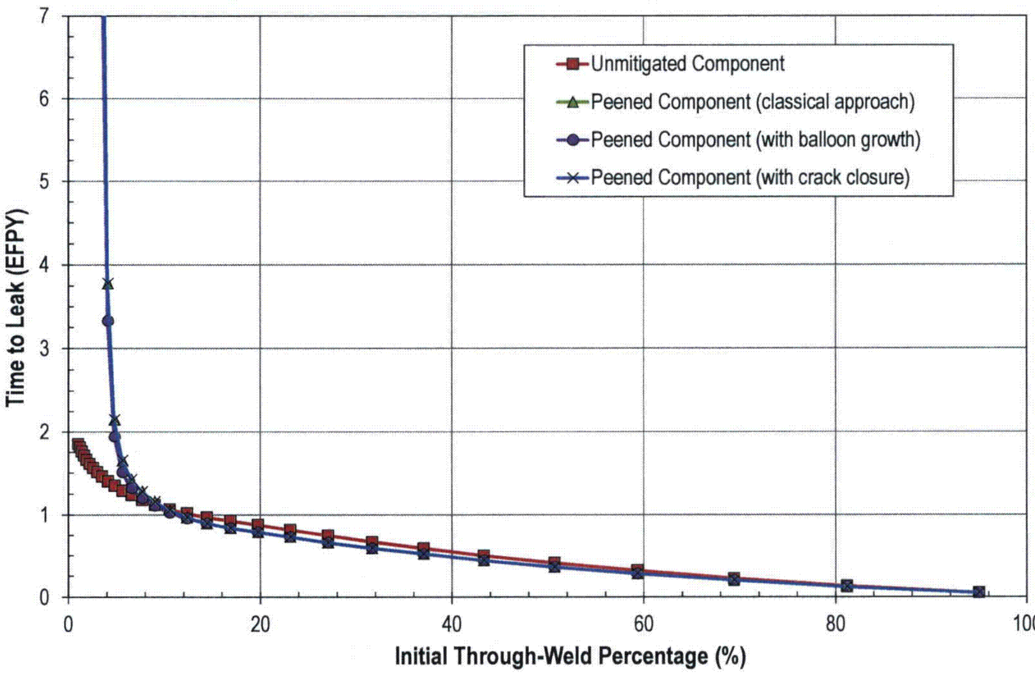

Figure 5-25
Time to Through-Weld Growth vs. Initial Crack Depth for Weld Radial Crack on Uphill J-Groove Weld ($2c_0/a_0=4.5$)

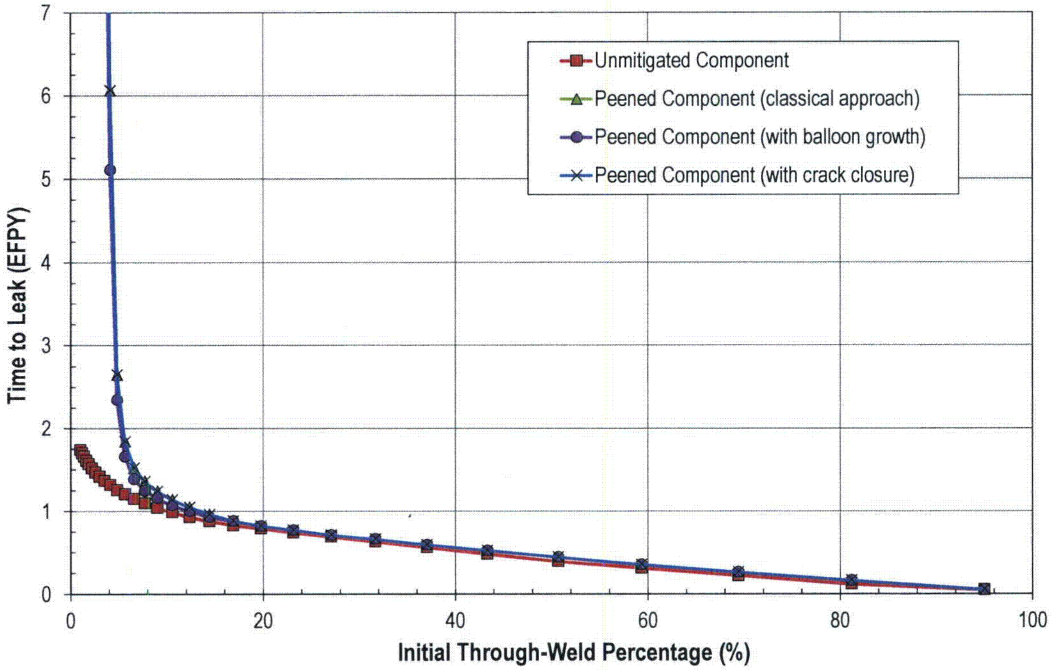

Figure 5-26
Time to Through-Weld Growth vs. Initial Crack Depth for Weld Radial Crack on Downhill J-Groove Weld ($2c_0/a_0$=4.5)

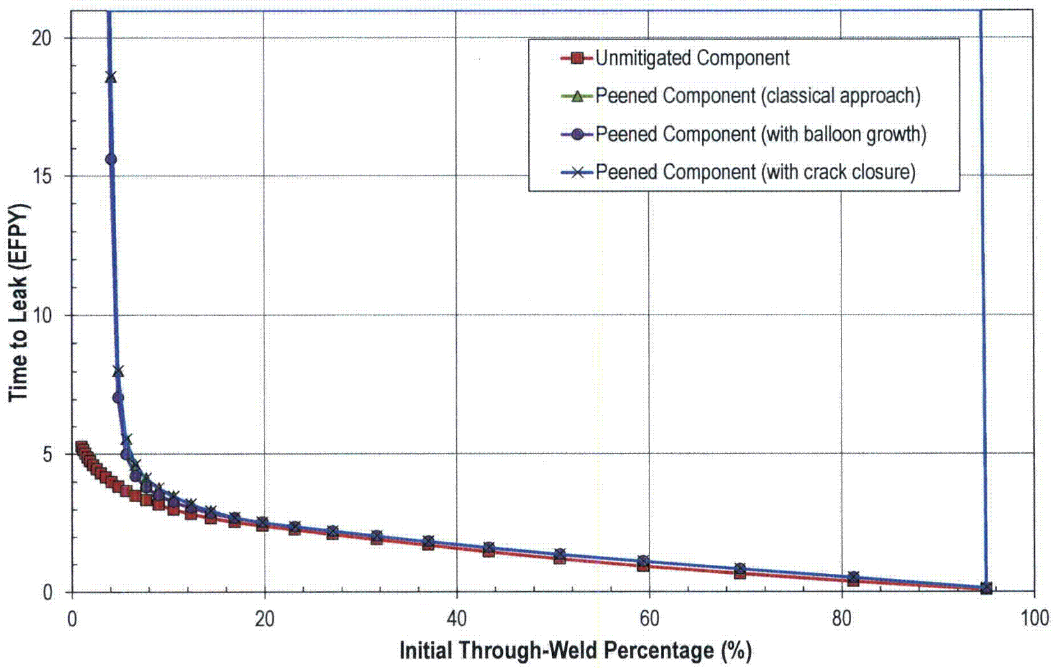

Figure 5-27
Time to Through-Weld Growth vs. Initial Crack Depth for Weld Crack on Downhill J-Groove Weld on a Cold Head RPVHPN ($2c_0/a_0$=4.5)

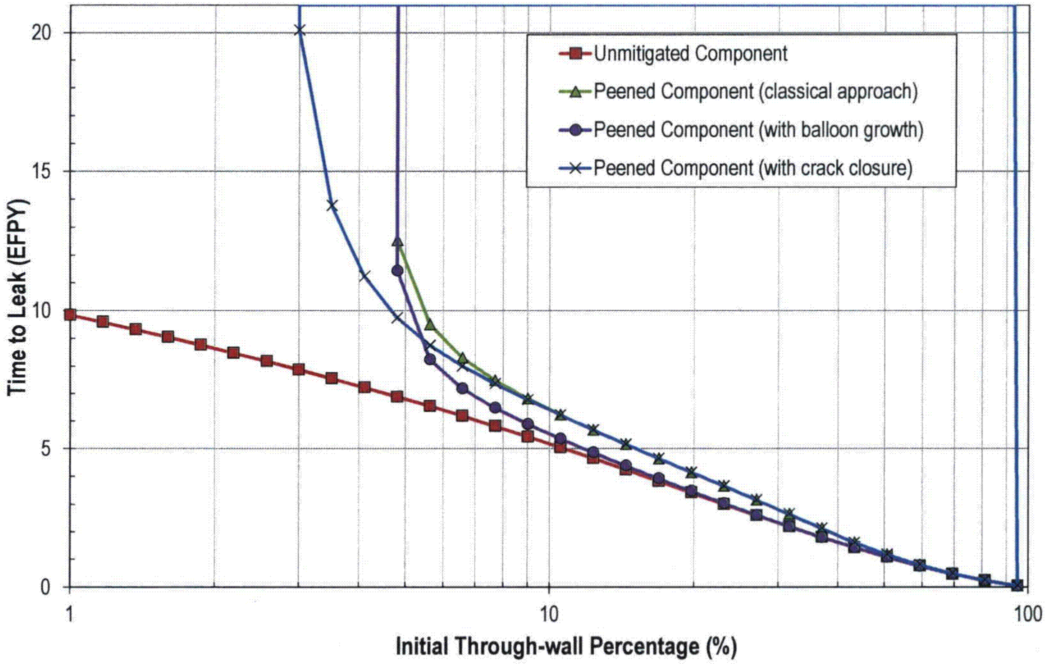

Figure 5-28
Time to Through-Weld Growth vs. Initial Crack Depth for Axial Crack on Uphill Penetration Nozzle ID Subject to More Compressive Peening Residual Stress Profile ($2c_0/a_0$=4.5)

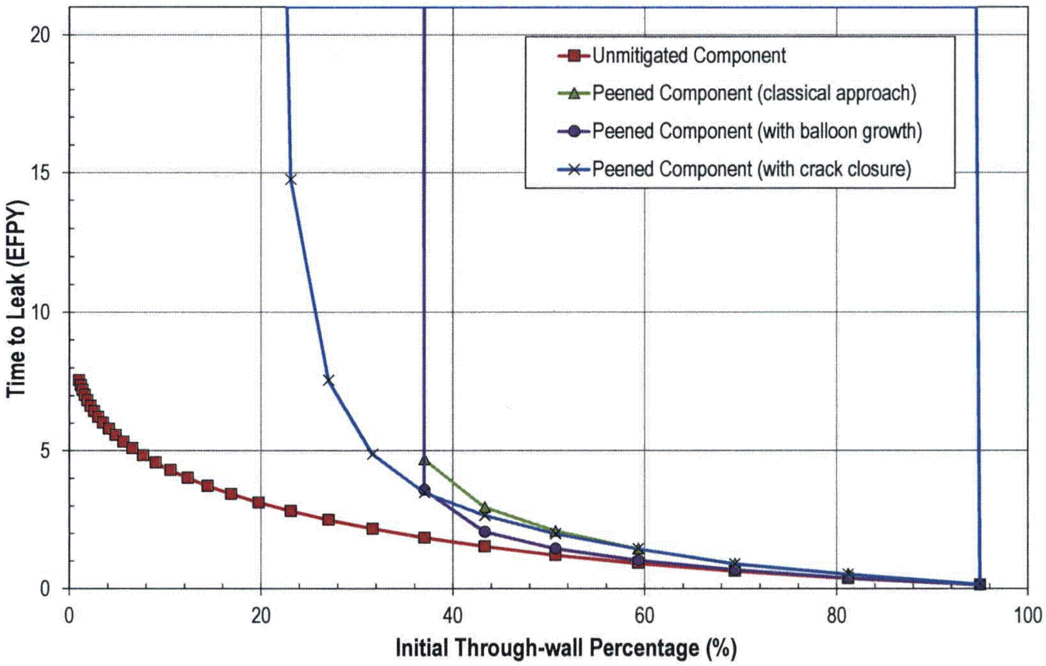

Figure 5-29
Time to Through-Weld Growth vs. Initial Crack Depth for Weld Crack on Uphill Penetration Nozzle OD Subject to More Compressive Peening Residual Stress Profile ($2c_0/a_0$=4.5)

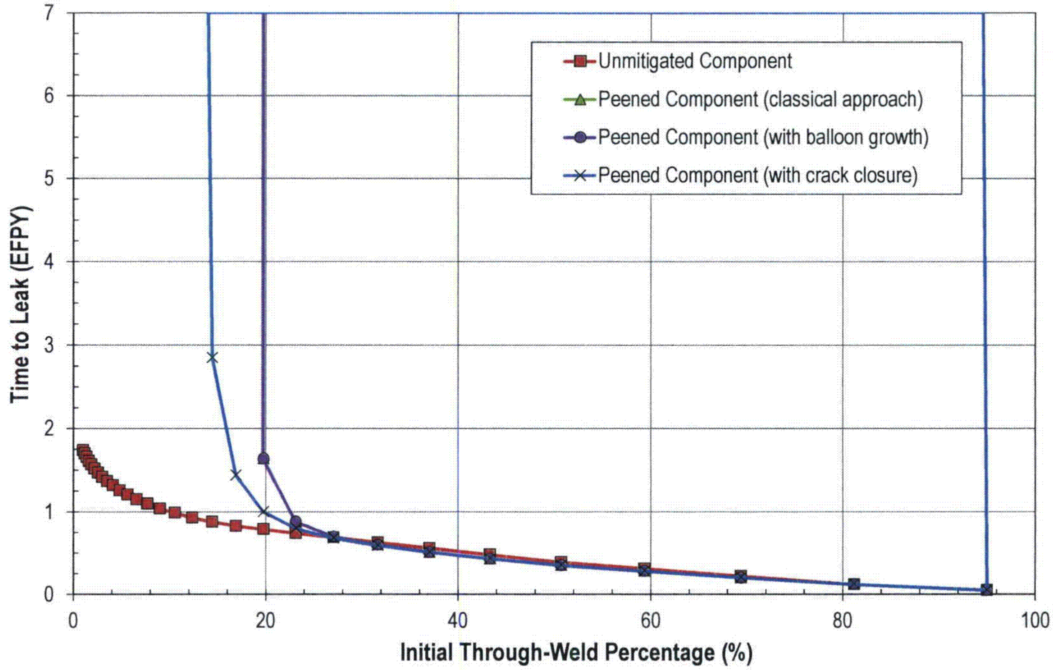

Figure 5-30
Time to Through-Weld Growth vs. Initial Crack Depth for Weld Crack on Downhill J-Groove Weld Subject to More Compressive Peening Residual Stress Profile ($2c_0/a_0$=4.5)

