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MRP Materials Reliability Program MRP 2016-023
(via email)

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DATE: July 27, 2016

TO: Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, DC 20555-001

FROM: Bernie Rudell, Exelon, MRP Integration Committee Chairman
Anne Demma, EPRI, MRP Program Manager

SUBJECT: Transmittal of MRP's review comments on draft Safety Evaluation for MRP-335 Revision 3

This letter formally transmits MRP's review comments on the accuracy of information and the identification of proprietary information in the draft Safety Evaluation for MRP-335 Revision 3 transmitted to EPRI on July 1, 2016. There is no proprietary information contained in MRP-335 Revision 3 or in the draft Safety Evaluation, so comments in the attached table are only on the accuracy of the information and for clarification of the language in the draft SE.

Sincerely,

B.C. Rudell

Bernie Rudell
Chairman, Materials Reliability Program

Anne Demma
EPRI MRP Program Manager

Cc: Joe Holonich, NRC

Attachments:

1. NRC Draft Safety Evaluation on MRP-335, Revision 3: MRP Technical Error or Misinterpretations Review Comments
2. Draft Safety Evaluation on the Topical Report

D035
NRR

NRC Draft Safety Evaluation on MRP-335, Revision 3: MRP Technical Error Misinterpretations Review Comments

No.	Location in SE	Text in Question	Technical Error Misinterpretations Review Comments
1	Section 3.4.3 Page 10	For example, MRP reported that for a 1.3-percent deep circumferential flaw (0.040 inches),	The original text from Section 5.2.2.1 of MRP-335R3 is as follows: "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..." 1.3% of 2.75 inches is 0.036 inches, and not 0.040 inches. The text should be corrected to: *"For example, MRP reported that for a 1.3-percent deep circumferential flaw (**0.036** ~~0.040~~ inches),"*
2	Section 3.4.3 Page 11	The MRP's sensitivity study shows that only three of 72 cases for peened DMWs result in leakage after the extension of the inspection interval whereas nine of 24 cases for unpeened DMWs result in leakage per the current inspection requirements.	The text incorrectly references the results presented in Section 5.2.3 and summarized in Table 5-3 of MRP-335R3. The text should be corrected to: *"The MRP's sensitivity study shows that only three of 72 cases for peened DMWs result in leakage after the extension of the inspection interval whereas **24 of 72** ~~nine of 24~~ cases for unpeened DMWs result in leakage per the current inspection requirements."*
3	Section 3.4.4 Pages 12 and 13	The parameters that MRP sampled were the operating time, component temperature, and loads. MRP also analyzed uncertainty in crack initiation model, crack growth model, flaw inspection and detection model, and effect of peening on residual stress.	Operating time and effective loads were not sampled parameters for the DMW probabilistic assessment. The text should be corrected to: *"The parameters that MRP sampled were the ~~operating time,~~ component temperature~~,~~ **and welding residual stress profiles, as well as model parameters for** ~~and loads. MRP also analyzed uncertainty in~~ **the** crack initiation model, crack growth model, flaw inspection and detection model, and effect of peening on residual stresses."*

No.	Location in SE	Text in Question	Technical Error Misinterpretations Review Comments
4	Section 3.4.4 Page 13	Specifically, the cumulative leakage probability after peening is predicted to be reduced by a factor of 9 to 11, depending on when the follow-up inspection is performed.	Section A.10 of MRP-335R3 states: *"Specifically, the cumulative leakage probability after the hypothetical time of peening is predicted to be reduced by:* • *A factor of approximately 11 when the follow-up UT inspection is scheduled two cycles after peening and no subsequent UT inspections are scheduled after follow-up examinations are performed* • *A factor of approximately 12 when the follow-up UT inspection is scheduled three cycles after peening and no subsequent UT inspections are scheduled after follow-up examinations are performed* • *A factor of approximately 9 when the follow-up UT inspection is scheduled six cycles after peening and no subsequent UT inspections are scheduled after follow-up examinations are performed"* As these resulting factors of reduction range from 9 to 12, the text should be corrected to: *"Specifically, the cumulative leakage probability after peening is predicted to be reduced by a factor of 9 to* ***12*** *~~11~~, depending on when the follow-up inspection is performed."*
5	Section 3.4.6 Page 19	The sampled inputs include component geometry, operating time, RPVHPN operating temperature, welding residual stresses, and operating loading. MRP also treated uncertainties in the crack initiation model, crack growth model, flaw inspection and detection model, post-peening effects, and flaw stability model.	Operating time and operating loading were not sampled parameters for the RPVHPN probabilistic assessment. The text should be corrected to: *"The sampled inputs include component geometry, ~~operating time,~~ RPVHPN operating temperature,* ***and*** *welding residual stresses,* ***as well as model parameters for*** *~~and operating loading. MRP also treated uncertainties in~~ the crack initiation model, crack growth model, flaw inspection and detection model,* ***effect of peening on residual stresses*** *~~post-peening effects~~, and flaw stability model."*
6	Section 4.2 Page 23	Cracks anywhere on RPVHPNs can lead to leakage. [two locations]	This statement is incorrect. Circumferential flaws in RPVHPNs below the J-groove weld do not lead to leakage, as this portion of the CRDM nozzle tube is not part of the pressure boundary. These sentences should be modified to acknowledge this exception.

No.	Location in SE	Text in Question	Technical Error Misinterpretations Review Comments
7	Section 4.2 Page 24	Section 5.2.1 of MRP-335R3 states that "the peening compressive stress at the RPVHPN inside diameter surface is set to result in a net tensile stress of 10 ksi, and a residual stress value that results in a net stress of 0 ksi is assumed for the peened surface of the RPVHPN outside diameter and J-groove weld because the operating stress in those regions is small."	This is not a direct quotation of Section 5.2.1. Section 5.2.1 of MRP-335R3 states: "*the peening compressive stress at the surface is set to result in a net tensile stress of +70 MPa (+10 ksi) in the direction of maximum operating stress for flaws on the nozzle ID surface, and a residual stress value that results in a net stress of 0 MPa (0 ksi) is assumed for the peened surface of the nozzle OD and weld since the operating stress in those regions is small.*" Note that as discussed in Comment 10 a net tensile surface stress of +10 ksi was assumed for RPVHPNs in the deterministic matrix in Section 5.2.3 of MRP-335R3.
8	Section 4.2 Page 25	In that one set of tests, initiation occurred in two exposures at 360°C between 65,000-85,000 hours at a stress ratio as low as 0.78 between the applied stress and the test temperature yield stress. If these data are adjusted to account for lower temperature operation in service, the test exposures equate to greater than 222,000 hours of operation at hot leg temperatures.	Results shown in Table 2-2 of MRP-335R3 are incorrectly referenced. The test duration for the Alloy 82 specimen with a stress ratio of 0.78 was 53,500 hours. This corresponds to a test duration of 418,200 hours at 325°C. The test duration for the Alloy 82 specimen with a stress ratio of 0.93 was 28,500 hours. This corresponds to a test duration of 222,900 hours at 325°C. The text should be corrected to: *"In that one set of tests, initiation occurred in two exposures at 360°C between* ***28,500 and 53,500*** *~~65,000-85,000~~ hours at a stress ratio as low as 0.78 between the applied stress and the test temperature yield stress. If these data are adjusted to account for lower temperature operation in service, the test exposures equate to greater than* ***222,900*** *~~222,000~~ hours of operation at hot leg temperatures."*
9	Section 4.4 Page 31	The NRC staff finds that the proposed inspection requirements for the hot leg DMWs unacceptable. For the hot leg DMWs, the NRC calculations support the timing of the first follow-up examination to follow the schedule described in ASME Code Case N-770-1, i.e. on the second refueling outage for hot leg temperatures above 625° F and by the fifth year for hot leg temperatures less than or equal to 625° F. This is reflected in Condition 5.3. In both cases the second follow-up examination would occur within ten years after peening.	The wording should be corrected to state that NRC finds the proposed inspection requirements for hot leg DMWs at operating temperatures less than or equal to 625°F to be acceptable. The current wording implies that this is not the case. An operating temperature of 625°F bounds the hot leg operating temperatures in U.S. PWRs. ASME Code Case N-770-1 describes pressurizer locations as hot leg locations with temperature greater than 625°F. Pressurizer locations of Alloy 82/182 piping butt welds are not considered to be candidates for peening. Therefore Condition 5.3 is expanding the applicability of MRP-335R3 beyond the intended bound of 625°F.
10	Section 4.5 Page 31	However, the NRC staff finds that MRP's flaw analysis of RPVHPN in Section 5 of MRP-335R3 used a value for stress at operating conditions on RPVHNs of 0 ksi on the outside diameter and J-groove weld surfaces, yet the performance criteria specified in Section 4.3 of MRP-335R3 indicate the stress at operating conditions may be up to +10 ksi for the inside and outside diameter surfaces of the RPVHPN and J-groove weld.	This statement is factually incorrect. For the deterministic matrix of analyses added to the report as Section 5.2.3 of Revision 3, the total stress at both the inner and outer RPVHPN surfaces (ID, OD below weld, and weld wetted surface) was set to +10 ksi tensile.

No.	Location in SE	Text in Question	Technical Error Misinterpretations Review Comments
11	Section 4.5 Page 31	In addition, the period for small flaws to grow to 10% through-wall or leakage, as shown in the RPVHPN and the J-groove weld summary tables in Section 5 of MRP-335R3, do not seem to be consistent with operating stress profiles that range from 10 ksi tension on the inside diameter to a tensile stress of 30 to 60 ksi at depths of 0.01 to 0.04-inches.	This statement is not correct. An operating stress of 10 ksi tension on the inside diameter was applied by MRP in these calculations. The stress profile assumption for the MRP calculations being cited (Section 5.2.3.2) are shown in Figures 5-35 and 5-36 of MRP-335R3.
12	Condition 5.2 Page 36	(c) A root cause analysis report must be submitted to the NRC within six months of the discovery.	In Condition 5.2(c) the term "root cause analysis report" has very specific requirements associated with it in the industry. This should be changed as follows: *"**An appropriate causal analysis report consistent with the licensee corrective action program** ~~A root cause analysis report~~ must be submitted to the NRC within six months of the discovery."*
13	Condition 5.2 Page 36	(d) The inspection relaxation in MRP-335R3 is no longer applicable to the affected component. The affected component shall be inspected in accordance with the requirements of 10 CFR 50.55a, unless an alternative is authorized.	In Condition 5.2(d) the word "component" is unclear and should be "RPVHPN or DMW." This should be changed as follows: *"The inspection relaxation in MRP-335R3 is no longer applicable to the affected **RPVHPN or DMW** ~~component~~. The affected **RPVHPN or DMW** ~~component~~ shall be inspected in accordance with the requirements of 10 CFR 50.55a, unless an alternative is authorized."*
14	Table 2	"Volumetric exam every second refueling outage"	The "Current ISI Volumetric & Surface Examination" entry for "Unmitigated DMW at hot leg with temperature > 625 degrees F" should be corrected to: *"Volumetric exam every second refueling outage **for uncracked DMWs**"*
15	Table 3	For "RPVHPNs with EDY < 8 years": "If no flaw is found VE is every 3rd RFO & VT-2 performed during VE is not performed"	This table should be corrected to indicate that the VE interval proposed for cold heads in MRP-335R3 is every 3rd RFO or 5 calendar years, whichever is less. *"If no flaw is found VE is every 3rd RFO **or 5 calendar years, whichever is less,** & VT-2 performed during **RFO in which** VE is not performed"*
16	Table 4	Row: *RPVHPNs with effective degradation years (EDYs) ≥ 8 years* Column: *Follow-up Examination* Row: *RPVHPNs with effective degradation years (EDYs) ≥ 8 years* Column: *ISI Bare Metal Visual Exam (VE)* Row: *Hot leg DMWs with temperature ≤ 625 degrees F* Column: *Follow-up Examination*	The items in these table entries are italicized, indicating that the draft NRC authorized inspection frequencies are different than those proposed in MRP-335R3. However, these items in Table 4 are the same as those in Table 3, showing that there is no difference in these inspection requirements. Thus these entries in Table 4 should be un-italicized to show that they are not different from the inspection requirements proposed in MRP-335R3.
17	Table 4	For "RPVHPNs with EDY < 8 years": "*Performed in the second RFO after peening if RPVHPN contains no flaw(s).* *Performed in the first and second refueling outage (RFO) after peening if RPVHPN contains flaw(s)*"	This requirement of the draft SE is an unclear restatement of Condition 5.4 as written, and thus clarification is needed. The wording "contain flaw(s)" in Condition 5.4 is interpreted that the additional follow-up exam is only required for individual nozzle(s) that contain flaws that were not removed during a previous repair.

DRAFT SAFETY EVALUATION ON THE TOPICAL REPORT
"MATERIALS RELIABILITY PROGRAM: PRIMARY WATER STRESS CORROSION CRACKING MITIGATION BY SURFACE STRESS IMPROVEMENT (MRP-335 REVISION 3)"
TAC NUMBER MF2429

1.0 INTRODUCTION

1.1 PURPOSE

By letter dated May 1, 2013 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML13126A009), the Electric Power Research Institute (EPRI) on behalf of nuclear power industry's Materials Reliability Program (MRP), submitted to the U.S. Nuclear Regulatory Commission (NRC) staff for review and approval the topical report (TR), "Materials Reliability Program: Topical Report for Primary Water Stress Corrosion Cracking Mitigation by Surface Stress Improvement (MRP-335, Revision 1)," EPRI, 3002000073, January 2013.

By letters dated October 10, 2014, and June 12, 2015 (ADAMS Accession Nos. ML14288A370 and ML15167A112, respectively), MRP responded to the NRC staff's requests for additional information.