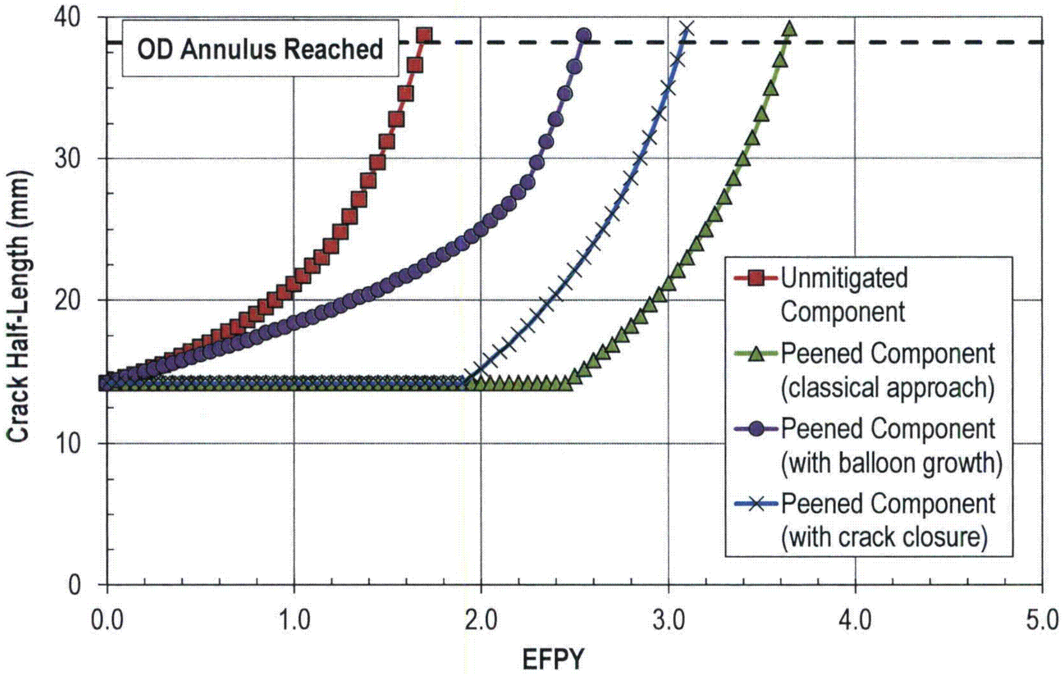

Figure 5-31
Half-Length along Nozzle Surface vs. Time for Uphill OD Axial Crack on Unmitigated and Peened Component Subject to More Compressive Peening Residual Stress Profile (a_0/t=40% [6.3 mm] and $2c_0/a_0$=4.5)

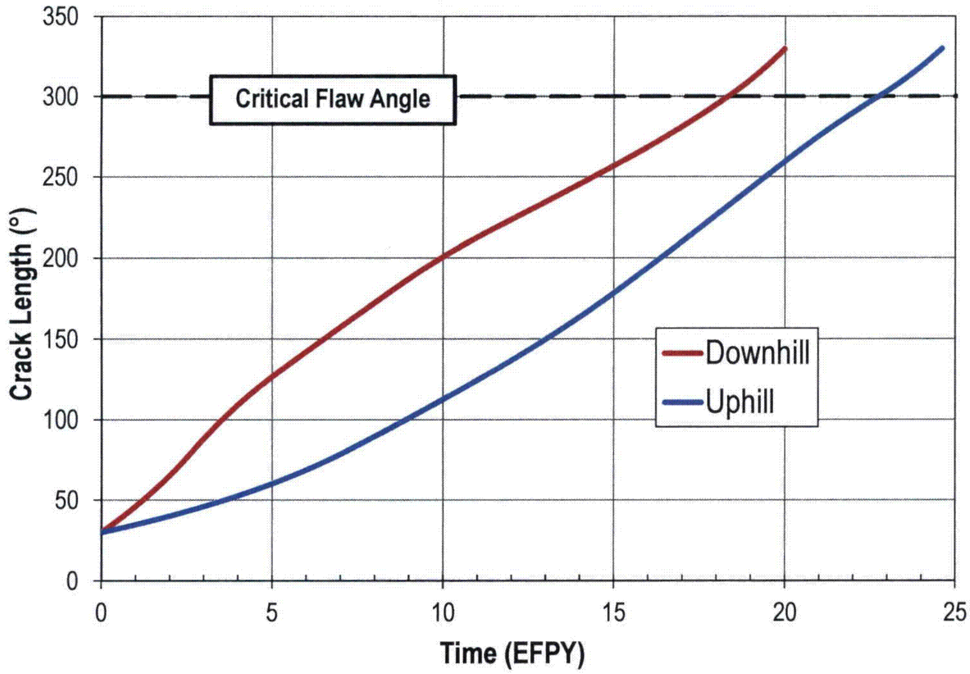

Figure 5-32
Circumferential Crack Length vs. Time for Through-Wall Cracks Along the Weld Contour

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 [6] 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.

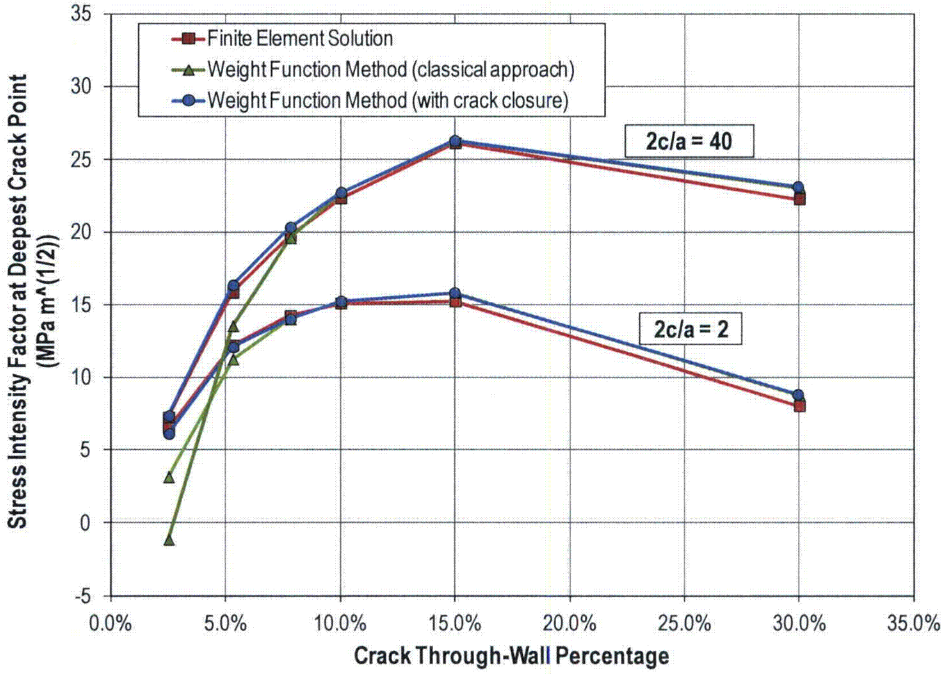

Figure 5-33
Results of Stress Intensity Factor Calculation Method Validation Study

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 rupture).

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

5.3.1 Dissimilar Metal Welds (DMWs)

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

Figure 5-34 provides an important example result depicting cumulative leakage probability versus post-peening inspection schedule characteristics (i.e., the number of cycles between peening and the follow-up inspection; the in-service inspection frequency) for a hot leg DMW component. 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 DM weld 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 leakage probabilities 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 nozzle, 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 nozzle), 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 cumulative leakage probability versus post-peening inspection schedule characteristics (i.e., the number of cycles between peening and the follow-up inspection; the in-service inspection frequency) for a hot reactor head. Figure 5-36 provides an important example result depicting average ejection frequency (AEF) versus post-peening inspection schedule characteristics for a hot reactor head.

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

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

probability of leakage after peening was predicted to decrease by a factor of approximately five for both hot and cold heads.

For the cold head reactor, the AEF after peening was predicted to improve compared to the unmitigated case when a post-peening ISI frequency of every ten years (one interval) was used. A post-peening ISI of 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.

For the hot head reactor, using a post-peening ISI interval of ten 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 174% of the unmitigated reactor 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.

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 peened cold reactor head base case (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 reactor head was 3.60. For a peened hot reactor head (with a follow-up inspection one cycle after peening and an ISI interval of 5 cycles), the ratio of maximum IEF to AEF was 3.12. The same ratio for the unmitigated hot reactor head was 1.42. The risk concentration was not substantially worse for the peened case than for the unmitigated case.

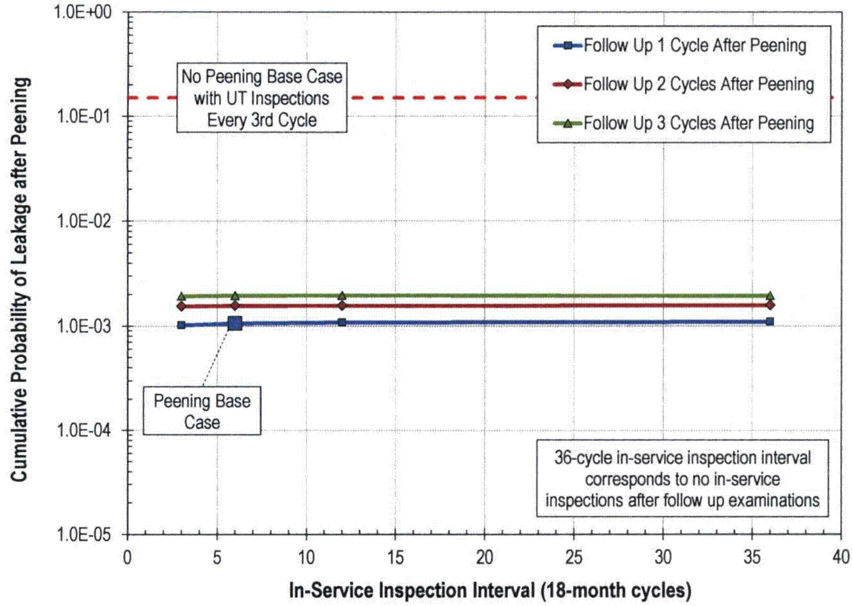

Figure 5-34
Cumulative Probability of Leakage after Hypothetical Time of Peening vs. ISI Frequency for a RVON

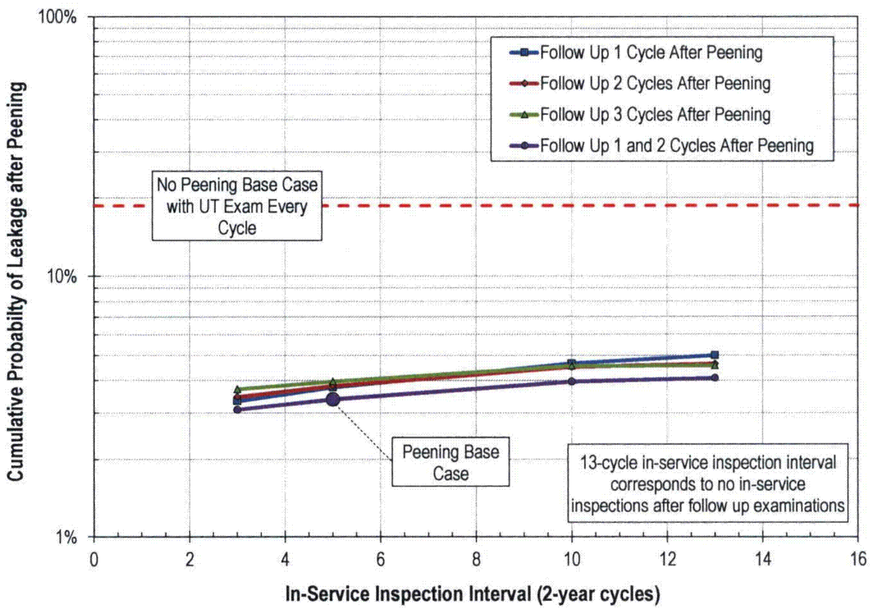

Figure 5-35
Cumulative Probability of Leakage after Hypothetical Time of Peening vs. ISI Frequency for Hot Reactor Head

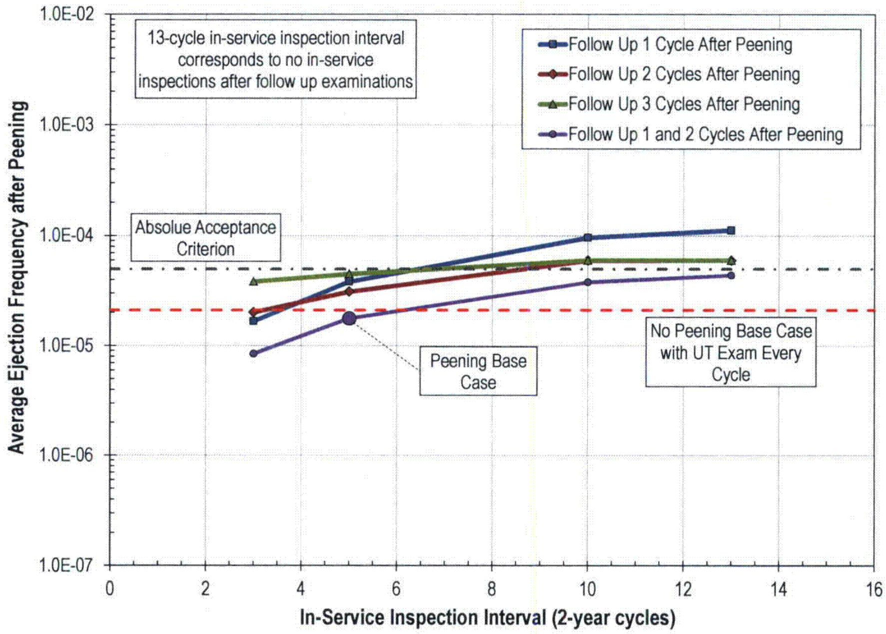

Figure 5-36
Average Ejection Frequency after Hypothetical Time of Peening vs. ISI Frequency for Hot Reactor Head

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 shall be no greater than +10 ksi (+69 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 [7]. 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 minimum 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 [4] as part of the technical basis for the inspection requirements for unmitigated RPVHPNs in N-729-1 [8]. In most cases, circumferential cracking in the nozzle tube at or near the top of the weld has not been detected for leaking RPVHPNs [5].
- 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.
- 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.