By letter dated August 14, 2015 (ADAMS Accession No. ML15230A173), MRP submitted MRP-335, Revision 2, 3002006654, EPRI, August 2015 (ADAMS Accession Nos. ML15230A174, ML15230A172, ML15230A175, and ML15230A177).

By letter dated February 19, 2016 (ADAMS Accession No. ML16055A216), MRP submitted MRP-335, Revision 3 (MRP-335R3), 3002007392, EPRI January 2016 (ADAMS Accession Nos. ML166055A215, ML166055A218, ML166055A219, ML166055A220, and ML166055A221).

MRP proposed to apply peening as a mitigation method to prevent primary water stress corrosion cracking (PWSCC) from occurring at dissimilar metal butt welds (DMWs) in primary loop piping, reactor pressure vessel head penetration nozzles (RPVHPNs), and associated J-groove welds that are fabricated from nickel-based Alloy 600/82/182 material. As part of peening, the MRP proposed to relax the current inspection requirements for the peened DMWs and RPVHPNs. MRP-335R3 contains the technical basis for peening application, including affected components, peening processes, performance criteria, analyses, and alternative inspection requirements.

1.2 BACKGROUND

Pressurized-water reactor (PWR) plants have experienced PWSCC in Alloy 82/182 DMWs, Alloy 600 RPVHPNs, and associated Alloy 82/182 J-groove welds. Circumferential and axial cracks have been found in these components in several U.S. and international nuclear power plants, challenging the leak-tightness and structural integrity of the subject components. As a result of PWSCC, the NRC requires augmented inspections for these DMWs, RPVHPNs, and associated J-groove welds as summarized in Table 2 at the end of this safety evaluation (SE) and as specified in the following NRC regulations:

Title 10 of the *Code of Federal Regulations* (10 CFR) Section 50.55a(g)(6)(ii)(D), "Reactor Vessel Head Inspections," requires PWR plants to augment their inservice inspection (ISI) of the RPVHPNs and associated J-groove welds using American Society of Mechanical Engineers *Boiler and Pressure Vessel Code* (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," with conditions.

Paragraph 10 CFR 50.55a(g)(6)(ii)(E), "Reactor Coolant Pressure Boundary Visual Inspections," requires PWR plants to augment their ISI of Class 1 components that are fabricated from Alloy 600/82/182 materials based on ASME Code Case N-722-1, "Additional Examinations for PWR Pressure Retaining Welds in Class 1 Components Fabricated With Alloy 600/82/182 Materials Section XI, Division 1," with conditions.

Paragraph10 CFR 50.55a(g)(6)(ii)(F) requires augmented inservice volumetric inspection of DMWs in PWR plants in accordance with 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," with conditions.

In addition to the NRC regulations, TR MRP-267, Revision 1, "Materials Reliability Program: Technical Basis for Primary Water Stress Corrosion Cracking Mitigation by Surface Stress Improvement," MRP, Palo Alto, CA, 2012. 1025839, provides the mockup testing to demonstrate the effectiveness of peening.

2.0 Scope of NRC Staff Review

The NRC staff limited its review of MRP-335R3 to determining whether MRP proposed inspection intervals provide reasonable assurance of structural and leak tight integrity of the DMWs and RPVHPNs given the peening performance criteria (e.g., area of coverage, magnitude of residual stresses on the peened surfaces), stress/depth profile and associated analyses.

In making the above determination, the NRC staff concentrated on three issues. First, whether the proposed post-peening operating stresses at the surface of the subject components are sufficient to prevent PWSCC initiation. Second, whether the proposed inspections requirements are sufficient to monitor the presence and growth of postulated PWSCC cracks which predate the peening process and were not discovered in the pre-peening inspection. Third, how the peening process considers fabrication flaws or other defects that may penetrate past the peening layer and grow later.

Of equal importance to what is included in this safety evaluation (SE) is what is not included. Three concepts central to peening are not included. The first issue is the regulatory authority by which peening may be conducted. As will be discussed below, this issue has been resolved and requires no further consideration here. The second issue not addressed in the SE is the qualification of a specific peening process and whether the application of the peening process meets the requirements contained in MRP-335R3. Additional information concerning this issue is also provided below. The third issue not included in this SE is regulatory authority to take any action regarding peening application. As described below, this authority will lie in a plant-specific licensing action.

Relative to the first and third issues, the NRC staff has determined that the application of peening, as described in MRP-335R3, is not in conflict with any aspect of the ASME Code, Sections III and XI, or NRC regulations. The NRC staff notes that relief from the ASME Code and NRC regulations is not required to perform peening on DMWs or RPVHPNs. The NRC staff further notes that the peening application as described in MRP-335R3 is distinctly different than peening for the purpose of distortion control as described in the ASME Code, Section III.

Each nuclear power plant may apply peening to components and evaluate its acceptability in accordance with the requirements of 10 CFR 50.59, "Changes, Tests, and Experiments." However, the ability of a licensee to self-evaluate the acceptability of peening plant components does not extend to the modification (i.e., relaxation) of current inspection requirements of peened components. The current inspection requirements for DMWs and RPVHPNs are promulgated in 10 CFR 50.55a which incorporates by reference the inspection requirements of ASME Code, Section XI, and relevant ASME code cases. Should a licensee desire to modify inspections of peened components, a licensing action (i.e., a proposed alternative under 10 CFR 50.55a(z)) is required to be submitted for NRC review and authorization prior to implementing inspection relaxation.

Relative to the second issue, this SE does not address the qualification of a specific peening process or whether a specific peening application has achieved the required performance criteria such as, stresses on the peened surface of a component. Specifically, the SE does not address the uncertainty associated with the measurement of weld residual stresses on the surface and effective depth of peened components. The stress on the surface and effective depth is a significant parameter in crack growth calculations and affects the inspection frequency (intervals) after peening application. These issues should be addressed via demonstration testing, including the effects of measurement uncertainties, in a plant-specific relief request with respect to the inspection requirements of the ASME Code and NRC regulations under 10 CFR 50.55a(z).

Relative to the third issue, this SE, in and of itself, has no impact on any regulatory requirement. This SE may, however, be cited in a plant-specific relief request to document the NRC's evaluation of proposed inspection requirements based on successful application of peening. Additionally, the plant-specific relief request should describe the peening process used, including issues associated with quality control, and demonstrate that the essential variables and performance criteria assessed in this SE are satisfied.

The NRC staff notes that MRP made changes to Revisions 1 and 2 of MRP-335. This SE is applicable to MRP-335, Revision 3, only.

3.0 Summary of MRP-335, Revision 3

3.1 Affected Components of Peening Application

MRP proposed to apply peening to the following components and locations:

- The inner diameter surfaces of DMWs in PWR reactor coolant system piping.
- The inside diameter and outside diameter surfaces of RPVHPNs in the area with high weld residual stresses caused by the presence of J-groove attachment welds.
- The surfaces of the J-groove attachment welds at RPVHPNs, including the surfaces of the Alloy 82/182 filler and butter metal that are normally wetted during operation.

3.2 Proposed Peening Processes

MRP-335R3 discussed two major peening processes (methods): laser peening and water jet peening, also known as cavitation peening. The key aspects of peening processes are performance criteria (e.g., stress improvement depth, geometric limitations, surface conditions, and peening coverage), process variables, inspectability, and quality control and quality assurance.

MRP stated that the effectiveness of peening in preventing crack initiation is independent of the peening process and is dependent only on the final compressive stresses and depth into the part that compressive stresses exist. As such, MRP noted that the proposed inspection requirements are acceptable irrespective of the peening process used provided that the performance criteria as specified in MRP-335R3, such as depth of compression, magnitude of compression, and area peened, are satisfied.

MRP further stated that each peening vendor is required to demonstrate that the acceptable essential variable values of its peening process documented in the application-specific procedures will satisfy the requirements and applicable performance criteria in MRP-335R3 such as coverage and compressive stress magnitude and depth parameters. MRP noted that the vendor will demonstrate satisfaction of these requirements through representative mockup testing. MRP requires that this testing and the proof of peening effectiveness be documented in a plant-specific report.

3.3 Proposed Alternative

Table 1 at the end of this SE summarizes MRP proposed performance criteria for peening parameters (e.g., the area of the component that will be peened, the effective depth of peening, and the stresses that will be achieved after peening).

Table 3 at the end of this SE summarizes MRP proposed inspection requirements, which include a pre-peening examination, follow-up examinations, ISI examinations, and bare metal visual examinations. The following paragraphs describe significant aspects of proposed inspection requirements.

DMWs

Pre-Peening Examination

For DMWs, MRP stated that prior to peening an ultrasonic examination and an eddy current examination of the DMW inner surface will be performed during the same refueling outage when peening is applied.

Follow-up Examination

For DMWs in hot leg piping, MRP stated that a volumetric and surface examination will be performed within 5 years following the peening application. In addition, a second volumetric and surface examination will be performed within 10 years following the peening application.

For DMWs in cold leg piping, MRP stated that a volumetric and surface examination will be performed once within 10 years, but no sooner than the third refueling outage following the peening application.

ISI Examination

MRP stated that all of the peened DMWs will receive a surface and a volumetric examination once each inspection interval (nominally 10 years). MRP specified that the surface examination shall be performed from the DMW inside surface and the volumetric examination shall be performed from either the inside or outside surface of the DMW.

RPVHPNs

Pre-Peening Examination

MRP stated that before peening application but during the same refueling outage, a volumetric examination of each RPVHPN tube will be performed as the baseline inspection. As an alternative, a surface examination will be performed on the nozzle inner surface and the wetted surface of the nozzle outside diameter and J-groove weld. This examination will be considered as the baseline inspection. Additionally, a demonstrated volumetric or surface leak path assessment through all J-groove welds will be performed.

Follow-up Examination

MRP stated that a volumetric examination of 100 percent of the required volume or equivalent surfaces of the RPVHPN tube and a leak path examination will be performed as part of the follow-up examination. The frequency of the follow-up inspections is as follows:

For plants whose nozzles have experienced greater than or equal to 8 effective degradation years (EDY) at the time of peening, a follow-up inspection is performed in the first and second refueling outages after peening application. For plants with fewer than 8 EDY, a follow-up inspection is performed in the second refueling outage after peening application.

ISI Examination

MRP stated that after peening, a bare metal visual examination (VE) will be performed for RPVHPNs each refueling outage. This interval may be extended in the following cases for RPVHPNs with less than 8 EDYs at the time of peening:

For RPVHPNs where the VE interval immediately before peening is permitted to be at least two refueling outages, the interval for performance of VE after peening is every second refueling outage. In this case, a VE must be performed either during the refueling outage of the peening or during the subsequent refueling outage.

If no unacceptable flaws are detected in the two refueling outages following peening, the interval for VE of RPVHPNs may be extended to every third refueling outage or 5 calendar years, whichever is less.

MRP states that VT-2 examinations of peened RPVHPNs under the insulation through multiple access points are required to be performed during refueling outages in which the VE is not performed.

In addition to the VE and VT-2, MRP stated that volumetric or surface examinations of peened RPVHPNs are performed once at an interval not to exceed one inspection interval (nominally 10 years). In addition, a demonstrated volumetric or surface leak path assessment through all J-groove welds is performed each time the periodic volumetric or surface examination is performed.

3.4 Basis for Use

MRP performed deterministic and probabilistic flaw analyses with the intent of demonstrating that the safety of the plant is either maintained or improved when the peened DMWs and RPVHPNS in conjunction with the proposed inspection relaxation is compared to the unmitigated condition with the current inspection requirements. MRP's flaw analyses will demonstrate that the length of time for a postulated flaw to grow to the unacceptable size in the peened components will be longer than the proposed inspection intervals (frequencies). Following the proposed inspection requirements, a licensee would detect the flaw early in the peened components and take corrective actions. Thereby, the structural integrity and leak-tightness of the peened components are adequately monitored and maintained.

3.4.1 Deterministic Analyses—General Information

MRP's deterministic analyses investigate the impact of peening on PWSCC crack growth versus time at various assumed crack locations from various initial crack sizes. MRP considered stress profiles which it proposed to be representative of those present in components before peening and after peening. MRP stated that 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 through the layer 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. However, the deterministic crack growth analyses demonstrate that flaws significantly deeper than the compressive layer tend to grow in depth at a rate similar to that for the unmitigated case. MRP calculated crack growth based on stress profiles which it proposed to be representative of those present in components before and after peening.

MRP characterized the post-peening stress profile by a thin compressive layer near the peened surface followed by a rapid transition to the pre-peening 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 (i.e., depth of effect).

MRP also performed sensitivity studies on crack growth based on combinations of key input variables to investigate the effect of input variability. The key variables considered were PWSCC crack growth rates, weld residual stresses, operating temperatures, initial crack aspect ratios, initial crack depths, and bending loads. The end result of the sensitivity studies is the time for the initial postulated crack to reach the detectable limit and the time for the crack to grow from the detectable limit to leakage. From the sensitivity studies, MRP determined acceptability of the proposed inspection requirements in detecting potential flaw growth in the peened component before the flaw challenges the structural integrity and leak tightness of the peened components.

3.4.2 Probabilistic Analyses—General Information

MRP's probabilistic analyses use the deterministic crack growth methodology to assess the effectiveness of follow-up and ISI examinations in addressing the effects of any pre-existing flaws not detected during the pre-peening examination. The MRP's probabilistic analyses predict the effect of peening on PWSCC, considering component loading, crack initiation, crack growth, and crack detection. The probabilistic model, which integrates the various models into a probabilistic simulation framework, allows the prediction of PWSCC throughout the operating lifetime of the plant. The end condition (component failure) of the probabilistic analysis for the DWM is leakage and for the RPVHPN is nozzle ejection.

The integrated probabilistic model includes a loading and stress model, a crack initiation model, a crack growth model, a nondestructive examinations model, and a leakage criterion. MRP also performed sensitivity studies with respect to various probabilistic model parameters to characterize the impact of probabilistic modeling assumptions and input uncertainty on leakage and nozzle ejection predictions.

The probabilistic modeling framework for DMWs accepts both deterministic and distributed inputs. The values of the deterministic inputs are constant for every Monte Carlo realization. The values of the distributed inputs are determined by sampling probability distributions (e.g., normal distribution, log-normal distribution, triangular distribution, etc.) during each Monte Carlo realization. The probabilistic model accepts an array of inputs that is used to define the distribution of each distributed input. For example, for DMW, the inputs are component geometry, operating time, temperature, and component loading.

MRP also performed sensitivity studies for the probabilistic models. MRP investigated variations in modeling and inspection scheduling such as magnitude and depth of the peening stresses, and inspection frequencies.

3.4.3 Deterministic Analyses—DMW

Definition of Component Failure

MRP predicted crack growth versus time, at various assumed crack locations, from various initial crack sizes to 100 percent through wall. The failure of a peened DMW in the deterministic analysis is defined as a leaking DMW.

DMW Configuration

MRP postulated a circumferential flaw located at the point of maximum tensile bending and an axial crack (of arbitrary location) in the DMWs at the reactor vessel inlet (cold leg) and outlet (hot leg) nozzles. MRP used a DMW with a wall thickness of 2.75 inches, an outside diameter of 35.5 inches, and a weld width of 1.752 inches based on a typical Westinghouse reactor design. The normal operating pressure used in the calculations is 2,250 psi. The MRP calculation assumes that the hot leg temperature is 625 degrees Fahrenheit (F) and the cold leg temperature is 563 degrees F.

Stress Profile

For the bounding case, MRP modeled the post-peening residual stress profile in a DMW 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 residual stress magnitude at the surface and the penetration depth – the depth to which peening imparts compressive residual stresses. MRP assumed that for DMWs, the residual plus normal operating stress remains compressive for all wetted surfaces along the susceptible material. Thus, the bounding peening compressive stress at the peened surface is set to result in a total (operating plus residual) stress of 0 ksi (ksi = 1000 pound per square inch) at the circumferential location and for the principal stress direction with the maximum operating stress.

For the sensitivity study cases, MRP assumed a compressive residual stress of 100 ksi at the peened inside surface of the DMW. MRP stated that data and other information from peening vendors suggest that a compressive surface stress magnitude between 58 to 145 ksi can be achieved by peening. While thermal and load cycling may reduce the compressive stress over the operating lifetime of the plant (with a large majority of relaxation occurring during the first operational cycle after peening), the stress for these cases is chosen to demonstrate the crack growth behavior in components where peening induces a highly compressive residual stress.

MRP stated that the uncertainty in measurement of the surface residual stress shall be considered in the analysis to determine the surface stress including operating and residual stress. MRP further stated that the basis for that consideration shall be documented in the relief request.

Depth of Peening Effect

MRP assumed compressive residual stresses exist from the peened surface to a depth of 0.04 inches. MRP stated that the nominal depth refers to the depth of the compressive residual stress that is reliably obtained in demonstration testing, i.e., for at least 90% of the locations measured.

MRP clarified that some advanced peening processes result in a very thin surface layer (i.e., within 0.001 to 0.002 inch from the surface) where the residual stress is tensile. The tensile residual stresses in this very thin surface layer may be excluded when the above requirement (i.e., compressive stresses achieved at a depth of 0.04 inches) is met. The testing shall demonstrate that the nominal depth of the compressive surface residual stress field, excluding the very thin layer of tensile stress at the surface, is at least 0.04 inches. The depth measurement shall be from the surface to the point where the compressive residual stress becomes neutral.

Peening Coverage

MRP stated that the required peening coverage (the area that will be peened) 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. In addition, the peening coverage shall be extended at least 0.25 inches beyond the area of susceptible material.

Examination Coverage

MRP stated that 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), essentially 100% coverage is required for the examination for axial flaws instead of the requirements in -2500(c) of ASME Code Case N-770-1.

Crack Growth Calculation

MRP used the following three crack growth models:

1) A model based on the classical weight function method to predict the stress intensity factors at the crack surface and deepest point locations.

2) A model that disregards the effect of peening on the growth of the crack surface point locations. This convention is used to approximate the realistic "balloon"-type growth of the crack front below the peening compressive layer. Numerical studies have demonstrated that the depth growth of a realistic crack is generally bounded by the classical weight function approach and balloon growth approximation.

3) A model that 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.

MRP used the crack growth rates based on the 75th percentile of material variability, consistent with MRP-115, "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.

Results of DMW Deterministic Analysis

MRP reported that peening is most effective on the arrest of micro-crack growth in a peened DMW. For example, the growth of an axial flaw with an initial depth of 0.7 percent (0.02 inches) through wall will be arrested completely.

MRP stated that peening will slow the growth of small cracks. For example, MRP reported that for a 1.3-percent deep circumferential flaw (0.040 inches), it took approximately 4.3 effective full power years (EFPY) and 2.6 EPFY to grow 100-percent through wall for the peened and unpeened DMW, respectively. For a 1.3-percent deep axial flaw, it took approximately 3.6 EFPY and 1.8 EFPY to grow 100-percent through wall for the peened and unpeened DMW, respectively.

MRP noted that peening has a limited effect on the growth of a relatively large flaw size such as an initial through-wall of 10 percent depth (0.3 inches) or more. The 10-percent deep circumferential flaw in the peened DMW would reach 100-percent through-wall in 2.4 EPFY whereas as the same flaw in an unpeened DMW would reach 100-percent through-wall in 1.85 EFPY, delaying crack growth by approximately 7 months. For a 10-percent depth axial flaw, the crack growth to leakage is delayed by less than 1 month between the peened and unpeened DMW (1.35 EFPY vs. 1.25 EFPY).

MRP noted that a longer crack in length, with the same initial depth, is predicted to grow through 0 to 40 percent of wall thickness faster than the shorter crack. The lower operating temperature of a reactor vessel inlet nozzle (cold leg) results in a much greater period of growth before a crack penetrates through wall (i.e., the lower the operating temperature the slower the crack growth).

The MRP's sensitivity study shows that only three of 72 cases for peened DMWs result in leakage after the extension of the inspection interval whereas nine of 24 cases for unpeened DMWs result in leakage per the current inspection requirements. MRP noted that the leakage cases in the peened DMWs resulted from using conservative inputs which may not occur in the field (high tensile weld residual stresses, high operating temperature and 95th percentile crack growth rate). MRP stated that the sensitivity study demonstrates that peened DMWs with proposed inspection relaxation will result in less leakage than unpeened DMW with the current inspection requirements.

3.4.4 Probabilistic Analyses—DMW

Definition of Component Failure

The failure of a DMW in the probabilistic analyses is defined as when the initial crack becomes 100 percent through wall (i.e., leakage) at which point Monte Carlo simulation ends and summary statistics are compiled.

Crack Initiation Model

MRP used a statistical Weibull approach to predict crack initiation. It allows for adjustments for operating temperature and surface stress which are significant parameters for crack initiation prediction. The model allows for independent initiation of multiple flaws with axial or circumferential orientations. The crack size, location, capacity for growth, material properties, and environmental conditions were also considered.

Load and Stress Model

Load models are used to calculate the stress in the DMW component during each Monte Carlo realization. Separate load models are used for hoop stresses (propagating axial cracks) and axial stresses (propagating circumferential cracks). The load models account for pre-peening and post-peening welding residual stresses, internal pressure, and piping loads (dead weight, thermal expansion, and thermal stratification, if applicable). In addition, a peening residual stress model is introduced for modeling crack growth during cycles after a peening application. The load models differentiate between residual stress and operational stress (which can all be combined to obtain total stress) as well as membrane stress and bending stress.

MRP assumed that after the peening application, no new cracks will initiate. As with weld residual stress, the peening stress profile is assumed to be axisymmetric and varying through wall. The through-wall post-peening residual stress, in both the hoop and axial directions, is modeled using a piecewise stress equation that captures the minimum depth of the compressive residual stress layer and the limiting magnitude of the residual plus normal operating stress. MRP modeled the post-peening profile into the following four general regions:

- the compressive region (nearest to the peened surface)
- the first transition region
- the second transition region
- the "minimally affected" region (farthest from the peened surface)

Crack Growth Model

MRP used a model to allow the prediction of PWSCC growth rate as a function of crack geometry, component loading, and other conditions. Assuming that cracks maintain a semi-elliptical shape as they grow through wall, the model predicts growth rates of the surface tips (in the length direction) and the deepest point (in the depth direction) of the crack. The model incorporates the major factors affecting flaw growth rate: temperature and stress intensity factor.

MRP also performed a sensitivity study to show the effect of the balloon crack growth phenomenon by allowing crack length growth independent of peening (i.e., using the pre-peening stresses).

Examination Model

The probabilistic analyses include examination models to simulate ultrasonic examinations of DMWs. MRP used probability of detection curves to estimate the likelihood of a crack being detected, given its size. The examination models are used to predict leakage probabilities because cracks that lead to leaks are often those that are undetected during one or more scheduled examinations. The models include methods of examination schedules before and after peening, the probability of detection, the crack geometry, and detection and repair modeling.

Uncertainty

The probabilistic modeling framework for DMWs accepts both deterministic and distributed inputs. The values of the deterministic inputs are constant for every Monte Carlo realization. The values of the distributed inputs (i.e., probabilistic modeling) are determined by sampling probability distributions (e.g., normal distribution, log-normal distribution, triangular distribution, etc.) during each Monte Carlo realization. The probabilistic model accepts an array of inputs that is used to define the distribution of each distributed input.

MRP managed uncertainty propagation by sampling input and parameter values from selected probability distributions (with appropriately selected bounds). MRP stated that, for simplicity, the model does not treat epistemic (i.e., caused by incomplete knowledge) and aleatory (i.e., caused by random variation) uncertainties differently. The parameters that MRP sampled were the operating time, component temperature, and loads. MRP also analyzed uncertainty in crack initiation model, crack growth model, flaw inspection and detection model, and effect of peening on residual stress.

Results of Probabilistic Analysis of DMW

MRP predicted that for the reactor vessel outlet nozzle (hot leg), the cumulative probability of leakage after peening (1.0×10^{-3} to 2.5×10^{-3}) would be reduced by a factor of between 60 and 150, as compared to cumulative leakage probabilities on the same span of time for an unmitigated reactor vessel outlet nozzle (1.5×10^{-1}), depending on the post-peening follow-up examination and ISI scheduling. MRP noted that, in general, the degree of improvement is not significantly influenced by the follow-up inspection time or the ISI frequency. MRP explained that the reason for the former is that most of the cracks that were undetected at the pre-peening inspection are small and, accordingly, grow slowly after peening. The reason for the latter is because 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 reactor vessel inlet nozzle (cold leg), MRP predicted that the cumulative probability of leakage after peening (8.8×10^{-5} to 2.3×10^{-4}) is reduced by a factor of between 8 and 24, as compared to cumulative leakage probabilities on the same span of time for an unmitigated reactor vessel inlet nozzle (2.1×10^{-3}) depending on the post-peening follow-up examination and ISI scheduling. This degree of improvement is smaller than that predicted for the reactor vessel outlet nozzle because the inspection schedule for an unmitigated inlet nozzle conservatively takes little credit for its reduced temperature in comparison to that for hot-leg locations. MRP stated that for both the reactor vessel outlet nozzle and inlet nozzle peening base cases, the probability of leaking after the follow-up inspection is very low.

MRP stated that the results of the probabilistic analysis of PWSCC on a peened reactor vessel outlet nozzle support the relaxed ultrasonic test (UT) inspection schedules. Specifically, the cumulative leakage probability after peening is predicted to be reduced by a factor of 97 and 142, depending on when the follow-up inspection is performed.

The MRP stated that the results of the probabilistic analysis of PWSCC on a peened reactor vessel inlet nozzle support the relaxed UT inspection schedules. Specifically, the cumulative leakage probability after peening is predicted to be reduced by a factor of 9 to 11, depending on when the follow-up inspection is performed.

The MRP concluded that the large reduction in leakage probability with peening (approximately between a factor of 10 and 100) supports the conclusion that rupture frequency (and boric acid wastage potential) is also reduced through peening application with inspection relaxation.

MRP stated that the sensitivity cases show that conclusions drawn from the base peening case results are not highly sensitive to the precise input values used. Specifically, sensitivity cases showed that only minimal risk benefit for peened DMWs with increased depth of the peening stress effect or with more compressive stresses at the peened surface. MRP stated that no case negates the prediction that a peened reactor vessel outlet nozzle or inlet nozzle can maintain a lower probability of leakage with a relaxed inspection schedule (as compared to the unmitigated component). This is because the large margin of improvement predicted for the base peening cases. The sensitivity studies also showed the importance of a pre-peening UT inspection.

3.4.5 Deterministic Analyses—RPVHPN

Definition of Component Failure

MRP stated that for the RPVHPN, the failure mode is nozzle ejection. MRP assumed that when leakage occurs because of a flaw at any location, this flaw immediately transitions to a through-wall circumferential crack that grows along the top of the J-groove weld contour until it is repaired or it becomes large enough to fulfill the ejection criterion.