5.5 References

1. *Materials Reliability Program: Technical Basis for Primary Water Stress Corrosion Cracking Mitigation by Surface Stress Improvement (MRP-267, Revision 1)*, EPRI, Palo Alto, CA: 2012. 1025839. [Freely Available at www.epri.com]

2. *Materials Reliability Program (MRP) Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick-Wall Alloy 600 Materials (MRP-55) Revision 1*, EPRI, Palo Alto, CA: 2002. 1006695. [Freely Available at www.epri.com]

3. *Materials Reliability Program Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 82, 182, and 132 Welds (MRP-115)*, EPRI, Palo Alto, CA: 2004. 1006696. [Freely Available at www.epri.com]

4. *Materials Reliability Program: Probabilistic Fracture Mechanics Analysis of PWR Reactor Pressure Vessel Top Head Nozzle Cracking (MRP-105 NP)*, EPRI, Palo Alto, CA: 2004. 1007834. [NRC ADAMS Accession No.: ML041680489]

5. *Materials Reliability Program: Reactor Vessel Closure Head Penetration Safety Assessment for U.S. PWR Plants (MRP-110NP): Evaluations Supporting the MRP Inspection Plan*, EPRI, Palo Alto, CA: 2004. 1009807-NP. [NRC ADAMS Accession No.: ML041680506]

6. *3-D Finite Element Software for Cracks: User's Manual v2.7*. Structural Reliability Technology – FEA Crack.

7. *Materials Reliability Program Generic Evaluation of Examination Coverage Requirements for Reactor Pressure Vessel Head Penetration Nozzles, Revision 1 (MRP-95R1NP)*, EPRI, Palo Alto, CA: 2004. 1011225. [NRC ADAMS Accession No.: ML043200602]

8. ASME Code Case N-729-1, "Alternative Examination Requirements for PWR Reactor Vessel Upper Heads With Nozzles Having Pressure-Retaining Partial-Penetration Welds," Section XI, Division 1, American Society of Mechanical Engineers, New York, Approval Date: March 28, 2006.

A
REVISED PROBABILISTIC ANALYSES FOR ALLOY 82/182 DISSIMILAR METAL WELDS (DMWS) IN PRIMARY SYSTEM PIPING

A.1 Introduction

This document includes revised input listings and results for the probabilistic DMW[1] assessment presented in Appendix A of MRP-335 Rev. 1 [1]. These inputs were updated in response to the second request for additional information (RAI) for MRP-335 Rev. 1 [2]. The updated inputs and results provided in this attachment will be incorporated in Appendix A of MRP-335 Rev. 2.

Detailed discussion of the probabilistic modeling methodology, incorporated models, and uncertainty propagation is provided in MRP-335 Rev. 1 [1] and will be included in MRP-335 Rev. 2. Parameter distributions, descriptions, and sources for all inputs used in the probabilistic assessment for DMWs are provided in Section A.2, with base case inputs listed in Section A.2.1. Sensitivity studies are performed with respect to various model parameters to characterize the impact of modeling assumptions and input uncertainty on leakage predictions. The parameters varied by each of these cases are documented in Section A.2.2. Results for base cases and sensitivity cases are presented in Section A.3.

A.2 Probabilistic Model Inputs

A.2.1 Base Case Inputs

The probabilistic inputs and results presented in this attachment are designed to bound the conditions for large-diameter piping Alloy 82/182 dissimilar metal butt welds in PWR primary system piping in the U.S. that are being considered for peening mitigation. The inputs presented in this subsection correspond to the reactor vessel outlet nozzle (hot-leg, RVON) and reactor vessel inlet nozzle (cold-leg, RVIN) base cases.

These inputs typically represent best-estimate values, with input distributions applied to handle uncertainties. However, there are several factors in the modeling approach that tend to make the analysis results and conclusions conservative:

- 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.
- No credit is taken for ET inspections.

[1] 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 [6].

- A UT probability of detection (POD) of zero is assumed for flaws with depth less than 10% through-wall. Furthermore, the mean UT POD curve is assumed to have a flaw detection rate below that of the worst-case qualified UT detection instrument.
- Each dissimilar metal weld is discretized such that circumferential and axial flaws can both initiate at multiple locations around the circumference. Each active flaw will continue to grow until it coalesces with another flaw, achieves through-wall growth (resulting in leakage), or is detected and repaired.
- The values for the initiation Weibull model are fitted to experience for all Alloy 82/182 dissimilar metal butt weld locations in primary system piping of U.S. PWRs; this results in a more aggressive initiation model than would be obtained from reactor vessel outlet/inlet nozzle experience alone because of the few reports (PWSCC indications in five nozzles at three U.S. PWRs including one leak) of PWSCC at these locations.

Input values for the hot-leg (RVON) and cold-leg (RVIN) base cases are provided in Table A-1 through Table A-6. The following subsections detail key updates to the DMW probabilistic model relative to MRP-335 Rev. 1.

A.2.1.1 Peening Residual Stress Effect

To accommodate the range of peening processes that may be applied, the inputs to the probabilistic assessment are the bounding values specified in the performance criteria listed in Attachment 2. Specifically, post-peening stress profiles (including peening stress on the surface with and without operating stresses), the depth of the compressive residual stress field, and the modeled inspection requirements are defined in Attachment 2. If a peening mitigation process meets the performance criteria in Attachment 2, the results of this probabilistic assessment are applicable.

A.2.1.2 Crack Initiation Model

Another significant update to the model inputs is the use of the PWSCC initiation Weibull model presented in xLPR-TR-CI-SCC Weibull v1.0 [3]. This is the latest available Weibull model fit for PWSCC initiation in DMWs and reflects U.S. PWR operating experience through the end of 2012. Detailed discussion of the updated model and operating experience will be provided in MRP-335 Rev. 2.

A.2.1.3 UT Probability of Detection

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

The median UT inspection POD curve used for cracking on DMW component IDs, shown in Figure A-1, is adapted from MRP-262 Rev. 1 [4]. Because the MRP-262 Rev. 1 curve was developed using only circumferential flaws, and a review of examination data suggests a generally lower POD for axial cracks, the POD predicted by the MRP-262 Rev. 1 curve is reduced by 20% for axial cracks. The value of the reduction factor is based on the specific detection test acceptance criteria included in Supplement 10 of Appendix VIII of ASME Section XI [5] for UT performance demonstration (a minimum detection rate between 0.68 and 0.82, depending on the number of flawed grading units). Because the performance demonstration

requirements for UT of DMWs and the data documented in MRP-262 Rev. 1 do not include flaws shallower than 10% of the wall thickness, the flaws with a depth up to 10% of the wall thickness are conservatively modeled to be undetectable (POD of 0).

A.2.1.4 Updates to Modeling Framework

The DMW modeling framework used in generating the results in this attachment is identical to that used in MRP-335 Rev. 1 [1] except for the following changes:

- Includes ability to set the peening surface stress by deterministically specifying the sum of the post-peening residual stress and normal operating stress at the peened surface
- Statistics reported for cycles after the hypothetical time of peening do not credit realizations where the component leaks and is removed from the modeled population prior to the hypothetical time of peening.
- Includes modified POD curve capable of using a POD of zero for flaws depths below a given through-wall fraction

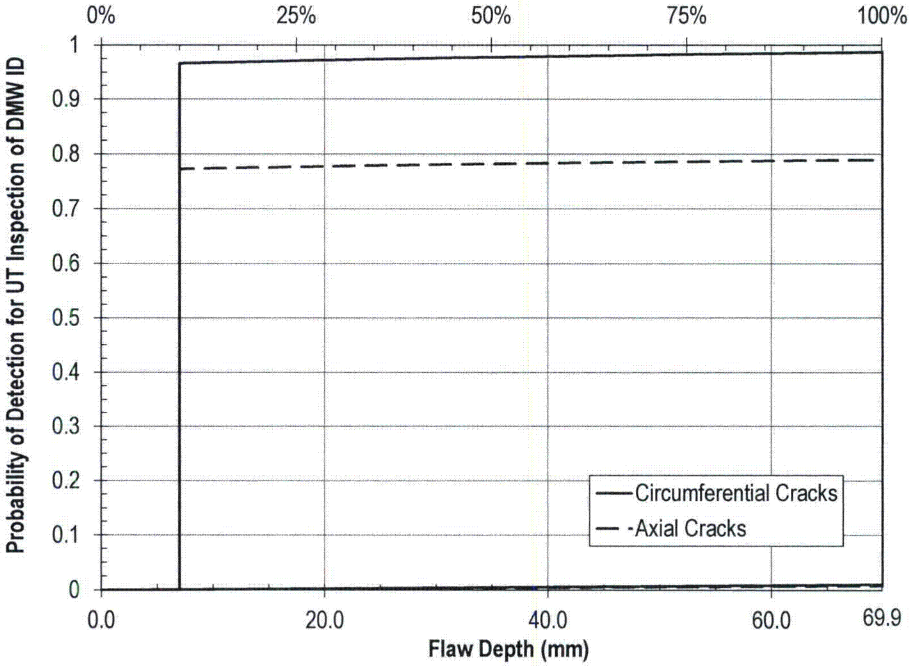

Figure A-1
Median Assumed UT Inspection POD Curve for DMW Cracking from the ID

Table A-1
Summary of General Inputs

Symbol	Description	Source	Units	Parameter Type	DMW Base Case
	Total number of trials	Convergence Study	# trials		1.00E+07
	Number of operating cycles	Selected to yield desired cumulative operating time	-	RVON	53
				RVIN	53
	Nominal cycle length	Representative cycle length at Westinghouse plant	years	RVON	1.5
				RVIN	1.5
CF	Operating capacity factor	Representative capacity factor for U.S. PWR	-	RVON	0.97
				RVIN	0.97
	Cycle of first UT inspection	Based on typical operating reactor service histories	Cycle number	RVON	14
				RVIN	15
	Pre-peening UT inspection interval	ASME Code Case N-770-1	# cycles	RVON	3
				RVIN	4
T	Operating temperature of RVON–DMW	Maximum Westinghouse hot leg operating temperature	°F	type	Normal
				mean	625.0
				stdev	4.6
				min	597.4
				max	652.6
	Operating temperature of RVIN–DMW	Maximum Westinghouse cold leg operating temperature	°F	type	Normal
				mean	563.0
				stdev	0.9
				min	557.5
				max	568.5
t	Wall thickness of RVON-DMW	Representative component thickness for Westinghouse plants	in.	RVON	2.75
	Wall thickness of RVIN-DMW			RVIN	2.75
D_o	Outer diameter of RVON-DWM	Representative component OD for Westinghouse plants	in.	RVON	35.5
	Outer diameter of RVIN-DWM			RVIN	35.5
w	Width of RVON-DMW	Representative weld width for Westinghouse plants	in.	RVON	1.75
	Width of RVIN-DMW			RVIN	1.75

Table A-2
Summary of Loading Inputs for DMW Model

Symbol	Description	Source	Units	Parameter Type	DMW Base Case
P_{op}	Normal operating pressure	Representative of U.S. PWRs	ksi		2.248
F_x	Effective loads for RVON-DMW (including deadweight, thermal expansion, and thermal stratification loading)	Representative reactor vessel nozzle loads for Westinghouse plant	kips		100
M_x			in-kips		0
M_y			in-kips		40000
M_z			in-kips		0
F_x	Effective loads for RVIN-DMW (including deadweight, thermal expansion, and thermal stratification loading)	Representative reactor vessel nozzle loads for Westinghouse plant	kips		100
M_x			in-kips		0
M_y			in-kips		40000
M_z			in-kips		0
σ_{0WRSa}	Weld residual axial stress on ID surface	xLPR Pilot Study	ksi	type	Normal
				mean	43.55
				stdev	15.95
				min	21.75
				max	79.91
X_c	Fractional through-thickness at which weld residual axial stress profile crosses zero	xLPR Pilot Study	-	type	Normal
				mean	0.25
				stdev	0.05
				min	0.125
				max	0.50
f_{WRSa}	Random scaling factor for weld residual axial stress on OD surface	xLPR Input	-	type	Uniform
				min	0.5
				max	1.0
σ_{0WRSh}	Weld residual hoop stress on ID surface	xLPR Pilot Study	ksi	type	Normal
				mean	43.55
				stdev	15.95
				min	21.75
				max	79.91
f_{WRSh1}	Random scaling factor for minimum weld residual hoop stress	Iterative random sampling, see MRP–335 Rev. 1 Section A.8.1.4	-	type	Normal
				mean	0.50
				stdev	0.10
				min	0.25
				max	0.75
f_{WRSh2}	Random scaling factor for weld residual hoop stress on OD surface	Iterative random sampling, see MRP–335 Rev. 1 Section A.8.1.4	-	type	Normal
				mean	1.00
				stdev	0.075
				min	0.80
				max	1.20
X_{min}	Fractional through-thickness at which weld residual hoop stress is minimum	Iterative random sampling, see MRP–335 Rev. 1 Section A.8.1.4	-	type	Normal
				mean	0.50
				stdev	0.075
				min	0.40
				max	0.75

Table A-3
Summary of Peening-Specific Inputs

Symbol	Description	Source	Units	Parameter Type	DMW Base Case
	Outage of peening application	Scheduled at next outage coinciding with a UT inspection	Cycle number	RVON	17
				RVIN	19
	Number of cycles between peening application and follow-up	Attachment 2	# cycles	RVON	2
				RVIN	6
	Inspection interval after peening	Attachment 2	# cycles	RVON	6
				RVIN	None
	Flag indicating if a UT pre-peening exam is performed	Attachment 2	-		TRUE
$\sigma_{0,PPRS}$ (t=0)	Sum of post-peening residual plus normal operating stress on ID surface	Attachment 2	ksi		0.0
$x_{1,PPRS}$	Depth of compressive residual stress layer from ID surface	Attachment 2	in.	type	Normal
				mean	0.039
				stdev	0.010
				min	0.000
				max	0.098
$f_{1,PPRS}$	Ratio of minimally-affected depth to peening penetration depth	See MRP-335 Rev. 1 Section A.3.3	-		2.0
$f_{2,PPRS}$	Fraction of depth between peening penetration depth and minimally-affected depth where peening results in no effect	See MRP-335 Rev. 1 Section A.3.3	-		0.7
f_{relax}	Estimated reduction factor of peening residual stresses after approximately 60 years at operational temperatures	Hitachi experimental data for relaxation of Alloy 182 specimens	$EFPY^{-1}$		0.0

Table A-4
Summary of Inputs for DMW Initiation Model

Symbol	Description	Source	Units	Parameter Type	DMW Base Case
t_1	Time at which failure fraction F_1 is reached	xLPR-TR-CI-SCC Weibull V1.0	EDY	type	Normal
				mean	11.40
				stdev	0.304
				min	3.14
				max	41.10
σ_c	Standard error in intercept of linearized Weibull fit	xLPR-TR-CI-SCC Weibull V1.0	ln(EDY)		0.304
F_1	Arbitrary failure fraction selected to define Weibull PWSCC initiation function	xLPR-TR-CI-SCC Weibull V1.0	-		0.010
β	Weibull slope for PWSCC flaw initiation	xLPR-TR-CI-SCC Weibull V1.0	-	type	Normal
				mean	1.419
				stdev	0.082
				min	0.927
				max	1.911
N_{crack}	Number of circumferential locations for crack initiation	xLPR Pilot Study	-		19
β_{flaw}	Weibull slope for PWSCC multiple flaw initiation	Based on representative value for formation of PWSCC at multiple locations in industry SGs	-	type	Normal
				mean	2.0
				stdev	0.5
				min	1.0
				max	5.0
ρ_{weld}	Correlation coefficient between PWSCC initiation and propagation rates for all cracks in Alloy 82/182 weld	xLPR Input	-		0.0
ρ_{ww}	Correlation coefficient between PWSCC initiation and propagation rates for indicidual crack	xLPR Input	-		0.0