Flaw Configuration

For its calculations, MRP used a wall thickness of 0.622 inches for the RPVHPN, nozzle outer diameter of 4 inches, a reactor vessel head thickness of 5.984 inches, a hot head temperature of 605 degrees F and cold head temperature of 561 degrees F. The normal operating pressure used is 2,250 psi.

MRP-335R3 postulated the following four types of crack on the RPVHPN (1) an axial crack on the nozzle inside diameter initiating above the J-groove weld, (2) an axial crack on the nozzle outside diameter initiating below the J-groove weld, (3) a crack initiating on the J-groove weld, and (4) a circumferential through-wall crack growing along the J-groove weld contour.

Stress Profile

Section 4.3.1 of MRP-335R3 requires that for the performance criteria of the RPVHPN, the residual stress in combination with the operating stress on the peened surface does not exceed +10 ksi tensile stress.

MRP stated that peening will prevent PWSCC initiation because the stresses imparted on the peened surface are below the threshold stress necessary for PWSCC initiation over plant life. MRP stated that while it is considered that there is no firm "threshold" below which PWSCC will never occur, a tensile stress of +20 ksi is a conservative lower bound of the stress level below which PWSCC initiation will not occur during plant life. MRP stated that the 20 ksi threshold stress corresponds to about 80% of the lower bound yield strength for Alloy 600 materials at operating temperatures. MRP noted that this limit applies to steady-state stresses during normal operation as stress corrosion cracking initiation is a long-term process, and does not apply to transient stresses that occur only for short periods of time.

MRP noted that consistent with the yield strength range known to be applicable to J-groove nozzles fabricated from Alloy 600 wrought material, laboratory testing for Alloy 600 materials with yield strengths could be up to 65 ksi. MRP concluded from its literature review that the room-temperature yield stresses for PWR plant Alloy 600 materials are in the range 35-60 ksi. Applying a factor of 0.8 to obtain the at-temperature yield stress and an 80% conservative margin factor, the stresses required for PWSCC initiation are 22-38 ksi. MRP explained that +20 ksi is a conservatively low limit for the stress level required for PWSCC initiation over plant service periods. A limit of +10 ksi provides substantial additional margin for post-peening stresses to prevent PWSCC initiation.

Depth of Peening Effect

MRP assumed a 0.01 inches deep layer of compressive residual stress exists on the inside diameter of a RPVHPN. For the outside diameter and J-groove weld wetted surfaces of a RPVHPN, MRP assumed the compressive residual stress exists on the surface to a depth of 0.04 inches of the peened RPVHPN.

For the sensitivity study case, MRP assumed a 0.02 inches deep layer of compressive residual stress on the inside diameter of a RPVHPN. For the outside diameter and J-groove weld wetted surfaces of a RPVHPN, MRP assumed a 0.12 inches deep layer of compressive residual stress.

Peening Coverage

MRP stated that the required peening coverage is the full wetted surfaces of the attachment weld, butter, and nozzle base material in the region defined in Figures 4-1 through 4-4 of MRP-335R3. MRP specified the peening coverage to ensure that areas susceptible to PWSCC initiation are mitigated. Section 4.3.8.1 of MRP-335R3 requires that the boundaries of the area required to be effectively peened in Figures 4-1 through 4-4 be extended a suitable distance for the specific peening method to provide high assurance that the areas susceptible to PWSCC receive the required peening effect.

Due to geometry, some peening techniques of interest cannot be used to peen the threaded areas that are present in some cases near the bottom of the nozzle tube. MRP-335R3 stated that because any such threaded areas are located below the weld toward the end of the nozzle and are not part of the pressure boundary, it is not necessary that peening be performed of the threaded regions when present.

Examination Coverage

MRP stated that the required examination volume and surface are defined in Figure 2 of ASME Code Case N-729-1. Note (5) of Table 4-3 of MRP-335R3 states that if the examination area or volume requirements of Figure 2 of Code Case N-729-1 cannot be met, the alternative requirements of Appendix I of Code Case N-729-1 shall be used and the evaluation shall be submitted to the regulatory authority having jurisdiction at the plant site. MRP stated that in accordance with 10 CFR 50.55a(g)(6)(ii)(D)(*6*), implementation of Note (5) of Table 4-3 requires prior NRC approval.

Crack Growth Calculation

Growth predictions for each crack type can be made for the uphill and downhill locations on the penetration by using stress profiles that are representative of each location. Consistent with the

DMW calculations, MRP used the 75th percentile value of crack growth rates in topical reports, MRP-55, "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, and MRP-115 to calculate crack growth in RPVHPNs.

For the first three crack types, MRP predicted growth 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. For the nozzle ejection calculation (i.e., the fourth crack type), MRP assumed an initial circumferential flaw that is 100 percent through wall and a length of 30 degrees in circumferential extent of the RPVHPN. When the initial circumferential flaw grows to the 300 degree circumferential extent, the nozzle is assumed to eject.

The critical crack length for ejection, or net section collapse, is based on calculations presented in MRP-110, "Materials Reliability Program: Reactor Vessel Closure Head Penetration Safety Assessment for U.S. PWR Plants (MRP-110 NP): Evaluations Supporting the MRP Inspection Plant," EPRI, Palo Alto, CA: 2004, 1009807(ADAMS Accession No. ML041680506).

Results of Deterministic Analysis of RPVHPN

MRP stated that for an axial crack on the inside diameter of a RPVHPN with an initial through-wall flaw depth of 1 percent (0.006 inches), the effect of peening is predicted to delay 100 percent through-wall growth by approximately 5 EFPY.

MRP stated that growth of axial cracks on the RPVHPN outside diameter through the wall does not cause leakage. Instead, leakage occurs once an outside diameter axial crack grows in length to reach the outside diameter nozzle annulus beyond the J-groove weld. MRP reported that the effect of peening on growth of axial outside diameter shallow flaws is large, delaying leakage by 1- 4 EFPY for flaws up to about 30 percent (0.20 inches) through-wall at the time of peening.

MRP reported that peening is predicted to arrest growth for cracks less than 80 percent of the compressive layer depth. Peening is predicted to be beneficial for slowing the growth of cracks significantly deeper than the compressive residual stress layer depth. MRP explained that 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). MRP further explained that the effect of peening on the crack growth time rapidly fades for weld cracks deeper than the compressive layer depth.

At the RPVHPN outside diameter and J-groove weld locations, where the peening penetration depth is assumed to be 0.118 inches, cracks less than approximately 15% - 35% through-wall may be arrested upon the application of peening.

For the first three crack configurations, the downhill locations tend to grow to leak faster because of characteristically more tensile weld residual stresses.

MRP noted that for some initial crack depths, leakage occurs in the peened RPVHPN slightly faster than in the unmitigated RPVHPN. MRP stated that this occurs for relatively deep cracks and is because of 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.

MRP showed that the if the RPVHPN is operated near the cold leg temperature, as opposed to the hot leg temperature, it would result in a longer period of growth before a crack grows through wall.

MRP noted that 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 J-groove weld locations, where crack surface length growth is constrained by the width of the J-groove weld.

MRP stated that downhill circumferential cracks in RPVHPN are predicted to cause ejection approximately 18 EFPY after crack initiation, and uphill circumferential cracks are predicted to cause ejection approximately 23 EFPY after crack initiation. In the rare case in which two circumferential through-wall cracks initiate—one from the uphill location and one from the downhill location—RPVHPN ejection is predicted approximately 9.5 EFPY after crack initiation.

3.4.6 Probabilistic Analyses—RPVHPN

Crack Initiation Model

Each RPVHPN is divided into an uphill and downhill side. Each cracking mode may initiate on either the uphill or downhill sides, both of which have their own unique loading conditions.

Inside diameter axial cracks (Mode 1)—partial through-wall cracks located on the RPVHPN inside diameter surface. These cracks are assumed to initiate in the region above the J-groove weld such that they immediately result in leakage if they penetrate through wall into the outside diameter nozzle annulus. These cracks are opened by hoop stresses in the RPVHPN.

Outside diameter axial cracks (Mode 2)—partial through-wall cracks located on the RPVHPN outside diameter surface below the J-groove weld. These cracks cause leakage if they grow in length to reach the nozzle outside diameter annulus. They may transition to through-wall axial cracks if they grow through wall before reaching the annulus. These cracks are opened by hoop stresses in the RPVHPN.

Radially oriented weld cracks (Mode 3)—cracks located on the J-groove weld that grow toward the weld toe. These cracks are opened by hoop stresses in the J-groove weld.

Through-wall axial cracks (Mode 4)—through-wall cracks located below the J-groove weld. These cracks may only form if an outside diameter axial crack reaches through-wall before reaching the nozzle outside diameter annulus. These cracks cause leakage if they grow long enough to reach the nozzle outside diameter annulus. These cracks are opened by hoop stresses in the RPVHPN.

Circumferential through-wall cracks (Mode 5)—through-wall cracks located on the weld contour above the J-groove weld. These cracks are assumed to occur immediately following leakage caused by any of the preceding crack modes, either by branching of the flaw causing the leakage or by initiation of a new flaw on the outside diameter surface of the nozzle. These cracks are opened by a complex stress field acting orthogonally to the weld contour.

MRP used a statistical Weibull approach for predicting crack initiation that is similar to the approach used in the DMW probabilistic analyses. The key difference in the initiation models is that the RPVHPN initiation model does not include a surface stress adjustment.

Load and Stress Model

MRP stated that total stresses and operational stresses (i.e., those stresses caused by loads present during operation) are derived from finite element analysis results, and welding residual stresses are attained from the difference between the total and operational stresses. After peening is applied, the post-peening residual stress profile is superimposed with the operational stresses to attain the total stress profiles used to predict crack growth.

MRP further stated that for RPVHPNs, the compressive residual stress depths are sampled from separate distributions for the inside diameter locations, as compared to the outside diameter and J-groove weld locations.

For J-groove weld locations, the through-element dimension is the weld path length instead of the RPVHPN thickness. Inside diameter peening stresses above the weld are assumed to have no effect on the growth of circumferential through-wall cracks. The growth of circumferential through-wall cracks is based on stress intensity factors that were calculated with finite element software.

MRP assumed that outside diameter peening stresses below the J-groove weld have no effect on the growth of partial through-wall axial outside diameter cracks that have grown under the weld far enough that the upper crack surface tip is outside of the peening compressive layer.

Inside diameter peening stresses do not affect nearly through-wall axial outside diameter cracks (i.e., the thin compressive region near the inside diameter is not given credit for abating the growth of most (90 to 100 percent) through-wall cracks).

Crack Growth Model

The crack growth model used for RPVHPN is similar to the crack growth model in the probabilistic analyses of DMW.

Examination Model

The examination model includes simulation of ultrasonic and visual examinations of RPVHPNs. The model includes the examination schedules before and after peening, probability of detection, and detection and repair modeling rules.

Uncertainty

The uncertainty treatment in the probability analysis of RPVHPN is similar to that of DMW probabilistic analysis. Uncertainty propagation is handled by sampling input and parameter values from selected probability distributions (with selected bounds), including correlations during each Monte Carlo realization. The sampled inputs include component geometry, operating time, RPVHPN operating temperature, welding residual stresses, and operating loading. MRP also treated uncertainties in the crack initiation model, crack growth model, flaw inspection and detection model, post-peening effects, and flaw stability model.

Sensitivity Study

MRP conducted sensitivity studies with the RPVHPN probabilistic model in order to demonstrate the relative change in the predicted results given one or more changes to modeling or input assumptions. MRP classified each sensitivity case as either a Model Sensitivity Case (in which an approximated input or model characteristic is varied) or an Inspection Scheduling Sensitivity Case (in which a controllable inspection option is varied).

Results of Probabilistic Analysis for RPVHPN

The results of the probabilistic analysis of PWSCC on a peened hot head: (a) MRP predicted that the cumulative leakage probability after peening will be reduced by a factor of approximately 5.5 relative to the unmitigated case. (b) MRP predicted that the average RPVHPN ejection frequency after peening will be reduced to 81% of the average ejection frequency of the unmitigated case.

The results of the probabilistic analysis of PWSCC on a peened cold head: (a) MRP predicted that the cumulative leakage probability after peening will be reduced by a factor of approximately 4.6 relative to the unmitigated case. (b) MRP predicted that the average RPVHPN ejection frequency after peening will be reduced to 64% of the average ejection frequency of the unmitigated case.

MRP showed that peening mitigation with proposed inspections results in an average nozzle ejection frequency of approximately 1.7×10^{-5} per reactor year or less. MRP stated that an ejection frequency of 1.7×10^{-5} will result in a core damage frequency that does not exceed the acceptance criterion contained in NRC Regulatory Guide (RG) 1.174, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis," for permanent changes in plant equipment (i.e., 1×10^{-6} events per reactor year).

In addition, the ratio of the maximum incremental RPVHPN ejection frequency to the time average nozzle ejection frequency is of an acceptable magnitude (only a factor of 3 - 4). Thus, MRP contended that the peening mitigation in combination with the proposed inspection requirements will result in an acceptably small effect of PWSCC. Furthermore, the probabilistic results show a reduced average nozzle ejection frequency with peening and the proposed inspection requirements compared to the case of no mitigation with current inspection regiment.

Lastly, cumulative probability of nozzle leakage after peening is reduced by about a factor of 5 to 8 for the case of peening mitigation compared to the no mitigation case. This demonstrates that the concern for boric acid corrosion of the RPVHPN is addressed by, and defense-in-depth is supported by, the peening and proposed inspections, which maintains the same basic intervals for periodic direct visual examinations for evidence of leakage as prior to peening.

MRP stated that its sensitivity cases show that conclusions drawn from the base case results are not highly sensitive to the precise input values used. Specifically, sensitivity cases showed minimal risk benefit for peened RPVHPNs with increased depth of the peening stress effect or with more compressive stresses at the peened surface. Sensitivity cases that model a range of bare metal visual (VE) examination frequencies indicate that performing VE examinations at an interval nominally equivalent to the examination frequency for unmitigated heads is effective in reducing the risk of nozzle ejection. MRP stated that performing VE more frequently for peened RPVHPN than for unpeened RPVHPN only provide a limited additional risk benefit for nozzle ejection. According to MRP, its sensitivity results show that there would be minimal benefit to requiring a more compressive stress effect than that specified by the performance criteria. All sensitivity cases for peened components result in a cumulative probability of leakage substantially below that of the equivalent sensitivity case for an unmitigated component. MRP noted that the probabilistic analyses presented in MRP-335R3 include the license renewal period (60 years) and subsequent license renewal period (80 years).

4.0 NRC STAFF EVALUATION

4.1 General Considerations

Based on independent research conducted by the NRC staff, which is not limited to the information contained in MRP-335R3, the NRC staff has determined the following:

1. Peening methods are currently available which, when executed in accordance with controlled procedures, are capable of imparting compressive stresses into the surface of a part without damaging the part through such mechanisms as cracking or spalling.

2. The NRC staff views the ability of the peened surface of a component to resist cracking to be a function of the compressive stresses achieved rather than the peening process employed. As a result, the NRC considered only the proposed set of input parameters in determining whether the analyses in MRP-335R3 supports the proposed inspection relaxation. The manner in which those stresses are achieved, e.g., the peening process, was not considered in this SE.

3. The NRC staff notes that the process of measuring residual stresses on the near surface of a peened component, particularly in welds, is not precise. At present there are significant differences in stress values obtained by various measurement methods and uncertainties in stress values obtained by a single method. The measurement uncertainty issue is not considered in this SE. Measurement uncertainties will need to be addressed by licensees in plant-specific relief requests for alternatives to the ASME Code inspection requirements.

4. Peening has been used on new parts in industries other than nuclear power plants as a way to reduce fatigue cracking.

5. The use of peening in the U.S. nuclear industry on safety-related components, to date, has been limited to steam generator tubes, repaired reactor vessel closure head penetration nozzles (e.g., abrasive water jet peening), and pressurizer heater sheaths. The NRC has not approved any inspection relaxation as a result of peening on these components.

6. Peening of nuclear reactor vessel internals and piping has been conducted outside the United States. However, the NRC staff is not aware of any relaxation in inspection requirements that has been authorized by international regulators in response to peening of DMWs and RPVHPNs.

7. The NRC staff finds probabilistic analyses to be useful tools in assessing changes in procedures or configurations of nuclear power plants. The NRC routinely uses probabilistic analyses in assessing structural integrity of reactor vessels and environmental fatigue degradation of piping. In each of these cases, the approach used in the probabilistic evaluation of these issues has been fully evaluated by the NRC staff and is the subject of an NRC SE or NUREG reports. Probabilistic analyses are very complex processes that require thorough verification, validation, and assessment of data input quality through sensitivity studies. The NRC staff did not evaluate the probabilistic model used in MRP-335R3 accordingly, did not base its regulatory decisions on the probabilistic analyses in MRP-335R3.

8. The NRC considered the MRP evaluation of a threshold stress for PWSCC initiation. The rationale for this threshold is described in section 2.3.4 of MRP-335R3. The MRP document states: "While it is considered that there is no firm "threshold" below which PWSCC will never occur, from a practical experience perspective a tensile stress of +20 ksi (+140 MPa) is a conservative lower bound of the stress level below which PWSCC initiation will not occur during plant lifetimes..." The NRC notes that initiation of PWSCC is a function of time, temperature, applied stress, material properties and environmental factors. While extensive testing and evaluation of service experience supports a conclusion that PWSCC initiation is unlikely when applied stresses are less than 80 percent of material yield strength, this conclusion is based on practical considerations rather than theoretical derivations. There may be combinations of materials, stress, temperature, time and environment variables, particularly at long test or operational durations, where PWSCC initiation may occur even though it is not expected. The NRC

staff use of the term "threshold" in this safety evaluation is consistent with the discussion in MRP-335R3. The "threshold" stress for PWSCC initiation is an applied surface stress below which initiation of PWSCC is unlikely for exposure durations that exceed plant operational periods.

9. Although beyond the scope of this SE, the NRC staff finds that the adequacy of the process should be demonstrated by peening mockups and by measuring residual stresses. Licensees should confirm that its peening process is performed with an acceptable set of essential variable values to ensure that the required stress and coverage parameters are met or exceeded in accordance with MRP-335R3 to demonstrate that the peening mitigation is effective. This information should be reported in plant-specific relief requests.

4.2 NRC Staff Evaluation Approach

The objective of this SE is to determine, given the peening input variables and performance criteria (e.g., area peened, effective peening depth, and compressive stresses on the peened surface), whether the analyses presented in MRP-335R3 support the requested inspection requirements. In performing this evaluation the NRC staff separately considered two questions: first, given the proposed peening parameters, will the initiation of new flaws be prevented; and second, with respect to cracks which predate peening, are the inspection intervals proposed in MRP-335R3 sufficient to maintain the level of plant safety currently achieved for non-peened components which are inspected in accordance with current regulations. In addressing both questions, the NRC staff adhered to the concepts described above, particularly that the peening process was done correctly, that full coverage was achieved, and that residual stresses and distributions proposed in MRP-335R3 are achieved (uncertainty in measurements is not considered). These issues, while important, are subject to future plant-specific review. The acceptance criteria applied to assessing the peened DMWs and RPVHPNs with inspection relaxation were reasonable, not absolute, assurance of the adequate protection of public health and safety.

Safety Implications

As a background information, PWSCC in reactor coolant system pressure boundary components can lead to the following safety issues:

1. Axial cracks in DMWs are stable even if they crack completely through wall because the maximum length of the crack is constrained to the susceptible material and the axial length of susceptible material in a DMW is much less than the length at which an axial crack could exhibit unstable crack growth. However, leakage from an axial crack can lead to boric acid corrosion of carbon and alloy steel surfaces of piping. Corrosion of low alloy steel piping surfaces adjacent to a leak can lead to a loss of coolant accident (LOCA).
2. Circumferential cracks in DMWs can grow to a size where unstable crack growth occurs, (e.g., 360 degrees in circumferential extent and 100% through wall) which would cause a LOCA.

3. Leaks from circumferential cracks in DMWs can lead to boric acid corrosion of adjacent steel surfaces of piping, which can lead to a LOCA.
4. Cracks anywhere on RPVHPNs can lead to leakage. Leakage can lead to initiation of circumferential cracks on the outside diameter surface, which can eventually lead to nozzle ejection, which would cause a LOCA.
5. Cracks anywhere on RPVHPNs can lead to leakage. Leakage can cause boric acid corrosion of nearby steel surfaces, such as the RPV head, which could cause a LOCA.

Of these five potentially safety significant effects of PWSCC, four of them, boric acid corrosion from leaking axial cracks in DMWs, boric acid corrosion from circumferential cracks in DMWs, boric acid corrosion from cracks in RPVHPNs, and outside diameter initiated circumferential cracking of RPVHPNs, involve a period of leakage during which it is possible to observe the boric acid and repair the leak prior to occurrence of boric acid corrosion severe enough to compromise the structural integrity of the reactor coolant pressure boundary. Periodic bare metal visual examinations are a means to detect leaks before the safety significant effects of severe boric acid corrosion occur. Ultrasonic examination is used to detect cracks. Cracks could grow to leaks or to unstable dimensions without exhibiting prior leakage. The combination of periodic bare metal visual examination and ultrasonic examination is used to minimize the potential for through wall leakage and rupture.

Current regulations require a combination of bare metal visual examinations and ultrasonic examinations be performed on susceptible materials to ensure PWSCC is detected and repaired or mitigated before plant safety is challenged.

Crack Initiation

The fundamental technical basis of peening is to prevent crack Initiation in DMWs and RPVHPNs. As such the NRC staff has considered the following assessment.

DMWs

MRP proposes that, once peened, DMWs will not develop new cracks because:

1. All susceptible surfaces plus a margin on each side of the DMW will be peened.
2. At room temperature without operational loading, the peening will result in compressive stresses from the DMW surface to a depth of 0.04 inches.
3. Under operating conditions, the stress at the wetted surface of the DMW will not be in tension (not more tensile than 0 ksi).

The NRC staff evaluated the basis for why crack initiation is not expected in DMWs following peening as proposed in MRP-335R3. As part of the review, the NRC staff notes the following design parameters:

1. The entire surface of susceptible material plus a margin will be peened,
2. Crack initiation is a surface phenomenon,

3. The wetted surface of the DMW will be inspected to identify any surface breaking flaws or significant fabrication defects in the DMW, and
4. At operating pressure, the surface stress will be more compressive (0 ksi) than MRP-335R3 proposed lower bound stress for PWSCC initiation (20 ksi in tension).

The NRC staff notes that the peening surface condition under operating conditions of 0 ksi is consistent with the NRC previously approved surface stress condition of Paragraph I-1 of Appendix I to ASME Code Case N-770-1, which is mandated by 10 CFR 50.55a(g)(6)(ii)(F) for the surface stress condition required for the Mechanical Stress Improvement Process (MSIP)™. The NRC staff notes that the MSIP™ process typically maintains a compressive stress field under operating conditions for approximately 50% of the weld depth.

The NRC also reviewed the MRP's deterministic analysis and performed independent calculations to determine if any missed PWSCC or fabrication flaws in the DMW from which PWSCC cracks could initiate, could threaten the structural integrity or leak tightness of the DMW. In considering such situations the NRC staff determined that the use of eddy current examinations in combination with volumetric examinations at the time of peening and in subsequent inspections provide reasonable assurance that a flaw would be detected at the time of peening or, if not, it would be detected prior to affecting plant safety, i.e., the loss of structural integrity. Therefore, given the design parameters above, the NRC staff finds that once a DMW is peened, there is reasonable assurance that cracking should not initiate. However, if initiation does occur, the inspections, identified in this SE, will provide reasonable assurance of structural integrity and leak tightness for peened DMW.

RPVHPNs

MRP proposes that, once peened, RPVHPN components will not develop new PWSCC cracks because:

1. All susceptible surfaces of the RPVHPN and J-groove weld will be peened.
2. At room temperature, the peening will result in compressive stresses from the outside diameter surface to a depth of 0.04 inches of the RPVHPN and J-groove weld, and from the inside diameter surface to a depth of 0.01 inch of the RPVHPN.
3. Under operating conditions the stress at the wetted surface of the RPVHPN will not exceed 10 ksi (tension) which is less than the MRP-335R3 proposed limit for PWSCC crack initiation of 20 ksi. Section 5.2.1 of MRP-335R3 states that "the peening compressive stress at the RPVHPN inside diameter surface is set to result in a net tensile stress of 10 ksi, and a residual stress value that results in a net stress of 0 ksi is assumed for the peened surface of the RPVHPN outside diameter and J-groove weld because the operating stress in those regions is small."

The NRC staff evaluated the basis for why crack initiation is not expected in RPVHPNs following peening. As part of the review, the NRC staff notes the following design parameters:

1. The inside and outside diameter surfaces of RPVHPN and J-groove weld that are susceptible to PWSCC will be peened,

2. Crack initiation is a surface phenomenon and,
3. At steady state operating conditions, the surface stress will be more compressive (10 ksi tension) than the MRP-335R3 proposed threshold for PWSCC crack initiation, 20 ksi tension. As stated previously, the threshold is the level of applied surface stress below which initiation of PWSCC is unlikely during RPVHPN lifetime.

The NRC notes three significant differences between the peening parameters for the DMW versus RPVHPN. First, a surface examination is not required on the RPVHPN and J-groove weld while a surface examination is required on the DMW. Second, a 10 ksi tensile steady state operating stress condition is permitted on the RPVHPN while 0 ksi is the maximum permitted on the DMW. Finally, for the RPVHPN, peening is to be performed on highly stressed alloy 600, 82 and 182 surfaces, with lower stressed surfaces remaining unpeened, while the entire surface of the DMW plus 0.25 inches beyond will be peened.

As the peening coverage does not cover the entire RPVHPN inside diameter and outside diameter region associated with PWSCC and as there are no surface examinations of the surfaces prior to peening, it is not possible to obtain absolute assurance that new cracks will not initiate. The only new initiations that are postulated to occur would be located at areas where subsurface original fabrication features such as hot tears and lack of fusion are located near the surface. The only ones of these hypothetical defects that can initiate are those that have not already initiated and grown into PWSCC during prior periods of unpeened service time. Their initiation requires a subcritical crack growth mechanism other than PWSCC (fatigue is a possibility) to cause them to propagate to the component surface where, once in contact with the reactor coolant, cracks would be initiated based on the PWSCC degradation mechanism.

The NRC reviewed the proposed stress threshold for PWSCC crack initiation provided in MRP-335R3. The topical report cited technical references describing multiple independent test programs to investigate the applied stress necessary to permit initiation of PWSCC. In all but one cited test program PWSCC did not initiate below the yield strength of the material. In that one set of tests, initiation occurred in two exposures at 360°C between 65,000-85,000 hours at a stress ratio as low as 0.78 between the applied stress and the test temperature yield stress. If these data are adjusted to account for lower temperature operation in service, the test exposures equate to greater than 222,000 hours of operation at hot leg temperatures.

The MRP report evaluated typical minimum yield strength values for Alloys 600, 82 and 182 and determined 30 ksi was a conservative minimum value. The ASME Code minimum specified yield strength is 35 ksi. The at-temperature yield strength is lower than the room temperature yield strength. The report discussed the ASME and other methods for estimating higher temperature yield strength using room temperature test data and concluded that the yield strength at 325°C would be approximately 80% of the room temperature yield strength.