Table A-4
Summary of Inputs for DMW Initiation Model (Continued)

Symbol	Description	Source	Units	Parameter Type	DMW Base Case
Q_i	Thermal activation energy for PWSCC flaw initiation	Distribution based on laboratory data and experience with Weibull analysis	kcal/mole	type	Normal
				mean	44.03
				stdev	3.06
				min	25.65
				max	62.41
$T_{ref,i}$	Reference temperature to normalize PWSCC flaw initiation data	Temperature used to adjust flaw initiation data assessed in this report	°R		1060
n	Exponent for surface stress adjustment to initiation time	EPRI TR-104030	-	type	Normal
				mean	4.0
				stdev	1.0
				min	0.0
				max	10.0
a_0/t	Initial depth assigned to newly initiated flaw	Based on expected performance of UT inspection technique	-	type	Log-Normal
				linear μ	0.053
				median	0.050
				log-norm μ	-3.00
				log-norm σ	0.35
				min	0.01
				max	0.42
AR_{circ}	Initial aspect ratio assigned to newly initiated circumferential flaw	Flaw initiation data from operating experience	-	type	Log-Normal
				linear μ	11.28
				median	8.66
				log-norm μ	2.159
				log-norm σ	0.727
				min	0.110
				max	679.7
AR_{ax}	Initial aspect ratio assigned to newly initiated axial flaw	Flaw initiation data from operating experience	-	type	Log-Normal
				linear μ	3.44
				median	1.74
				log-norm μ	0.554
				log-norm σ	1.167
				min	0.0016
				max	1912.2

Table A-5
Summary of Inputs for DMW Flaw Propagation Model

Symbol	Description	Source	Units	Parameter Type	DMW Base Case
$1/\Delta t$	Number of time steps per year for crack size increment	The value chosen provides sufficient convergence	1/yr		12
f_{weld}	Weld-to-weld factor: common factor applied to all specimens fabricated from the same weld to account for weld wire/stick heat processing and for weld fabrication	Fit to weld-to-weld variation data from MRP-115	-	type	Log-Normal
				linear μ	1.19
				median	1.00
				75%ile	1.49
				log-norm μ	0.000
				log-norm σ	0.589
				min	0.313
				max	2.64
f_{ww}	Within-weld factor: factor accounting for the variability in crack growth rate for different specimens fabricated from the same weld	Fit to within-weld variation from MRP-115 data after normalizing for weld-to-weld variation factor	-	type	Log-Normal
				linear μ	1.12
				median	1.00
				log-norm μ	0.000
				log-norm σ	0.481
				min	0.309
				max	3.24
α_{weld}	Flaw propagation rate equation power law constant for Alloy 182 weld	MRP-115	(in/hr)/ (ksi-in.$^{0.5}$)$^{1.6}$		1.62E-07
Q_g	Thermal activation energy for PWSCC flaw propagation	MRP-115	kcal/mole	type	Normal
				mean	31.07
				stdev	1.20
				min	23.90
				max	38.24
$T_{ref,g}$	Absolute reference temperature to normalize PWSCC flaw propagation data	MRP-115	°R		1077
$K_{I,th}$	K_I Stress intensity factor threshold	MRP-115	ksi-sqrt(in.)		0.0
$K_{I,min}$	Minimum allowable value for K_I	No technical basis for non-zero value	ksi-sqrt(in.)		0.0
b	Flaw propagation rate equation power law exponent for Alloy 82/182 weld	MRP-115	-		1.6
$1/F_{coalescence}$	Ratio of maximum crack depth that is used to evaluate the critical separation distance for coalescence	Set arbitrarily small such that coalescence occurs only once two cracks overlap	-		1.0E-06
	Flag indicating if crack growth will be predicted considering the effect of crack closure	Crack closure effects are neglected for base case	Logical		FALSE
	Flag indicating if cracks may grow in length without the effect of peening stresses	Sub-surface balloon growth of crack conservatively included for base case	Logical		TRUE

Table A-6
Summary of Inputs for DMW Examination Model

Symbol	Description	Source	Units	Parameter Type	DMW Base Case
	The through-wall fraction below which the small-flaw contingency (POD = 0) is used	Smallest flaw size used in UT mockup testing			0.10
ρ_{insp}	Correlation coefficient for successive UT inspection	Conservative assumption	-		0.50
$\beta_{1\,(B1)}$	POD model for 0th order logistic equation parameter for Category B1 components: RV Inlet and Outlet	Table 12-3 of MRP-262	-	type	Normal
				mean	3.244
				stdev	0.549
$\beta_{2\,(B1)}$	POD model for 1st order logistic equation parameter for Category B1 components: RV Inlet and Outlet	Table 12-3 of MRP-262	-	type	Normal
				mean	1.06
				stdev	1.32
$\rho_{\beta\,(B1)}$	Correlation coefficient for Category B1 component POD model parameters	MRP-262 Appendix B Wald Model Results	-		-0.8698
$f_{UT,axial}$	Reduction factor applied to POD predicted from circumferential crack detection data	See MRP-335 Rev. 1 Section A.8.4.2	-		0.80

A.2.2 Inputs for Probabilistic Sensitivity Studies

Sensitivity studies are performed with respect to various model parameters to characterize the impact of modeling assumptions and input uncertainty on leakage predictions. The results of these sensitivity studies are presented in Section A.3.3.

Table A-7 and Table A-8 list the values of the parameters that are varied in each sensitivity study. For each case, all parameters not included in the table remain identical to the base case inputs listed in Table A-1 through Table A-6. Studies listed in Table A-7 are classified as an Inspection Scheduling Sensitivity Case (in which a controllable inspection scheduling option is varied) and Table A-8 lists Model Sensitivity Cases (in which a modeling input or characteristic is varied).

Table A-7
Summary of Modified Inputs for DMW Inspection Scheduling Sensitivity Cases

Sensitivity Case	Description	Symbol	Units	Parameter Type	Base Case Value	Sensitivity Case Value
S1	Skip follow-up inspection and enter post peening ISI schedule		-	RVON	Perform follow-up UT 2nd cycle after peening	Skip follow-up UT inspection; first ISI after 6 cycles
				RVIN	Perform follow-up UT 6th cycle after peening	Do not perform UT inspection after peening
S2	Skip UT during pre-peening inspection		-		Perform UT during pre-peening inspection	Skip UT during pre-peening inspection

Table A-8
Summary of Modified Inputs for DMW Model Sensitivity Cases

Sensitivity Case	Description	Symbol	Units	Parameter Type	Base Case Value	Sensitivity Case Value
M1	Reduce Operating Capacity Factor	CF	-	RVON	0.97	0.92
				RVIN	0.97	0.92
M2	Reject trials with detections/ejections before given cycle (i.e. present day)		Cycle number	RVON	0	16
				RVIN	0	18
M3	Halve growth integration time step	$1/\Delta t$	1/yr		12	24
M4	Remove correlation between UT inspections	ρ_{insp}	-		0.5	0.0
M5	Linearly extraplolate POD to zero below 10% TW		-		Assume POD = 0 below 10% TW	Linearly extrapolate
M6	Decrease POD by 20%	$\beta_{1\,(B1)}$	-	mean	3.244	1.242
				stdev	0.549	0.210
		$\beta_{2\,(BI)}$	-	mean	1.06	0.055
				stdev	1.32	0.069
M7	Increase effective bending load per NB-3600 Eq. 10	M_y	in.-kips	RVON	40000	75987
		M_y	in.-kips	RVIN	40000	75987
M8	Increase effective bending load per NB-3600 Eq. 10 and decrease initiation characteristic time	M_y	in.-kips	RVON	40000	75987
		M_y	in.-kips	RVIN	40000	75987
		t_1	EDY	type	Normal	Normal
				mean	11.40	5.18
				stdev	0.304	0.304
				min	3.14	1.43
				max	41.10	18.68
M9	Decrease effective load to match Case C of ML112160169	M_y	in.-kips	RVON	40000	14721
		M_y	in.-kips	RVIN	40000	14721
M10	Include time-dependent stress relaxation	f_{relax}	$EFPY^{-1}$		0	5.10E-03
M11	Double standard deviation of peening penetration depth	$x_{1,PPRS}$	in.	type	Normal	Normal
				mean	0.039	0.039
				stdev	0.010	0.020
				min	0.000	0.000
				max	0.098	0.157
M12	Increase peening compressive surface stress and penetration depth	$\sigma_{0,PPRS}$ $(t=0)$	ksi		Normal operating plus residual stress is zero ksi	Residual stress is 100 ksi compressive
		$x_{1,PPRS}$	in.	type	Normal	Normal
				mean	0.039	0.118
				stdev	0.010	0.059
				min	0.000	0.000
				max	0.098	0.295
M13	Decrease initiation characteristic time by factor of 3	t_1	EDY	type	Normal	Normal
				mean	11.40	3.80
				stdev	0.304	0.304
				min	3.14	1.047
				max	41.10	13.70
M14	Increase multiple flaw initiation model slope	β_{flaw}	-	type	Normal	Normal
				mean	2.0	3.0
				stdev	0.5	0.5
				min	1.0	1.0
				max	5.0	6.0
M15	Include initiation-growth correlation	ρ_{weld}	-		0.0	-0.8
		ρ_{ww}	-		0.0	-0.8

Table A-8
Summary of Modified Inputs for DMW Model Sensitivity Cases (Continued)

Sensitivity Case	Description	Symbol	Units	Parameter Type	Base Case Value	Sensitivity Case Value
M16	Increase initiation activation energy to N-729-1 value	Q_i	kcal/mole	type	Normal	Normal
				mean	44.03	50.00
				stdev	3.06	3.06
				min	25.65	31.62
				max	62.41	68.38
M17	Remove stress adjustment of initiation times	n	-	type	Normal	Constant
				mean	4.0	0.0
				stdev	1.0	-
				min	0.0	-
				max	10.0	-
M18	Utilize crack closure methodology and decrease initial flaw depth		-		Do not utilize crack closure	Utilize crack closure
		a_0/t	-	type	Log-Normal	Log-Normal
				linear μ	0.053	0.0053
				median	0.050	0.0050
				log-norm μ	-3.00	-5.30
				log-norm σ	0.35	0.35
				min	0.01	0.001
				max	0.42	0.42
M19	Decrease median initial crack depth and impose minimum K value	a_0/t	-	type	Log-Normal	Log-Normal
				linear μ	0.053	0.005
				median	0.050	0.005
				log-norm μ	-3.00	-5.30
				log-norm σ	0.35	0.35
				min	0.01	0.001
				max	0.42	0.42
		$K_{I,min}$	ksi-sqrt(in.)		0.00	10.9
M20	Increase growth activation energy	Q_g	kcal/mole	type	Normal	Normal
				mean	31.07	33.46
				stdev	1.195	1.195
				min	23.90	26.29
				max	38.24	40.63
M21	Increase coalescence distance threshold	$1/F_{coalescence}$	-		1.0E-06	0.5
M22	Utilize crack closure methodology		-		Do not utilize crack closure	Utilize crack closure
M23	Prevent balloon growth		-		Prevent balloon growth	Allow balloon growth
M24	Increase peening compressive surface stress and penetration depth	$\sigma_{0,PPRS}$ $(t=0)$	ksi		Normal operating plus residual stress is zero ksi	Residual stress is 100 ksi compressive
		$x_{1,PPRS}$	in.	type	Normal	Normal
				mean	0.039	0.118
				stdev	0.010	0.059
				min	0.000	0.000
				max	0.098	0.295
	Utilize crack closure methodology		-		Do not utilize crack closure	Utilize crack closure
	Prevent balloon growth		-		Prevent balloon growth	Allow balloon growth

A.3 Probabilistic Model Results

A.3.1 Preliminaries

The primary statistics used to assess and compare the results of the probabilistic model are defined below:

- Incremental leakage frequency (ILF) is defined as the average number of new leaking reactor vessel inlet/outlet nozzles per year. A simulated flaw causes leakage if it propagates through the entire material thickness before it is detected and repaired. This statistic is derived for any given operational cycle by averaging the predicted number of new leaking nozzles for that operational cycle across all MC realizations. This is adjusted to a probability per year by dividing by the number calendar years per cycle.

$$ILF = \frac{\text{(Number of new leaks predicted during cycle across all realizations)}}{\text{(Number of realizations)(Calendar years per cycle)}} \qquad \text{[A-1]}$$

- Average leakage frequency (ALF) is the time-average of the ILFs following the hypothetical time of peening until the end of the operational service period of the plant. This statistic is averaged over the number of MC realizations that are active (have not yet leaked) following the hypothetical time of peening. Using this subset of realizations provides no credit to realizations where the component leaks and is removed from the modeled population prior to the hypothetical time of peening.

$$ALF = \frac{\sum_{i=i_{peen}}^{N_{cycle}} \text{(Number of new leaking nozzles predicted during cycle across all realizations)}}{\text{(Number of realizations)(Calendar years per cycle)}(N_{cycle} - i_{peen})} \qquad \text{[A-2]}$$

where:

N_{cycle} = number of cycles in operational service period
i_{peen} = cycle number associated with the hypothetical time of peening

- Cumulative probability of leakage (CPL) is defined as the fraction of reactor vessel inlet/outlet nozzles with a predicted leak across all active MC realizations across all cycles of interest. This document reports two versions of this statistic: (1) cumulated from the start of operation to a given cycle and (2) cumulated from the hypothetical time of peening to the end of plant operation. When calculating the CPL after the hypothetical time of peening, realizations in which leakage occurs prior to the time of peening are discarded and are not included in the reported statistic.

$$CPL = \frac{\text{(Total number of realizations with at least one predicted leak)}}{\text{(Number of realizations)}} \qquad \text{[A-3]}$$

More vital conclusions are drawn from the relative differences between these statistics predicted for different cases (e.g., between the CPL predicted for one peening schedule vs. the CPL

predicted with a different peening schedule). This approach minimizes any potential for bias introduced by the various modeling assumptions.

A.3.2 Base Case Results

The base case probabilistic runs resulted in a cumulative probability of leakage (CPL) of 1.6×10^{-3} for the hot-leg (RVON) base case with peening, which compares to a CPL of 1.5×10^{-1} for the base case without peening mitigation. This is shown in Figure A-2.

As PWSCC is a thermally activated degradation mechanism, the number of leaks for the cold-leg cases is expected to be lower than that for the corresponding hot-leg cases. Appropriately, the CPL for the cold-leg base case with peening is 2.3×10^{-4}, and the CPL for the cold-leg base case without peening mitigation is 2.1×10^{-3}. This is shown in Figure A-3.

Figure A-4 and Figure A-5 compare time-histories of ILF and CPL for peening and no-peening base cases. Figure A-6 provides a comparison of the ILF for hot-leg and cold-leg base cases after peening mitigation.

For both DMW cases evaluated, the peening base case provides a risk-neutral alternative to the no-peening base case. I.e., the peening base case provides equivalent or reduced risk with respect to the no-peening base case. Figure A-2 and Figure A-3 indicate that the cumulative probability of leakage from the hypothetical time of peening to the end of the plant operational service period for a peened component inspected in accordance with Attachment 2 is lower than that of an unmitigated component inspected per current requirements by two orders of magnitude for the hot-leg case and by one order of magnitude for the cold-leg case.

A.3.3 Sensitivity Study Results

All sensitivity cases for peened components result in a cumulative probability of leakage below that of the equivalent sensitivity case for an unmitigated component.

Figure A-7 (RVON) and Figure A-12 (RVIN) compare the cumulative probability of leakage from the hypothetical time of peening to end of plant operation for peened and unmitigated components for Inspection Scheduling Sensitivity cases.

Figure A-8 through Figure A-11 compare the cumulative probability of leakage from the hypothetical time of peening to end of the operational service period of the plant for peened (Figure A-8 and Figure A-9) and unmitigated (Figure A-10 and Figure A-11) RVON Model Sensitivity cases, respectively. Figure A-13 through Figure A-16 provide the equivalent comparison for RVIN cases.

The following cases have been selected for a more detailed discussion since they result in the greatest increases in CPL with respect to the base case:

- Inspection Scheduling Sensitivity Cases 1 and 2: Skipping pre-peening or follow-up UT inspections results in a substantial increase in cumulative probability of leakage. Skipping UT follow-up exams results in a CPL of 2.5×10^{-3} for the RVON and a CPL of 5.4×10^{-4} for the RVIN. Skipping UT pre-peening inspections results in a CPL of 1.1×10^{-2} for the RVON and a CPL of 9.4×10^{-4} for the RVIN. These sensitivity cases emphasize the importance of pre-peening and follow-up inspections, such that the pre-existing cracks that extend beyond the peening compressive layer are detected and repaired.

Modeling Sensitivity Case 6: Decreasing the UT POD curves by 20% results in an increased cumulative probability of leakage. The scaled POD curve results in a CPL of 4.5×10^{-3} for the peened RVON, a CPL of 1.9×10^{-1} for the unmitigated RVON, a CPL of 6.3×10^{-4} for the peened RVIN, and a CPL of 3.7×10^{-3} for the unmitigated RVIN. However, this sensitivity case results in a maximum POD just under 80% for near-through-wall circumferential flaws, which is significantly worse than the best-estimate POD curve derived from personnel and equipment representative of NDE methods applied in the field. Furthermore, the POD curve for axial flaws applied in this sensitivity case falls below the minimum detection rates (between 0.68 and 0.82) defined in Appendix VIII of ASME Section XI [5] for specimens with a mixture of circumferential and axial flaws.

- Modeling Sensitivity Case 8: Increasing the applied bending loads (and therefore effective load on the nozzle) and applying a reduction factor to the initiation time leads to an increased cumulative probability of leakage. The modified loads and initiation model result in a CPL of 3.2×10^{-3} for the peened RVON, a CPL of 3.7×10^{-1} for the unmitigated RVON, a CPL of 5.7×10^{-4} for the peened RVIN, and a CPL of 9.0×10^{-3} for the unmitigated RVIN. By comparing Modeling Sensitivity Cases 7 and 8, it is clear that this increase in CPL with respect to the base cases is entirely due to the modified initiation model in this sensitivity case. This sensitivity case results in the greatest CPL of all modeling sensitivity cases for the unmitigated RVON.
- Modeling Sensitivity Case 13: Reducing the initiation reference time by a factor of three greatly increases the cumulative probabilities of leakage for both mitigated and unmitigated components. The modified initiation model results in a CPL of 6.2×10^{-3} for the peened RVON, a CPL of 3.2×10^{-1} for the unmitigated RVON, a CPL of 1.4×10^{-3} for the peened RVIN, and a CPL of 1.2×10^{-2} for the unmitigated RVIN. This sensitivity case results in the greatest CPL of all modeling sensitivity cases for the mitigated RVON, mitigated RVIN, and unmitigated RVIN.

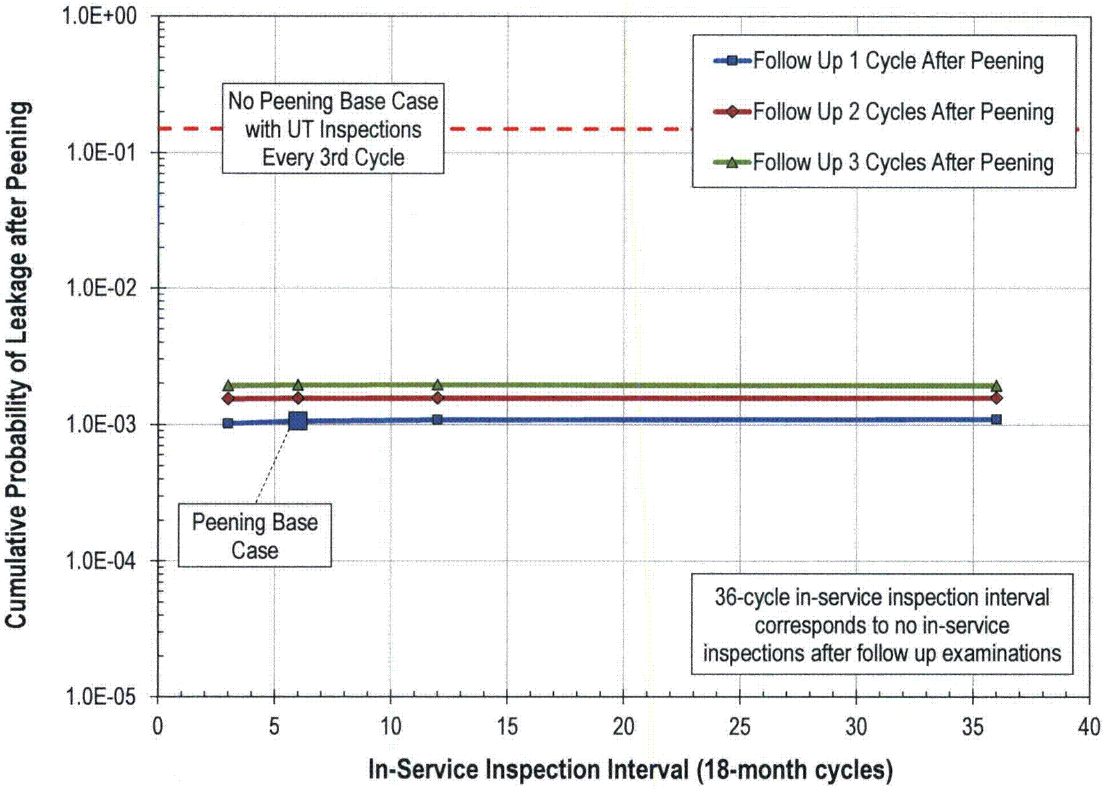

Figure A-2
Cumulative Probability of Leakage from Hypothetical Time of Peening to End of Operational Service Period vs. ISI Frequency for RVON

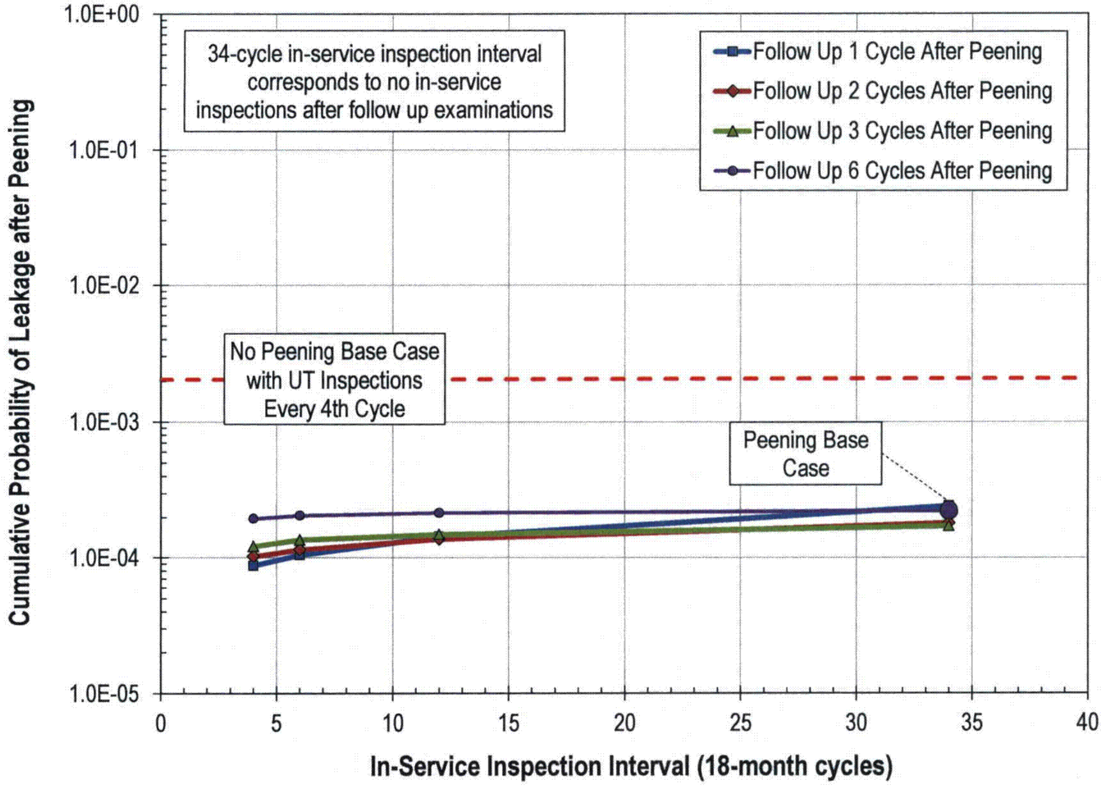

Figure A-3
Cumulative Probability of Leakage from Hypothetical Time of Peening to End of Operational Service Period vs. ISI Frequency for RVIN