The NRC staff used the information in the MRP report to calculate a conservative estimate of the minimum applied stress to support initiation (i.e., the threshold stress, the surface stress below which PWSCC is unexpected to occur during the RPVHPN lifetime). Using the ASME Code minimum specified of 35 ksi for minimum yield strength, a factor of 80% to convert room temperature yield strength to yield at 325°C and the 0.78 ratio between yield and applied stress in the test samples that exhibited PWSCC with the lowest ratio of applied to yield stress, the NRC estimates specimens exposed with less than approximately 22 ksi tensile stress at the surface will not initiate PWSCC cracks. This is consistent with past NRC determinations. For example, in NRC letter to Palo Verde Nuclear Generating Station Unit 1, dated May 5, 2004 (ADAMS Accession No. ML041260228) and NRC letter to Palo Verde Nuclear Generating Station Unit 2, dated February 23, 2005 (ADAMS Accession No. ML050540726) regarding reactor vessel head inspections, the NRC states: "The stress level of 20 ksi is a conservative value below which PWSCC initiation is unlikely." Additionally, NRC First Revised Order EA-03-009, specified the need to perform inspections on "... all RPV head penetration nozzle surfaces below the J-groove weld that have an operating stress level (including all residual and normal operation stresses) of 20 ksi tension and greater..." Since the proposed performance criterion of +10 ksi is lower than the threshold for PWSCC initiation, the NRC finds that the performance criterion of 10 ksi should prevent initiation of new cracks. The NRC staff is performing confirmatory research to validate that PWSCC initiation does not occur on peened specimens with surface stress of +10 ksi.

One method of assessing the safety implications of reducing crack initiation rates would be to perform probabilistic fracture mechanics evaluations to calculate the effect of reduced initiation on future cracking, degradation, and operation loading. MRP did perform a probabilistic fracture mechanics analysis but as stated previously, the NRC did not perform a detailed review of that analysis. However, it is possible to perform a qualitative assessment of the impact of applying peening on future initiation rates. Comparing crack initiation on unpeened surfaces, where crack initiation is equally likely anywhere, with crack initiation on peened surfaces, where crack initiation is only possible at these special hypothetical spots, ratioing the susceptible surface areas would be an appropriate method of assessing the potential number of expected initiations following peening. Given the very large differences in susceptible surface areas, the NRC concludes that peening will substantially reduce crack initiation. As will be discussed below, this reduction in the rate of crack initiation can be qualitatively assessed to reduce plant risk (i.e., improve plant safety). Alternatively, the reduction in the rate of crack initiation can be combined with an extension in inspection intervals in a manner which can be qualitatively assessed so as to show that the safety of the plant is improved from the current situation (i.e., unpeened components with current inspection intervals).

Despite the low probability of a crack initiating post-peening, the NRC staff considered the implications of the initiation of such a crack from the surface of a J-groove weld or RPVHPN. The NRC staff noted that, at the present, the J-groove weld cannot be volumetrically inspected.

In considering the implications of a crack which grows within the J-groove weld, the NRC staff notes that the crack will eventually reach the annulus between the nozzle and the reactor head. Such a crack will not be detected by volumetric examinations and will result in a leak. The NRC staff further notes that numerous means are available to detect significant leakage from these locations, such as, reactor coolant inventory balances, boric acid program walkdowns, radiation monitoring, and containment air cooler performance. The primary means for identifying leakage from this location, due primarily to the low volume of leakage, is bare metal visual examinations. MRP-335R3 does require bare metal visual examinations of peened RPVHPN. However, the

NRC believes that, due at least in part to the above scenario, additional bare metal visual examinations are appropriate and has imposed Condition 5.1 to increase the proposed frequency of bare metal visual examinations above both the levels proposed in MRP-335R3 and above the current regulatory requirements.

In considering the implications of a crack growing into the RPVHPN, the NRC staff notes that it will become detectible by way of volumetric examinations when the crack enters the wall thickness of the RPVHPN to a sufficient depth. The NRC staff also notes that such a crack will typically be oriented axially with respect to the nozzle. Such a crack could eventually grow through wall and elongate to the point where it intersects the annulus between the nozzle and the reactor vessel closure head. As proposed in MRP-335R3, during this growth period the nozzle would be subject to volumetric inspection at 10-year intervals. These inspections would be capable of identifying the crack if it is of sufficient size in the nozzle material. Should such a crack not be identified prior to reaching the annulus, a leak would result. As mentioned for the case in which the crack remains in the J-groove weld, a leak in the annulus is subject to detection by a wide variety of means and is specifically the subject of bare metal visual examinations as imposed by Condition 5.1.

The NRC staff further notes that the allowance of a 10 ksi tensile stress on the surface with increasing tensile stress into the thickness of the J-groove weld or RPVHPN provides no benefit to stop crack growth through these materials. The allowance of any tensile stress would allow growth of any potential missed existing cracks or cracks initiating from surface flaws. However, the allowed residual stress profile under steady state operating conditions of MRP-335R3 could allow a wider range of tensile stresses, even within the area of peening effectiveness identified in MRP-335R3. The NRC considered these aspects when evaluating the follow-up and inservice inspections for the RPVHPN.

Current regulatory requirements in 10 CFR 50.55a for unpeened RPVHPNs establish inspection periodicities and modalities (techniques) that ensure the probability of PWSCC crack growth to a through wall flaw size is sufficiently low to provide adequate assurance of structural integrity. The NRC considered the qualification and testing information on peening performance provided in the deterministic evaluations in MRP-335R3 and concluded that peened RPVHPNs will have lower probability of crack initiation as compared to unpeened RPVHPNs. The probability of PWSCC initiation on peened RPVHPNs will be lower because the potential sites for crack initiation will have surface stresses reduced by peening to a level below the threshold for crack initiation. The threshold represents the surface stress below which PWSCC is unexpected to occur during the RPVHPN lifetime. The reduction in crack initiation will reduce the probability of through wall cracking because when fewer cracks initiate, fewer cracks can grow through wall. MRP-335R3 states that two RPVHPNs, one with peened penetrations and one with no peening, subjected to the same inspections schedules, will result in different levels of safety. The peened RPVHPN would be more safe (has less frequent through wall cracks) than the unpeened case. The NRC staff finds that the peened RPVHPN will have a lower probability of failure than unpeened RPVHPN because the likelihood of crack initiation is lower in the peened RPVHPN than the unpeened RPVHPN.

The MRP seeks to establish alternative inspection schedules with longer inspection periods for peened RPVHPNs such that a peened RPVHPN subjected to the alternative schedule would have a probability of through wall cracking lower than the probability of through wall cracking that would be expected for an unpeened RPVHPN subjected to current regulatory requirements for inspection periodicity. MRP-335R3 uses a series of deterministic and probabilistic calculations to quantify the relationship among peening, inspection frequency and modality, and through wall cracking probability. The NRC reviewed the deterministic calculations in Section 5 of MRP-335R3. The NRC considered insights provided in the probabilistic analyses described in Appendix B of MRP-335R3. The NRC qualitatively considered the deterministic and probabilistic information and, combined with an understanding of the relationship between peening and a reduction in through wall cracking probability due to a reduction in surface stress, concluded that a peened RPVHPN with proposed inspection intervals could have the same or improved level of assurance of structural integrity as an unpeened head subjected to current regulatory requirements.

Given the design parameters above for RPVHPN and associated J-groove welds, the NRC finds there is reasonable assurance that crack initiation will be significantly reduced. However, the NRC does not find that crack initiation or growth could be entirely mitigated through peening such that there would be absolute assurance of no new cracking. Therefore, the NRC staff established conditions as shown in Section 5 of this SE, which when implemented along with the requirements of MRP-335R3 provide reasonable assurance of the structural integrity of the RPVHPN.

Inspections for Postulated Preexisting Cracks

The NRC staff evaluated the analyses presented in MRP-335R3 in support of the adequacy of the proposed inspection intervals. For each analysis type (DMW deterministic, DMW probabilistic, RPVHPNs deterministic, and RPVHPNs probabilistic) the NRC staff evaluated each significant topic of the analysis to determine its adherence to accepted standards and the quality of the data used. When applicable, the NRC staff also considered the sufficiency of MRP's sensitivity studies. Following the evaluation of each analysis topic, the NRC staff considered the effect of any shortcomings identified in each analysis topic on the overall analysis results.

In addition to the input variables and analyses provided, the NRC noted that MRP-335R3 contains additional examination requirements which the NRC considers in its evaluation. To determine the acceptability of each of these requirements, the NRC considered each requirement and its implications to the analyses conducted, the overall level of quality and safety of the peened components, and current regulatory requirements as contained in 10 CFR 50.55a, as appropriate.

The NRC staff established conditions as the final aspect of its evaluation. In previous phases of the NRC staff's evaluation, input variables had been considered fixed. In this portion of the evaluation, if the NRC staff discovered a deficiency in MRP's analysis to support the proposed inspection requirements, the NRC staff conditioned the MRP requirement, or the proposed inspection intervals, as appropriate, to achieve reasonable assurance of structural integrity of the peened components from one inspection to the next.

4.3 Probabilistic Analysis—DMW and RPVHPN

While the NRC staff regularly uses probabilistic fracture mechanics calculations to make regulatory decisions, this is only done after significant verification and validation on the probabilistic fracture mechanics computer codes and inputs. As an example, the NRC staff used the FAVOR code to develop the alternate pressurized thermal shock rules found in 10 CFR 50.61a. The FAVOR code has been extensively verified and validated by the NRC staff, and several NUREG reports describe the FAVOR code and its use. Additionally, since 2013, the NRC staff has collaborated with industry to develop the xLPR (Extremely Low Probability of Rupture) code which is a probabilistic fracture mechanics tool to estimate the frequency of failure for reactor coolant system piping. This program has some similarity to the probabilistic analyses performed for MRP-335R3 but remains under development. The NRC staff has not performed verification and validation of the probabilistic fracture mechanics calculations in MRP-355R3. Such work would take significant time and resources to perform and document.

Nevertheless, the NRC staff has reviewed MRP's probabilistic analysis as part of supporting the proposed inspection requirements. The NRC staff has identified several concerns regarding general uncertainties and basis for input parameters in the probabilistic analyses in MRP-335R3. The NRC staff's concerns limited, but did not preclude, its ability to rely upon the probabilistic analysis to review MRP's proposed inspection requirements. Therefore, the NRC staff used MRP's probabilistic analyses to provide information for MRP's deterministic analysis in the review of MRP proposed inspection requirements.

The NRC staff has identified inputs to MRP's probabilistic fracture mechanics analyses that contain significant uncertainties that can affect the final outcome of the analysis. The NRC staff has raised questions on some of these inputs, such as on the flaw initiation model and the weld residual stress profiles in the NRC's requests for additional information for previous version of MRP-335. The NRC staff determines that several variables, such as "α" in the crack growth equation, with very large uncertainties, can significantly alter the conclusions if the data used are nearer to one end of the distribution rather than another. The NRC staff determined that further uncertainty analyses would need to be conducted to identify models and input distributions that would most benefit from additional data collection or testing.

The NRC staff was able to use the results of both MRP and NRC deterministic analyses to evaluate the peening application. The NRC staff, did not review in detail the probabilistic fracture mechanics calculations in MRP-335R3. However, the NRC staff used the probabilistic results in combination with the deterministic analyses to confirm reasonable assurance of MRP's proposed inspection requirements, as no instances of significant failure were identified through the MRP's analysis.

MRP requested the NRC to complete the review of MRP-335R3 in a timely manner because some licensees plan to apply peening at their plants in year 2016. MRP proposed review schedule precludes the NRC from a detailed review of MRP's probabilistic analysis because it would take NRC significant time and resources to adequately review MRP's probabilistic fracture mechanics analysis. The NRC focused its review of MRP-335R3 on the deterministic analysis. The NRC staff may review the probabilistic analysis in MRP-335R3 at some future date.

4.4 Deterministic Analysis—DMW

DMW and Crack Configuration

The NRC staff finds that the physical parameters (dimensions) and operating conditions (pressure and temperature) used in the model of the DMW are representative of pressurized water reactor plants, but are not bounding for either hot or cold leg DMWs.

Peening Depth

The NRC staff finds that the peening depth used in MRP's deterministic analysis of DWM is consistent with the performance criteria specified in Section 4 of MRP-335R3 and, therefore, is acceptable.

Peening Coverage

The NRC staff notes that the required peening coverage for a DMW is the full area of the susceptible material along the entire wetted surface under steady-state operation, including the weld, butter, and base material. MRP requires that the peening coverage be extended at least 0.25 inches beyond the area of susceptible material. The NRC staff finds that the peening coverage for the DMW is acceptable because it covers the susceptible material, including 0.25 inches of non-susceptible base material.

Deterministic Time-to-Failure Analyses for DMW

Tables 5-5 to 5-11 of MRP-335R3 provide comparisons of the time to failure for DMW. This analysis is based on a variety of postulated crack growth rates, initial flaw sizes and residual stresses.

The deterministic calculations performed in MRP-335R3 used a 100% probability of detection (POD) for 0.04 inches deep flaws, based on the use of eddy current testing in accordance with the ASME Code, Section XI, Appendix IV. The NRC staff does not consider a 100% POD for PWSCC under field conditions (rough inside diameter surfaces, irregular geometries, etc.) in MRP's calculations conservative. The NRC staff noted that the weld residual stresses used in the deterministic calculations in MRP-335R3 varied in magnitude but not in overall stress profile, thereby, reducing their usefulness in the flaw analysis. Additionally, the assumed flaws in MRP-335R3 are smaller than or equal to the penetration depth of the peening method.