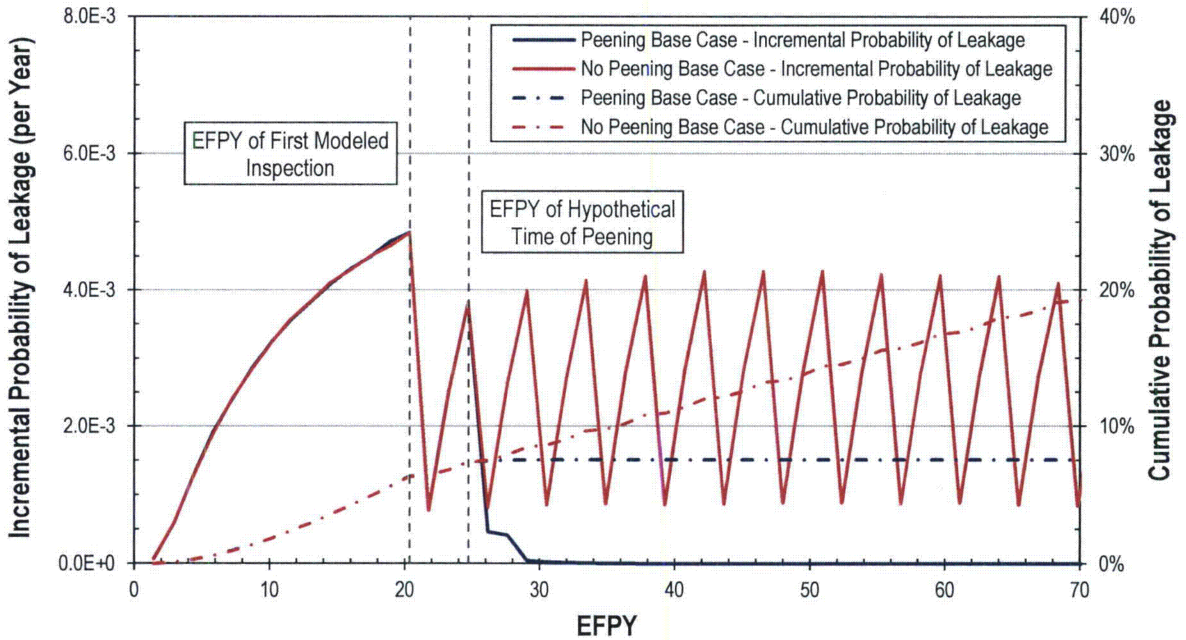

Figure A-4
Prediction of Leakage vs. Time for RVON

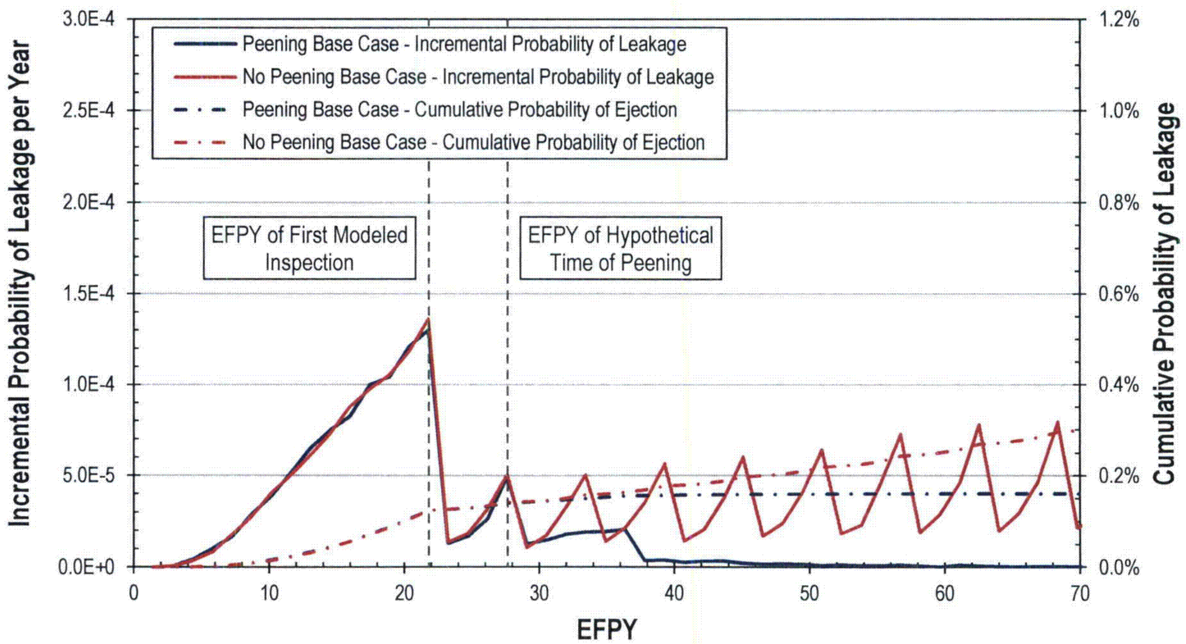

Figure A-5
Prediction of Leakage vs. Time for RVIN

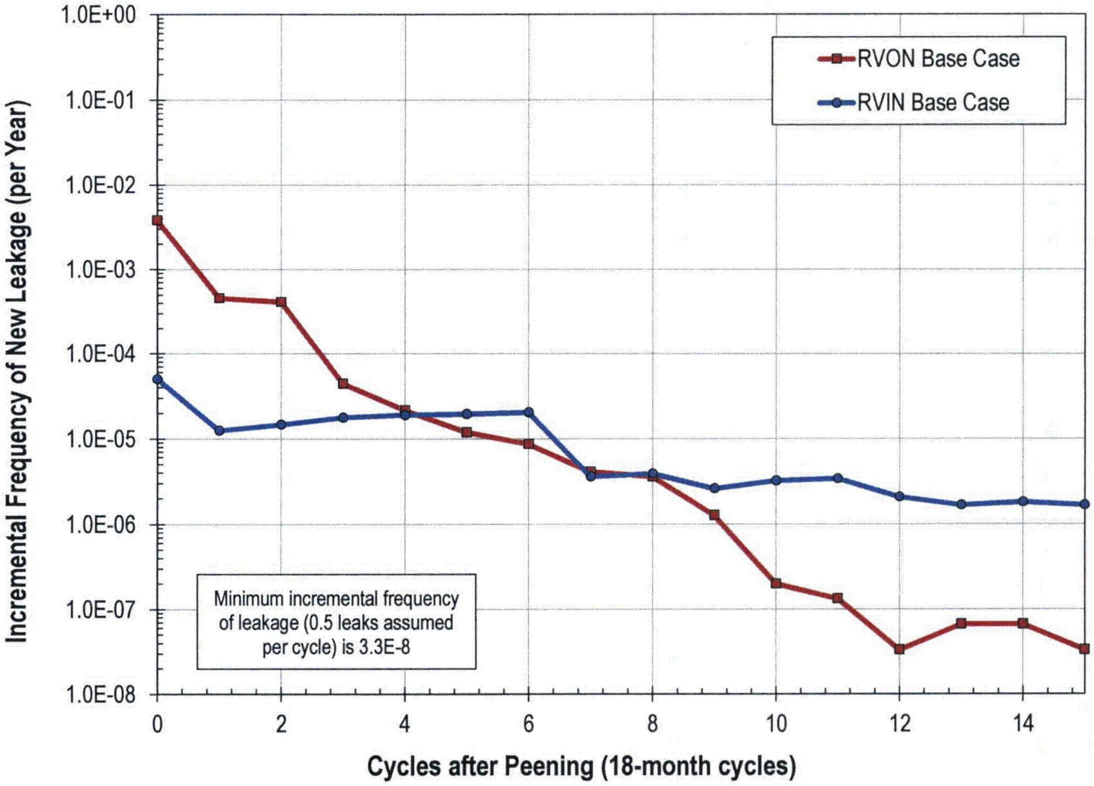

Figure A-6
Incremental Leakage Frequency after Peening with Relieved ISI Intervals

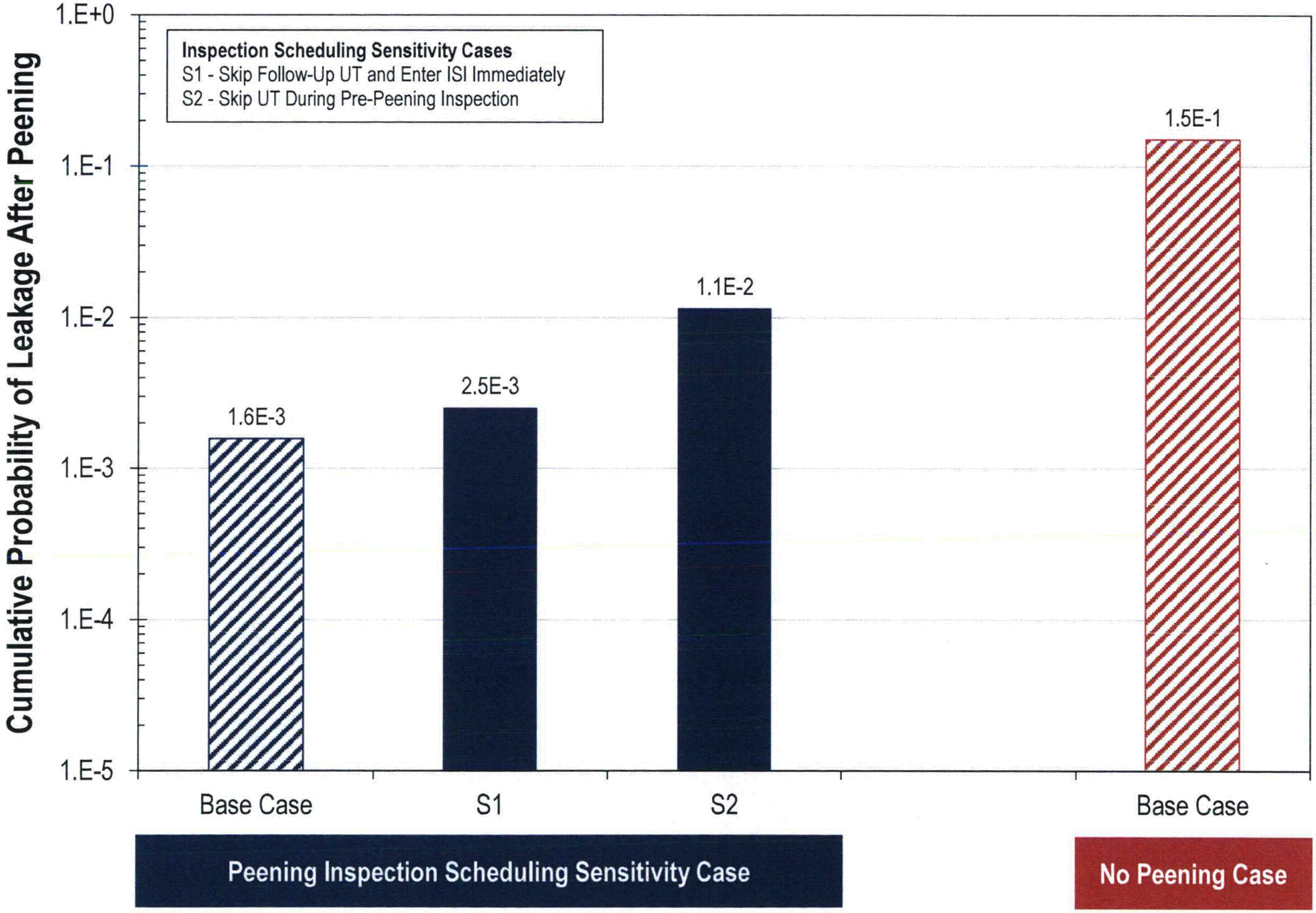

Figure A-7
Summary for Inspection Scheduling Sensitivity Results for RVON Probabilistic Model with Peening

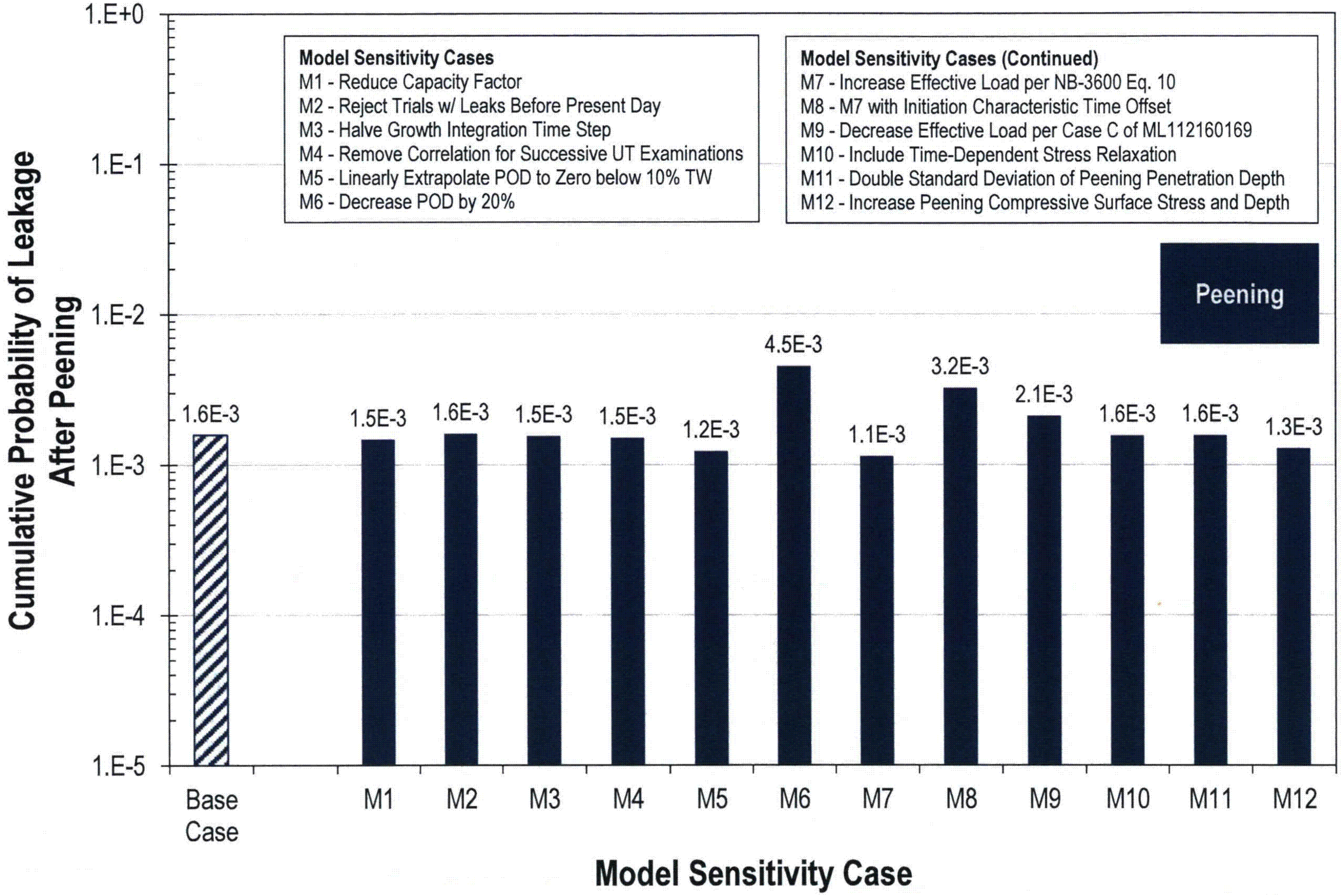

Figure A-8
Summary of Model Sensitivity Results for RVON Probabilistic Model with Peening

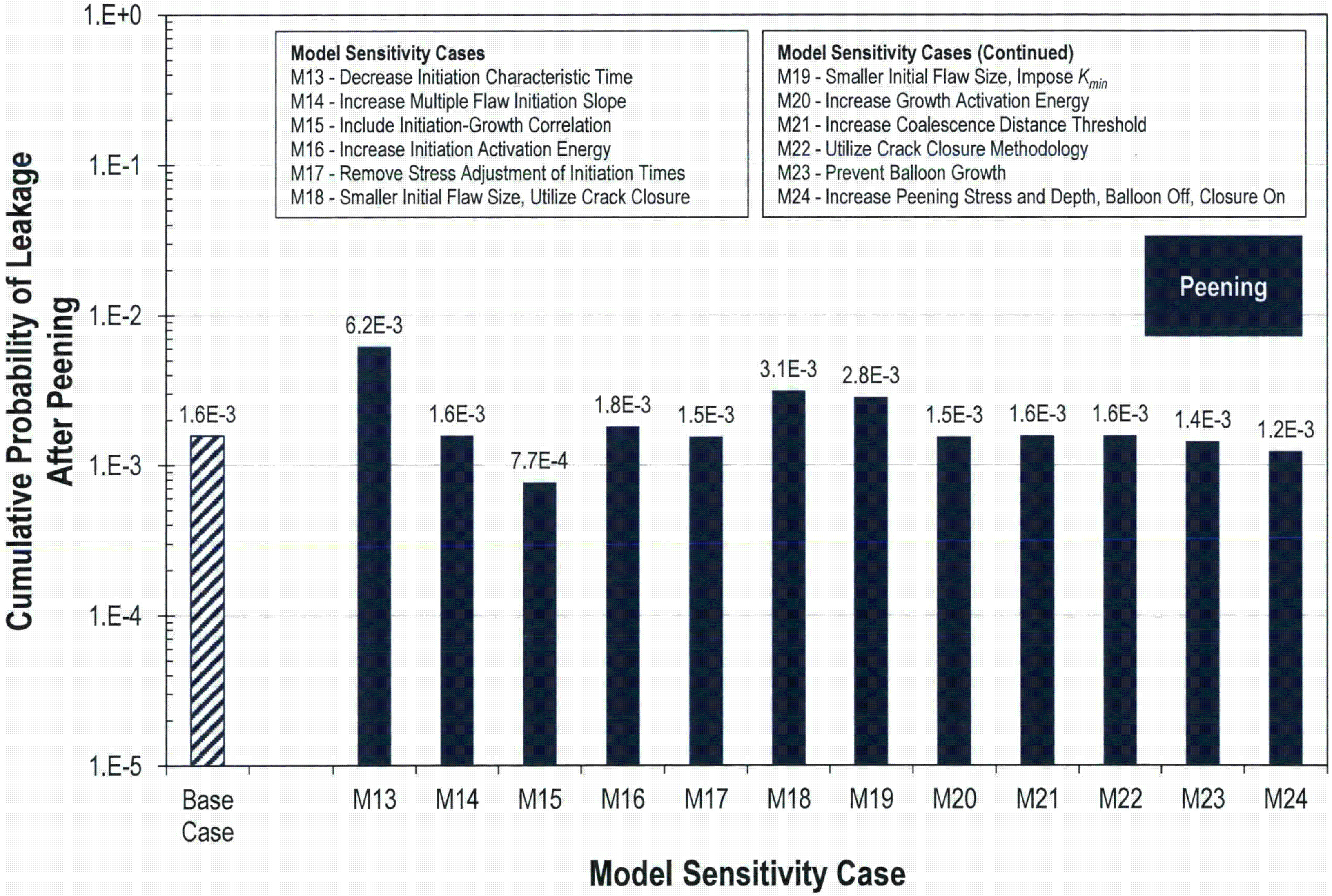

Figure A-9
Summary of Model Sensitivity Results for RVON Probabilistic Model with Peening (Continued)