The NRC staff performed an independent analysis using various weld residual stress profiles, including calculated axial and hoop stresses for components with and without safe ends, and with a variety of inner-diameter repair depths. Based on its independent calculations, the NRC staff finds that the proposed inspection requirements for the DMW for cold leg welds are acceptable. The NRC staff finds that the proposed inspection requirements for the hot leg DMWs unacceptable. For the hot leg DMWs, the NRC calculations support the timing of the first follow-up examination to follow the schedule described in ASME Code Case N-770-1, i.e. on the second refueling outage for hot leg temperatures above 625° F and by the fifth year for hot leg temperatures less than or equal to 625° F. This is reflected in Condition 5.3. In both cases the second follow-up examination would occur within ten years after peening.

4.5 Deterministic Analysis—RPVHPN

RPVHPN Crack Configuration

The NRC staff finds that the RPVHPN modeled in the deterministic analysis is consistent with the relevant design and fabrication of the RPVHPN at pressurized water reactor plants. The NRC staff also finds that MRP-335R3 has considered crack configurations and locations that are consistent with the currently accepted practice of analyzing the initiation and growth of cracks associated with the RPVHPN and J-groove weld. Therefore, the NRC staff finds the configuration of the RPVHPNs and cracks modeled in the deterministic analysis acceptable.

Peening Depth and Required Stresses

MRP-335R3 proposes that, following peening, the depth to which compression will exist in the inside diameter surface of the RPVHPNs is 0.01 inches. MRP-335R3 also proposes that, following peening, compression will exist in the J-groove weld and the outer diameter surface of the RPVHPN to a depth of 0.04 inches. Section 4.3 of MRP-335R3 stated that the operating stress plus the residual stress for the peened RPVHPN (inside and outside diameter surfaces) and J-groove weld shall not exceed 10 ksi (tension). However, the NRC staff finds that MRP's flaw analysis of RPVHPN in Section 5 of MRP-335R3 used a value for stress at operating conditions on RPVHNs of 0 ksi on the outside diameter and J-groove weld surfaces, yet the performance criteria specified in Section 4.3 of MRP-335R3 indicate the stress at operating conditions may be up to +10 ksi for the inside and outside diameter surfaces of the RPVHPN and J-groove weld. In addition, the period for small flaws to grow to 10% through-wall or leakage, as shown in the RPVHPN and the J-groove weld summary tables in Section 5 of MRP-335R3, do not seem to be consistent with operating stress profiles that range from 10 ksi tension on the inside diameter to a tensile stress of 30 to 60 ksi at depths of 0.01 to 0.04-inches. The NRC staff finds that MRP's flaw analysis for the RPVHPN is inconsistent with the performance criteria in Section 4 of MRP-335R3. Therefore, the NRC establishes Conditions 5.1 and 5.4 to address this issue.

Peening Coverage

The NRC staff finds that the peening coverage is adequate because Figures 4-1 through 4-4 of MRP-335R3 show the susceptible surface areas of the RPVHPN and J-groove weld that will be peened.

Section 2.3.3 of MRP-335R3 states that the proposed peening coverage zone for the RPVHPN covers surfaces that are susceptible to PWSCC initiation. MRP recognized that the proposed peening coverage is in contrast to the inspection coverage zone per ASME Code Case N-729-1. MRP explained that the difference between the proposed peening coverage and the inspection areas per ASME Code Case N-729-1 is the nozzle areas below the J-groove weld that are not susceptible to PWSCC initiation and that are not part of the pressure boundary. MRP noted that the proposed peening coverage required for RPVHPNs was established using the stress results in MRP-95R1 and the stress limit of +20 ksi (tensile). The NRC staff finds acceptable that the limited RPVHPN areas below the J-groove weld are not peened because those areas are not susceptible to crack initiation and are not part of the RCS pressure boundary. The NRC staff noted that even if a flaw is developed in the unpeened RPVHPN areas and grow into the peened areas, the flaw growth may be limited because the peened areas will have a 10 ksi stress to resist such growth. The 10 ksi stress state may delay the flaw growth. Therefore, the NRC finds that the proposed peening coverage for RPVHPN and J-groove weld is acceptable.

Deterministic Time-to-Failure Analyses for RPVHPN

Tables 5-13 to 5-19 of MRP-335R3 provide comparisons of the time to failure for the peened RPVHPN. MRP's deterministic analyses were based on a variety of postulated crack growth rates, initial flaw sizes and residual stress distributions. The NRC staff found the postulated flaw sizes and crack growth rates used to be both reasonably understood and consistent with the objectives of the analysis. The MRP used the deterministic analyses to demonstrate that there were very limited cases in which a hypothetical crack, missed during the pre-peening inspection or below NDE detectability limits, would grow to leakage under the proposed MRP-335R3 performance criteria.

The NRC staff also evaluated the pre-peening stress profiles for the RPVHPN and, to the extent possible, the post-peening stress profiles. As described below, the NRC staff found these stress profiles to be questionable for several reasons and the variability between high and low stress conditions was not sufficiently large to bound available data.

Of particular note was the NRC staff's comparison of the residual stress profiles in Figures 5-35 through 5-38 of MRP-335R3 with the residual stress profiles of MRP-95, Revision 1, "Generic Evaluation of Examination Coverage Requirements for Reactor Pressure Vessel Head Penetration Nozzles." Appendix A of MRP-95R1 provides the residual stress profiles for four limiting plants. The stress profiles in Figures 5-35 through 5-38 present the mean and plus one standard deviation and minus one standard deviation stress profiles calculated using a finite element analysis. The variability of the stress profiles from inside to outside diameter of the RPVHPN are significantly more varied in MRP-95R1 than those used in Figures 5-35 through 5-38 in part because MRP-95R1 reported bounding profiles while Figures 5-35 and 5-38 used a single standard deviation level for the limiting analyses. As such, the NRC staff finds the weld residual stress profiles for the deterministic calculations in MRP-335R3 were neither high enough nor low enough to bound the stress profiles of the peened RPVHPN.

The NRC staff performed a series of independent calculations of a hypothetical flaw of 0.01 inch based on 10 ksi tension at the surface of the component on the inside diameter surface of

RPVHPNs under operating conditions, the residual stress value will increase sharply with depth, the depth affected by peening is 0.01 inches, and the residual stress not affected by peening is approximately 20 to 70 ksi in tension. The NRC staff found that peening, in accordance with the performance criteria of MRP-335R3, may not prevent flaw growth and could allow flaws to grow through-wall. As a defense-in-depth measure, NRC staff finds that, in addition to the proposed inspections in MRP-335R3 (follow-up inspection at the second refueling outage), for peened RPVHPN and associated J-groove welds that, at the time of peening, have experienced < 8 effective degradation years (EDYs), and that contained flaws prior to peening, should also be examined in the first refueling outage following the peening application as specified in Condition 5.4.

4.6 NRC Review of Proposed Inspection Requirements

4.6.1 Pre-Peening Examinations

DMW

MRP-335R3 proposed to perform ultrasonic examination and eddy current testing on the inside diameter surface of DMW. The NRC staff evaluated these examinations and finds them to be acceptable because the proposed pre-peening examination requirement is consistent with ASME Code Case N-770-1 and 10 CFR 50.55a(g)(6)(ii)(F).

RPVHPN

MRP-335R3 proposed that pre-peening examinations for RPVHPNs consist of volumetric examination of each nozzle, or surface examination of nozzle inside diameter surface and wetted nozzle outside diameter surface and J-groove weld; and a demonstrated volumetric or surface leak path assessment for the J-groove weld. The NRC staff evaluated these examinations and finds them to be acceptable because the proposed pre-peening examination requirements are consistent with ASME Code Case N-729-1 and 10 CFR 50.55a(g)(6)(ii)(D).

4.6.2 Follow-up Examinations

DMWs

MRP proposed a volumetric and surface examination of all peened hot leg DMWs within 5 years and a second examination within 10 years following peening application. MRP proposed a volumetric and surface examination of all peened cold leg DMWs once within 10 years of peening but no sooner than the third refueling outage following peening application. As previously described, the NRC staff finds that the follow-up examinations for cold leg welds are acceptable as proposed. Also as previously described, the NRC staff finds that the follow-up examinations for hot leg welds are not acceptable. The NRC staff has established Condition 5.3 to adjust the follow-up examination frequency of hot leg DMWs so as to provide reasonable assurance of structural integrity of these welds. These findings are based on the NRC staff's evaluation which finds that, given that the hot leg DMWs are peened and inspected, there will be at least an equal level of safety when compared to the unpeened DMWs inspected per current regulations.

RPVHPN

MRP proposed that for RPVHPNs that had experienced equal to or greater than 8 total effective degradation years (EDY) at the time of peening, a volumetric examination or surface examination of nozzles; and a demonstrated volumetric or surface leak path assessment be performed in the first and second refueling outage after peening. The NRC staff finds that the proposed examination for RPVHPN ≥ 8 EDY during the first and second refueling outage after peening is acceptable because this inspection frequency is adequate to detect potential flaws, should they occur, after peening on RPVHPNs.

For RPVHPNs that have experienced less than 8 EDY at the time of peening, MRP proposed a volumetric examination or surface examination; and a demonstrated volumetric or surface leak path assessment to be performed in the second refueling outage after peening. The NRC staff does not object to the proposed inspection requirement except that the NRC staff determines that a separate examination schedule should be implemented for this category of RPVHPNs (i.e., < 8 EDY) that contains pre-existing flaws.

For RPVHPNs and associated J-groove welds which, at the time of peening, have experienced < 8 EDYs and do not contain pre-existing flaws, the NRC staff finds that the proposed follow-up examination in the second refueling outage after peening is acceptable. This is because based on the NRC staff's independent calculation, a flaw in the cold head (RPVHPN < 8 EDY) would not grow to a detectable size until second refueling outage after peening application.

For RPVHPN < 8 EDY containing pre-existing flaws, the NRC staff finds that the proposed follow-up examinations scheduled for the second refueling outage is inadequate. A RPVHPN that contains pre-existing flaw(s) needs to be examined more frequently than a RPVHPN without pre-existing flaws. To provide an equivalent level of safety to the current situation (i.e., inspect unpeened RPVHPNs per current regulations), the NRC staff finds that RPVHPNs and associated J-groove welds which, at the time of peening, have experienced < 8 EDYs and contain pre-existing flaws, must be inspected in the first and second refueling outage after peening as indicated in Condition 5.4.

4.6.3 ISI Examinations

DMWs

For ISI examinations, MRP proposed that a volumetric and surface examination (eddy current) be performed on hot leg and cold leg DMWs once every 10 years beginning 10 years after peening application. The NRC staff finds that the proposed ISI examinations for DMWs are acceptable because, as described above, there is reasonable assurance that new PWSCC cracks will not likely to initiate following peening and, based on NRC staff calculations, preexisting cracks which have not already been identified by the time ISI examinations begin will not grow from an undetectable size to through wall in less than 10 years.

RPVHPN

For the ISI examination, MRP proposed a volumetric or surface examination of all peened RPVHPNs and a demonstrated volumetric or surface leak path assessment be performed each 10-year ISI interval beginning 10 years after peening application. In addition, MRP proposed a bare metal visual examination and VT-2 examination be performed on all RPVHPNs as specified in Table 3 of this SE. The NRC staff finds that the proposed volumetric examinations are acceptable because they provide: defense in depth for the potential that a new PWSCC crack would initiate post-peening; crack detection capability for slow growing flaws which originate in the inspectable areas of the nozzle and were not identified in the follow-up examinations; and potential identification of cracks which originate in the uninspectable areas of the J-groove weld and grow into inspectable area of the nozzle.

The NRC staff finds that the proposed bare metal visual examinations for the RPVHPN are not acceptable. Due to the fact that the J-groove weld is not volumetrically inspectable, under both the current situation (no peening) and the proposed situation (peening) the bare metal visual examination is relied upon to identify cracking, which can originate and remain in uninspectable areas of the J-groove weld before significant corrosion of the head or nozzle ejection occur. The NRC staff has determined that in order to provide reasonable assurance of structural integrity of peened RPVHPN, it is necessary to perform bare metal visual examinations for all peened RPVHPNs every refueling outage. The NRC staff has created Condition 5.1 to address this issue.

Discovery of Cracks and/or Leakage Post-Peening

MRP-335R3 acknowledges that when peening is performed there may be some preexisting cracks that will grow from a size which is undetectable at the time of peening to a detectable size either within the time period of the follow-up examinations or, for slow growing cracks, during the period of ISI examinations. MRP-335R3 also acknowledges that there are very rare instances in which the proposed inspections may not identify a crack prior to leakage. The NRC staff finds MRP's assessment to be reasonable. However, the NRC staff notes that the discovery of a crack or leakage post-peening could indicate that the peening process was not effective. As a result, the NRC staff has a vested interest in ensuring that an adequate investigation into the crack or leak is conducted and that the appropriate information is communicated to the NRC in a timely manner. To that end, the NRC has established Condition 5.2. Furthermore, the NRC staff has determined that the peened DMW or RPVHN in which the flaw was identified shall be inspected in accordance with applicable current regulations (ASME Code Cases N-770-1 or N-729-1) or until a new alternative to the current regulation for that specific RPVHPN or DMW has been authorized by the NRC staff via a relief request as specified in Condition 5.2.

5.0 Conditions

As a compensating measure, the NRC staff imposes the following conditions for those licensees that wish to cite MRP-335R3 in plant-specific relief requests to deviate from the current regulatory inspection requirements for peened DMWs and RPVHPNs. The NRC authorized inspection requirements for peened DMWs and RPVHPNs are specified in Table 4 of this SE.