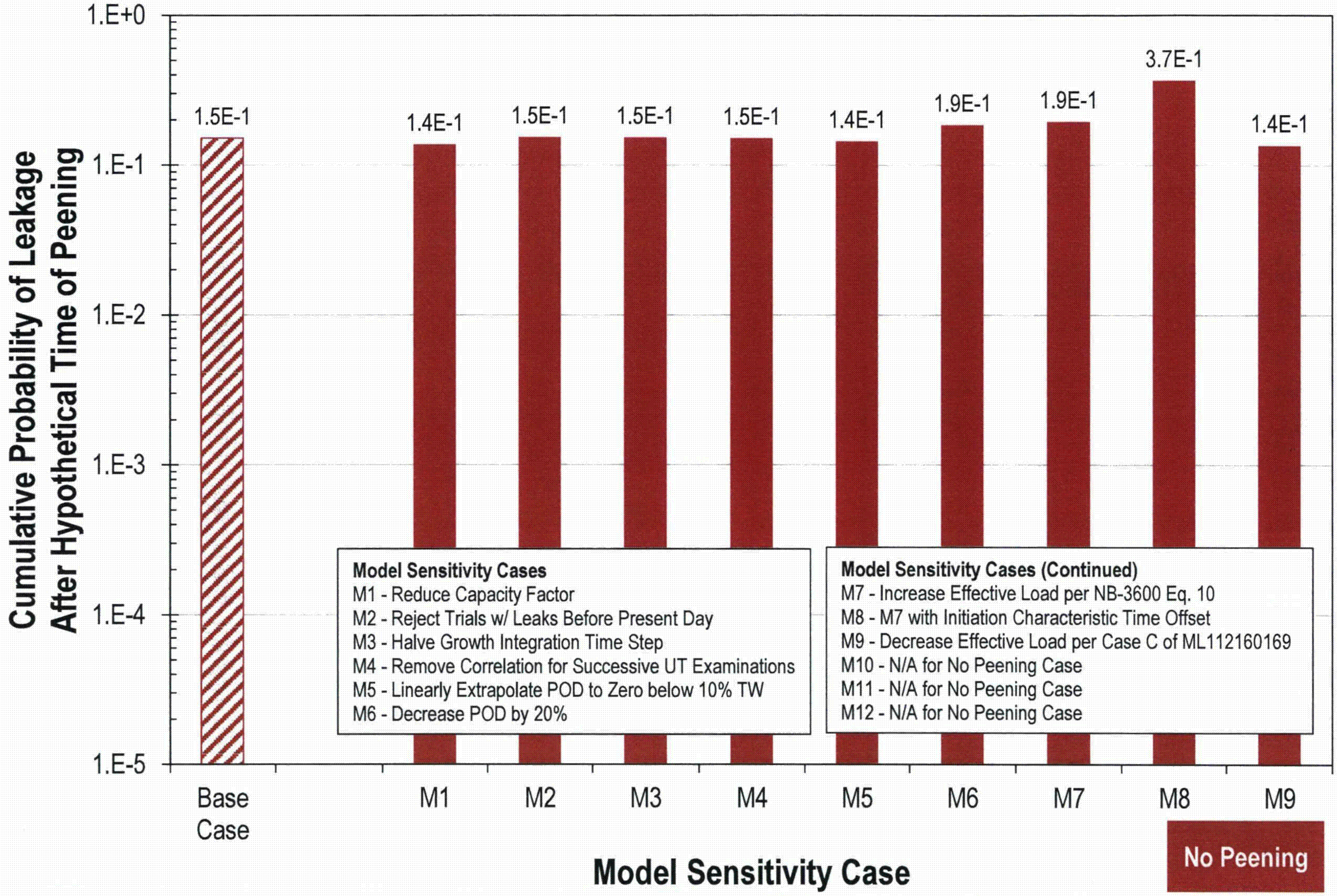

Figure A-10
Summary of Model Sensitivity Results for RVON Probabilistic Model without Peening

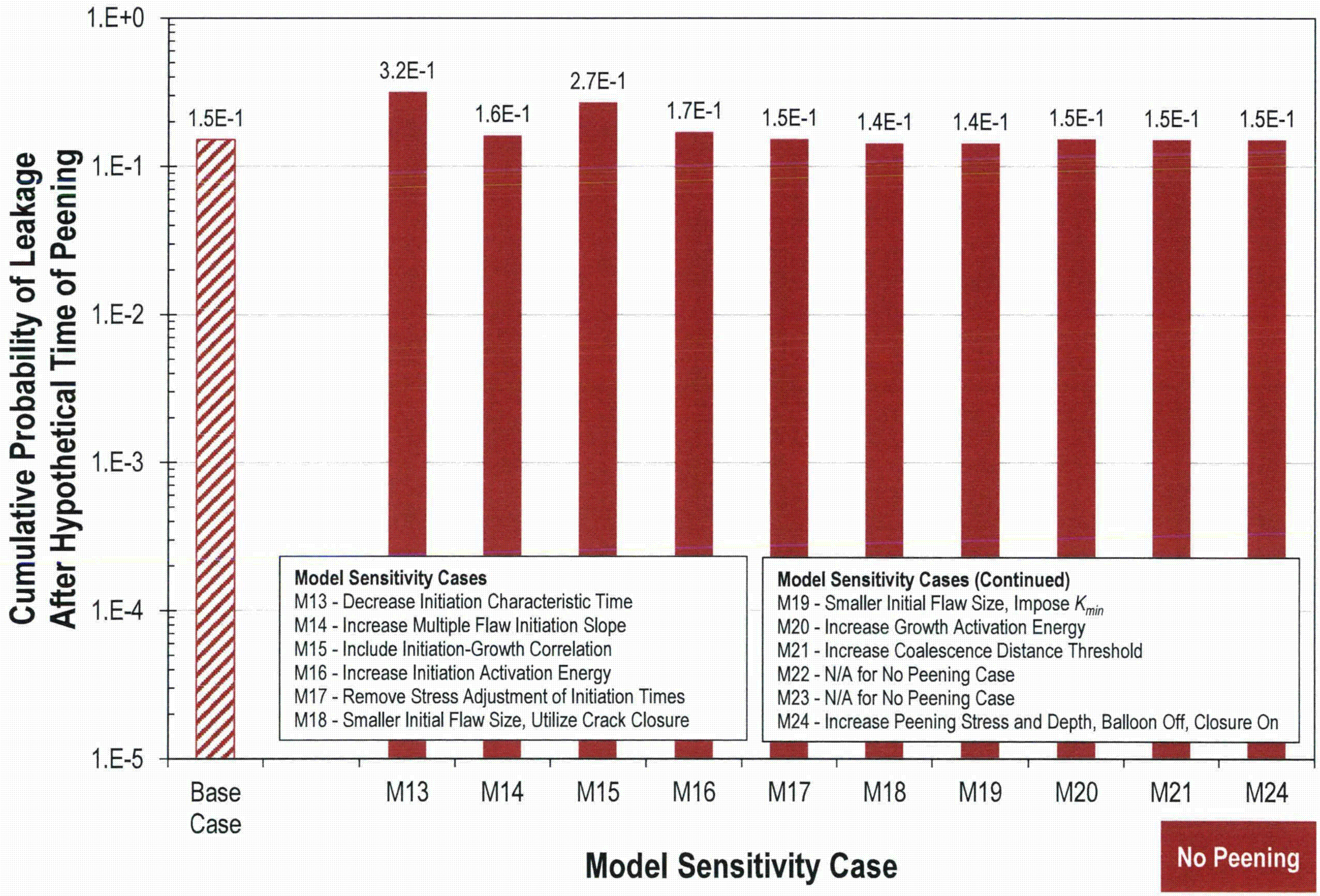

Figure A-11
Summary of Model Sensitivity Results for RVON Probabilistic Model without Peening (Continued)

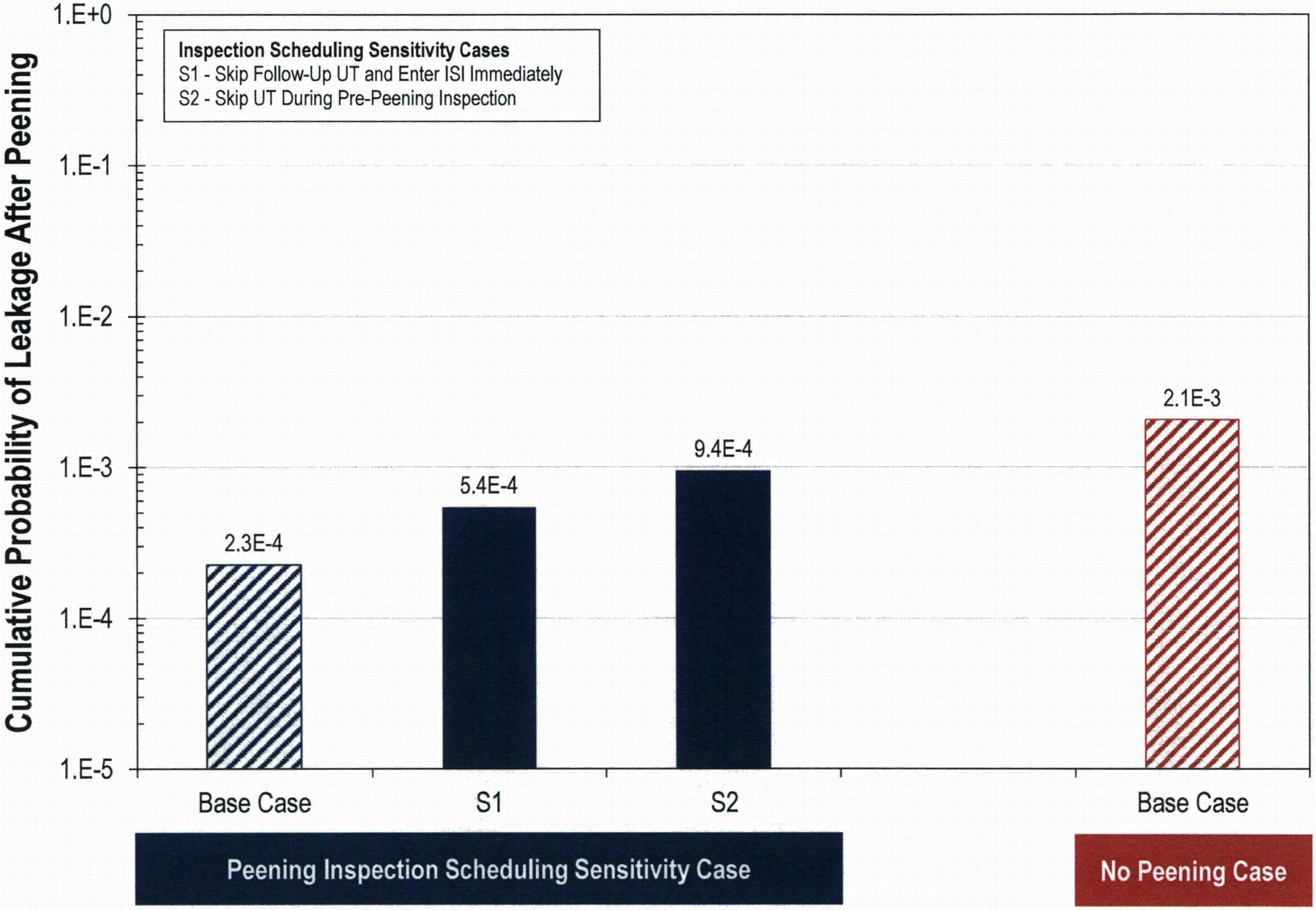

Figure A-12
Summary for Inspection Scheduling Sensitivity Results for RVIN Probabilistic Model with Peening

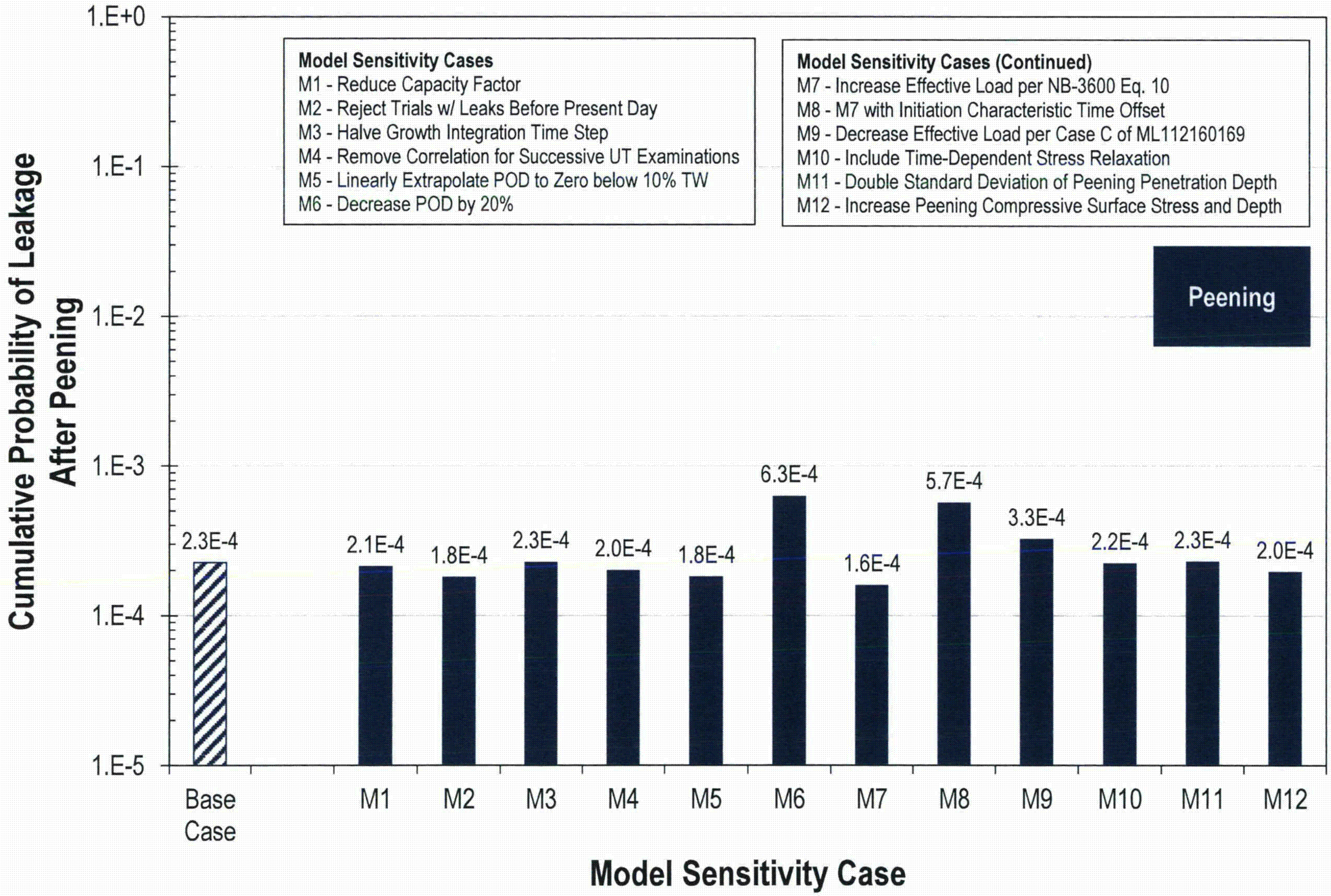

Figure A-13
Summary of Model Sensitivity Results for RVIN Probabilistic Model with Peening