5.1 The bare metal visual examinations of all peened RPVHPNs and J-groove welds must be performed every refueling outage.

5.2 If a wetted surface-connected flaw, an unacceptable flaw based on the ASME Code, Section XI, or unacceptable flaw growth is observed in a peened DMW, RPVHPN, or J-groove weld, (a) a report summarizing the evaluation, including inputs, methodologies, assumptions, extent of conditions, and causes of the new flaw, unacceptable flaw, or flaw growth, must be submitted to the NRC prior to the plant entering into Mode 4. (b) A sample inspection of the peened components in the population must be performed to assess the extent of condition. (c) A root cause analysis report must be submitted to the NRC within six months of the discovery. (d) The inspection relaxation in MRP-335R3 is no longer applicable to the affected component. The affected component shall be inspected in accordance with the requirements of 10 CFR 50.55a, unless an alternative is authorized.

5.3 The follow-up inspection for peened hot leg DMWs must be performed on the following schedule: (a) For hot leg DMWs above 625°F, perform a volumetric examination and a surface examination on the second refueling outage after the application of peening and a second examination within 10 years following the application of peening. (b) For hot leg DMWs equal to or less than 625°F, perform a volumetric examination and a surface examination within 5 years following the application of peening and a second examination within 10 years following the application of peening.

5.4 In addition to the proposed follow-up examinations in the second refueling outage after peening, RPVHPNs and associated J-groove welds which, at the time of peening, have experienced < 8 EDYs and contain flaws, shall also be inspected in the first refueling outage after peening.

Practical Considerations

The information contained in this section is beyond the scope of this review and, therefore, was not considered in assessing the acceptability of MRP-335R3. However, this information is of significant interest to the NRC and may be of value to licensees preparing plant-specific relief requests to take advantage of inspection relaxation provided in MRP-335R3. This SE makes numerous assumptions regarding the process by which peening is conducted and qualified. If any of the assumptions below are not met, the use of MRP-335R3 and associated NRC SE are not permitted. Although not designed to be exhaustive, a list of issues significant to the NRC follows.

Peening Coverage – the extent to which peening must cover the areas of interest is specified in MRP-335R3. This SE assumes that these coverage areas are met. It is necessary that the required levels of surface compression are achieved in all areas for which coverage is required.

Residual Stresses at End of Plant Life – To use MRP-335R3 and this SE, it is necessary that the prescribed beneficial surface stresses be present at the end of plant life (i.e., the stresses that will prevent crack initiation and, to certain extent, minimize crack growth). The NRC notes that residual stresses resulting from peening degrade with time at temperature and due to thermal cycles. For this SE, the NRC has assumed that the beneficial stresses proposed will be present at the end of plant life.

Uncertainty of Residual Stress Measurements – For the purposes of this SE, the NRC staff has assumed that the precise residual stress measurement specified will be achieved. The NRC staff is aware of a substantial body of data which indicates that there is considerable uncertainty in residual stress measurements. In future plant-specific proposed alternative to ASME Code inspection requirements the licensee needs to address this uncertainty. As an example, if the performance criteria is a surface stress of 10 ksi under operating conditions, the licensee should consider the uncertainties associated with both the residual stress measurements and calculations to ensure compliance.

Use of X-Ray Diffraction to Determine Residual Stresses – The NRC staff is aware of substantial data which indicates that X-Ray diffraction has significant uncertainties associated in its measurements of surface residual stresses in welds. The licensee needs to address this issue in future plant-specific alternatives to the ASME Code inspection requirements for the peened DMWs and RPVHPNs.

6.0 CONCLUSION

The NRC staff finds that MRP-335R3 has adequately described the affected components, processes for peening, the supporting analyses of the peening application, testing used to verify the effectiveness of peening, and the proposed inspection requirements of peened components. The NRC staff also finds that MRP has demonstrated that there is a beneficial effect from peening on the residual stress in the DMW and RPVHPN. MRP has demonstrated by mockup testing as shown in MRP-267, Revision 1 and analyses in MRP-335R3 that the peening application will achieve a certain post-peening stress profile to minimize PWSCC initiation.

Based on information provided in MRP-335R3, and operating experience such as shot peening applied to steam generator tubes and abrasive water jet machining (peening) applied to repaired RPVHPNs, the NRC staff finds that peening application is a viable mitigation to minimize PWSCC initiation.

However, the NRC staff had questions regarding the details of the peening application, such as the adequacy of the post-peening stress field, the compression stress depth, and the potential for the small flaws that are not detected before peening that may grow after peening. The NRC staff finds that, given the input variables proposed in MRP-335R3, the analyses provided do not fully support the inspection intervals proposed in MRP-335R3. Therefore, the NRC staff has imposed conditions to ensure that the proposed inspection requirements in MRP-335R3 will provide adequate monitoring of the peened DMWs and RPVHPNs between required inspections.

The NRC staff concludes that the peening application, in combination with the proposed inspection requirements in MRP-335R3 and conditions imposed in this SE, will provide reasonable assurance of the adequate protection of public health and safety.

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Date: To be added in final SE

Table 1 MRP Proposed Performance Criteria (key criteria)

Affected Components	**Operating Condition**			
	Peened Area	**Depth of Effect**	**Stress at Peened Surface**	**Stress At Peened Depth**
Hot Leg DMW	full area of the susceptible material + 0.25 inches beyond susceptible material	Minimum nominal depth of 0.04 inch	Residual stress plus normal operating stress shall be < 0 ksi	Unspecified, tensile stresses allowed
Cold Leg DMW	full area of the susceptible material + 0.25 inches beyond susceptible material	Minimum nominal depth of 0.04 inch	Residual stress plus normal operating stress shall be < 0 ksi	Unspecified, tensile stresses allowed
Hot RPVHPN Head				
OD	Peened area defined in Figures 4-1 through 4-4 of MRP-335R3	0.04 inch	Residual stress plus normal operating stress < +10 ksi	Unspecified, tensile stresses allowed
ID		0.01 inch		Unspecified, tensile stresses allowed
J-groove weld		0.04 inch		Unspecified, tensile stresses allowed
Cold RPVHPN Head				
OD	Peened area defined in Figures 4-1 through 4-4 of MRP-335R3	0.04 inch	Residual stress plus normal operating stress < +10 ksi	Unspecified, tensile stresses allowed
ID		0.01 inch		Unspecified, tensile stresses allowed
J-groove weld		0.04 inch		Unspecified, tensile stresses allowed

Table 2 Inspection Requirements in Current Regulations

Components	**Current ISI Volumetric & Surface Examination**	**Current ISI Bare Metal Visual Examination (VE)**
RPVHPN EDY≥ 8 years	Every 8 years or Prior to RIY ≥ 2.25, whichever is less Volumetric exam or surface exam; and a demonstrated volumetric or surface leak path assessment.	Each refueling outage (RFO)
RPVHPN EDY< 8 years	Every 8 years, or Prior to RIY ≥ 2.25, whichever is less Volumetric exam or surface exam; and a demonstrated volumetric or surface leak path assessment.	Each RFO If no flaws, VE every 3rd RFO or 5 calendar years, whichever is less. VT-2 in outages that the VE is not performed
RPVHPN with indications of cracking, either acceptable or not for further operation.	Each RFO Volumetric exam or surface exam; and a demonstrated volumetric or surface leak path assessment.	Each RFO
Unmitigated DMW at hot leg with temperature > 625 degrees F	Volumetric exam every second refueling outage	Each RFO
Unmitigated DMW at hot leg with temperature ≤ 625 degrees F	Volumetric exam every 5 years for uncracked DMWs	Each RFO
Unmitigated DMW at cold leg with temperature ≥ 525 degrees F and < 580 degrees F	Volumetric exam every second ISI period, not exceeding 7 years for uncracked DMWs	Each ISI interval

Notes:

1. The above table presents only key inspection requirements in the current regulations. The detailed ISI examination requirements for the unmitigated RPVHPN and DMWs without flaws are presented in ASME Code Cases N-729-1 and N-770-1, respectively. ASME Code Case N-722-1 also provide requirements for the bare metal visual examination of DMWs. Additional examination requirements are provided in 10 CFR 50.55a(g)(6)(ii)(D), 10 CFR 50.55a(g)(6)(ii)(E), and 10 CFR 50.55a(g)(6)(ii)(F).

Table 3 MRP Proposed Alternative Examination[*1]

Peened Components	Pre-Peening Examination	Follow-up Examination	ISI Examination	ISI Bare Metal Visual Exam (VE)
RPVHPNs with effective degradation years (EDYs) ≥ 8 years	Volumetric exam of each nozzle, or surface exam of nozzle ID surface and wetted surface of nozzle OD and J-groove weld. And, a demonstrated volumetric or surface leak path assessment thru J-groove weld	Volumetric exam or surface exam of nozzles; and a demonstrated volumetric or surface leak path assessment. Performed in the first and second refueling outage (RFO) after peening	Volumetric or surface exam of nozzles and a demonstrated volumetric or surface leak path assessment Each ISI interval (i.e., once every 10 years)	Each RFO
RPVHPNs with EDY < 8 years	Volumetric exam of each nozzle, or surface exam of nozzle ID surface and wetted surface of nozzle OD and J-groove weld. And, a demonstrated volumetric or surface leak path assessment thru J-groove weld	Volumetric exam or surface exam; and a demonstrated volumetric or surface leak path assessment. Performed in the second RFO after peening	Volumetric or surface exam and a demonstrated volumetric or surface leak path assessment Each ISI interval (i.e., once every 10 years)	Each RFO or, if VE is every 2 RFO before peening, after peening, VE is every 2nd RFO & VT-2 performed during VE is not performed If no flaw is found VE is every 3rd RFO & VT-2 performed during VE is not performed
Hot leg DMWs with temperature ≤ 625 degrees F	Ultrasonic exam and eddy current testing (ET) on DMW ID surface	Volumetric and surface exam of all peened welds within 5 years and a second exam within 10 years following peening application	Surface and volumetric examination on all peened welds each 10-year ISI interval. Surface exam from ID surface and volumetric exam performed from either ID or OD surface	No VE or VT-2 specified
Cold leg DMWs with temperature ≥ 525 degrees F and < 580 degrees F	Ultrasonic exam and eddy current testing (ET) on DMW ID surface	Volumetric and surface exam of all peened welds once within 10 years of peening but no sooner than the 3rd refueling outage following peening application	Surface and volumetric examination of all peened welds each 10-year ISI interval. Surface exam from ID surface and volumetric exam performed from either ID or OD surface	No VE or VT-2 specified

Footnotes-

[*1] "Materials Reliability Program: Topical Report for Primary Water Stress Corrosion Cracking Mitigation by Surface Stress Improvement (Revision 3)" (MRP-335R3), Tables 4-1 and 4-3, provide detailed alternative examination requirements. The key examination requirements are presented above.

Table 4 NRC Authorized Inspections for Peened DMW and RPVHPN

Peened Components	**Pre-Peening Examination**	**Follow-up Examination**	**ISI Examination**	**ISI Bare Metal Visual Exam (VE)**
RPVHPNs with effective degradation years (EDYs) ≥ 8 years	Volumetric exam of each nozzle, or surface exam of nozzle ID surface and wetted surface of nozzle OD and J-groove weld. And, a demonstrated volumetric or surface leak path assessment thru J-groove weld	Volumetric exam or surface exam of nozzles; and a demonstrated volumetric or surface leak path assessment. *Performed in the first and second refueling outage (RFO) after peening*	Volumetric or surface exam of nozzles and a demonstrated volumetric or surface leak path assessment Each ISI interval (i.e., once every 10 years)	*Each RFO*
RPVHPNs with EDY < 8 years	Volumetric exam of each nozzle, or surface exam of nozzle ID surface and wetted surface of nozzle OD and J-groove weld. And, a demonstrated volumetric or surface leak path assessment thru J-groove weld	Volumetric exam or surface exam; and a demonstrated volumetric or surface leak path assessment. *Performed in the second RFO after peening if RPVHPN contains no flaw(s).* *Performed in the first and second refueling outage (RFO) after peening if RPVHPN contains flaw(s).*	Volumetric or surface exam and a demonstrated volumetric or surface leak path assessment Each ISI interval (i.e., once every 10 years)	*Each RFO*
Hot leg DMWs with temperature > 625 degrees F	*Ultrasonic exam and eddy current testing (ET) on DMW ID surface*	*Volumetric and surface exam of all peened welds performed in the 2nd RFO and a second exam within 10 years following peening application*	*Surface and volumetric examination on all peened welds each 10-year ISI interval.* *Surface exam from ID surface and volumetric exam performed from either ID or OD surface*	*None*
Hot leg DMWs with temperature ≤ 625 degrees F	Ultrasonic exam and eddy current testing (ET) on DMW ID surface	*Volumetric and surface exam of all peened welds performed within 5 years and a second exam within 10 years following peening application*	Surface and volumetric examination on all peened welds each 10-year ISI interval. Surface exam from ID surface and volumetric exam performed from either ID or OD surface	None
Cold leg DMWs with temperature ≥ 525 degrees F	Ultrasonic exam and	Volumetric and surface exam of all peened welds once	Surface and volumetric examination of all peened	None

and ≤ 580 degrees F	eddy current testing (ET) on DMW ID surface	within 10 years of peening but no sooner than the 3rd refueling outage following peening application	welds each 10-year ISI interval. Surface exam from ID surface and volumetric exam performed from either ID or OD surface	

For the peened DMW and RPVHPN, the NRC required inspection frequencies that are different from the MRP proposed inspection frequencies are in italics.