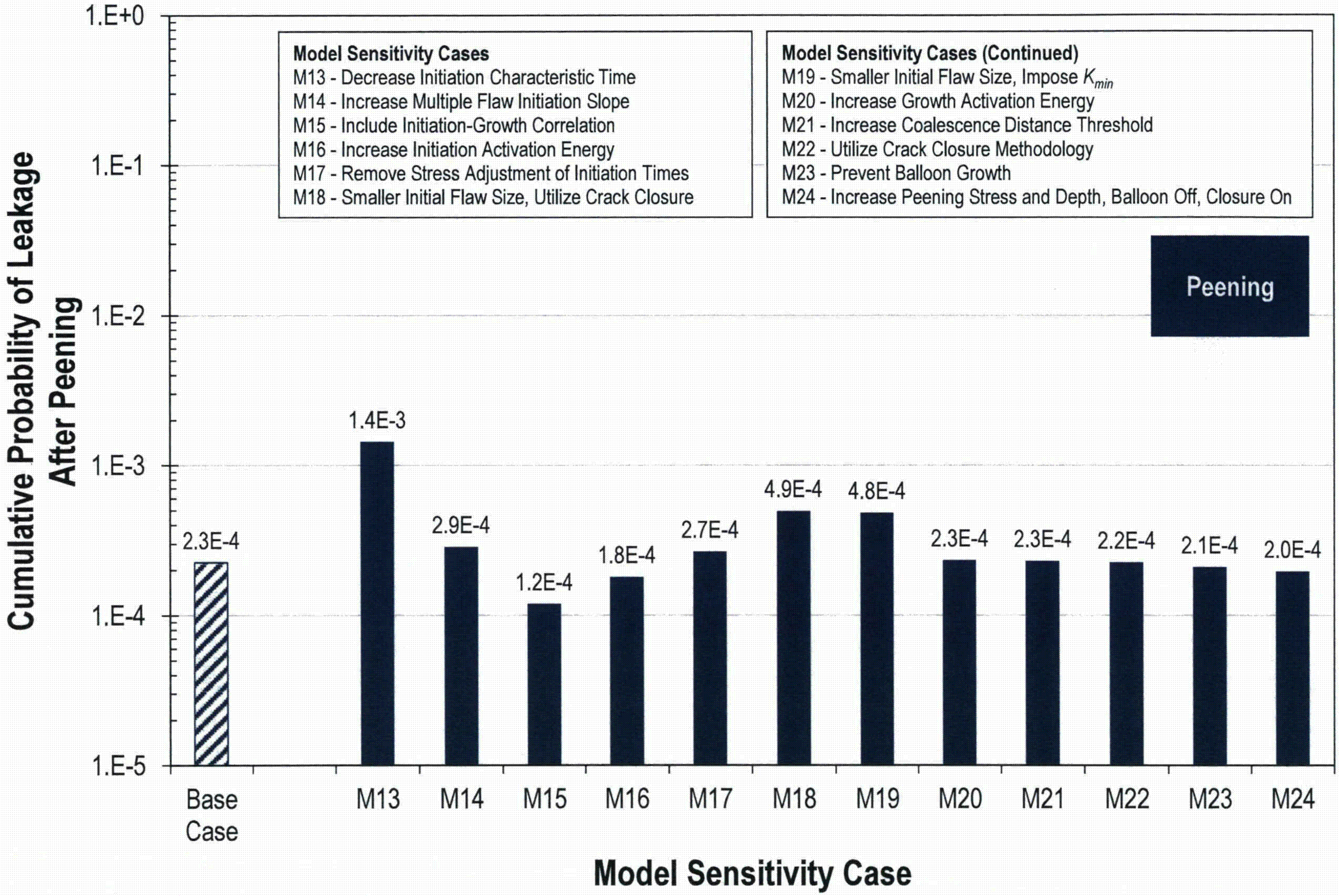

Figure A-14
Summary of Model Sensitivity Results for RVIN Probabilistic Model with Peening (Continued)

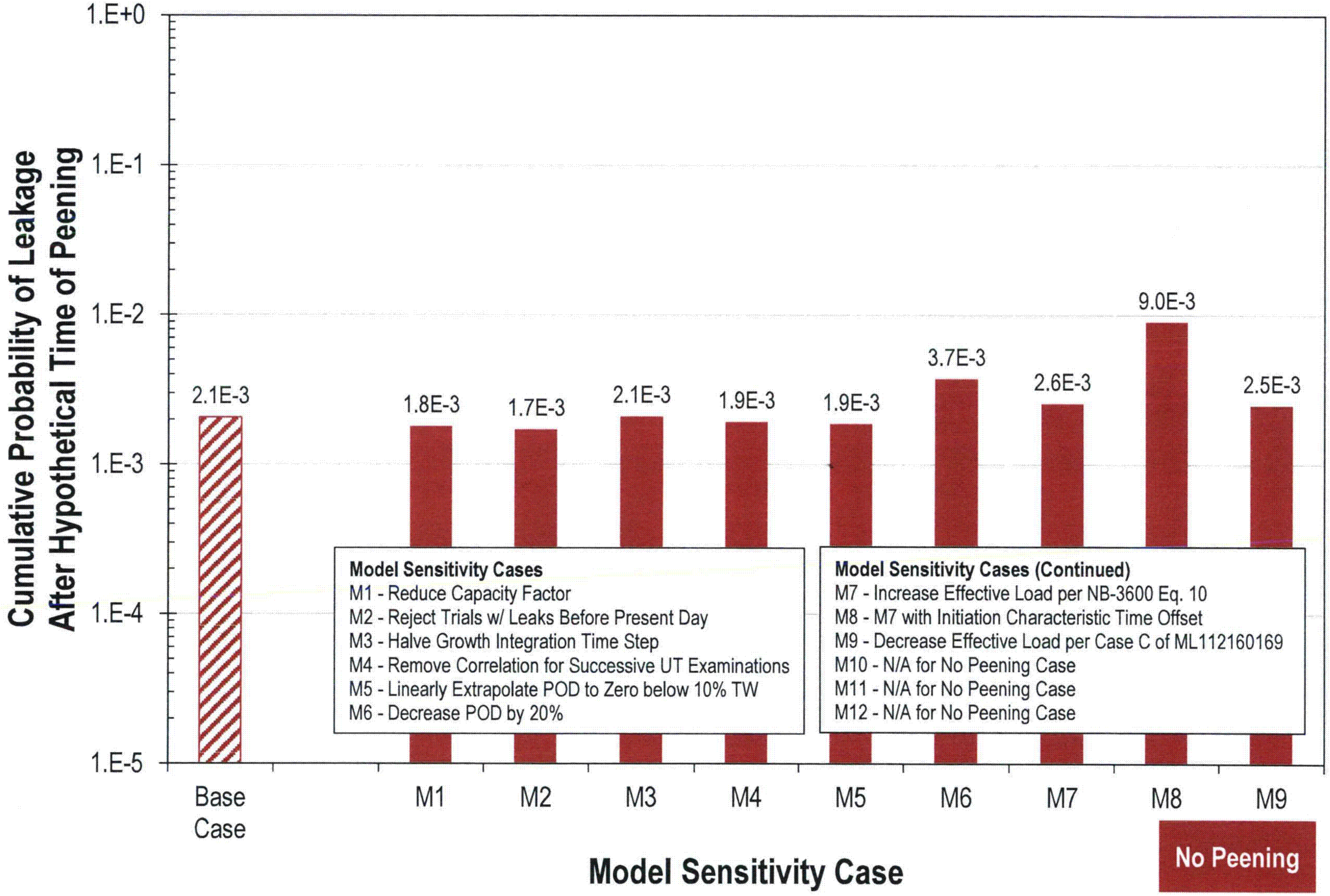

Figure A-15
Summary of Model Sensitivity Results for RVIN Probabilistic Model without Peening

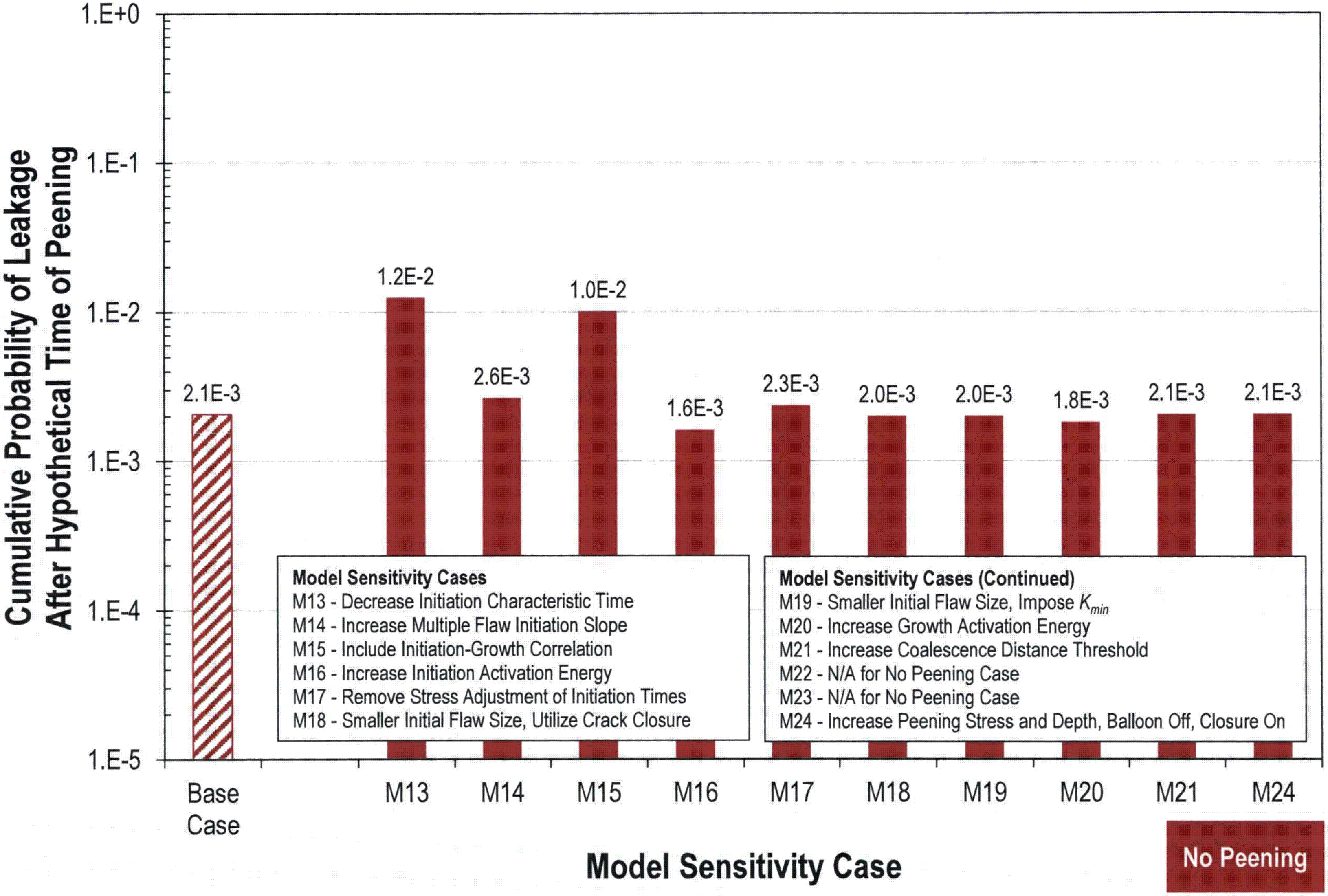

Figure A-16
Summary of Model Sensitivity Results for RVIN Probabilistic Model without Peening (Continued)

A.4 References

1. *Materials Reliability Program: Topical Report for Primary Water Stress Corrosion Cracking Mitigation by Surface Stress Improvement (MRP-335, Revision 1).* EPRI, Palo Alto, CA: 2013. 3002000073. [Freely Available at www.epri.com]

2. U.S. NRC, Second Request for Additional Information for MRP-335, Revision 1, "Topical Report for Primary Water Stress Corrosion Cracking Mitigation by Surface Stress Improvement (Peening)" (TAC No. MF2429), April 2, 2015. [NRC ADAMS Accession No.: ML15057A028]

3. xLPR-TR-CI-SCC-Weibull, *Development of xLPR 2.0 Inputs for Weibull Crack Initiation Model*, Version 1.0. August 2013.

4. *Materials Reliability Program: Development of Probability of Detection Curves for Ultrasonic Examination of Dissimilar Metal Welds (MRP-262, Revision 1) – Typical PWR Leak-Before- Break Line Locations*. EPRI, Palo Alto, CA: 2009. 1020451. [Freely Available at www.epri.com]

5. *ASME Boiler and Pressure Vessel Code 2013, Section XI, Mandatory Appendix VIII*, ASME, 2013.

6. ASME Code Case N-770-1, "Alternative Examination Requirements and Acceptance Standards for Class 1 PWR Piping and Vessel Nozzle Butt Welds Fabricated With UNS N06082 or UNS W86182 Weld Filler Material With or Without Application of Listed Mitigation Activities," Section XI, Division 1, American Society of Mechanical Engineers, New York, Approval Date: December 25, 2009.

7. *xLPR Pilot Study Report*. U.S. NRC-RES, Washington, DC, and EPRI, Palo Alto, CA: NUREG-2110 and EPRI 1022860. 2012. [Freely Available at www.epri.com]

8. *PWSCC Prediction Guidelines*, EPRI, Palo Alto, CA: 1994. TR-104030. [Freely Available at www.epri.com]

9. *Materials Reliability Program Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 82, 182, and 132 Welds (MRP-115)*, EPRI, Palo Alto, CA: 2004. 1006696. [Freely Available at www.epri.com]

10. *ASME Boiler and Pressure Vessel Code 2013, Section III, Subsection NB*, ASME, 2013.

11. Memo from A. Csontos (NRC-NRR) to T.R. Lupold (NRC-NRR), "Hot Leg Flaw Evaluation Summary", dated August 18, 2011. [NRC ADAMS Accession No.: ML112160169]

12. ASME Code Case N-729-1, "Alternative Examination Requirements for PWR Reactor Vessel Upper Heads With Nozzles Having Pressure-Retaining Partial-Penetration Welds," Section XI, Division 1, American Society of Mechanical Engineers, New York, Approval Date: March 28, 2006.