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FINAL SAFETY EVALUATION

BY THE OFFICE OF NUCLEAR REACTOR REGULATION

FOR PRESSURIZED WATER REACTOR OWNERS GROUP TOPICAL REPORT

PWROG-15109-NP, REVISION 0,

“PWR PRESSURE VESSEL NOZZLE APPENDIX G EVALUATION”

EPID L-2018-TOP-0009

1.0 INTRODUCTION

By letter dated March 5, 2018 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML18067A228), as supplemented by letter dated March 27, 2019 (ADAMS Accession No. ML19091A089), the Pressurized Water Reactor (PWR) Owners Group (PWROG) submitted to the U.S. Nuclear Regulatory Commission (NRC) topical report (TR) PWROG-15109-NP, Revision 0, “PWR Pressure Vessel Nozzle Appendix G Evaluation,” (ADAMS Accession No. ML18067A229) for review and approval.

The TR addresses the potential for pressure-temperature (P-T) limit curves (or P-T limits) for inlet or outlet nozzle corners of pressurized water reactors (PWRs) to be more limiting than those of the shell (and associated welds) of the “traditional” beltline region of the reactor pressure vessel (RPV) and closure flange regions. The PWROG developed the TR to demonstrate that the RPV nozzle corner P-T limits are bounded by the NRC-approved P-T limits of the shell (and associated welds) in the RPV traditional beltline region for a 60-year license for U.S. PWRs. Specifically, the TR presented generic PWR fracture mechanics analyses of RPV inlet and outlet nozzle corners to show that P-T limits for nozzles corners, developed in accordance with the requirements of Appendix G, “Fracture Toughness Requirements,” to Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, are bounded by the P-T limits of the shell (and associated welds) in the RPV traditional beltline region.

2.0 REGULATORY EVALUATION

The NRC has established requirements in 10 CFR Part 50 to protect the integrity of the reactor coolant pressure boundary in nuclear power plants. The NRC staff (the staff) evaluates the acceptability of a facility's proposed P-T limits based on the following NRC regulations and guidance:

- Section 50.60 of 10 CFR, “Acceptance criteria for fracture prevention measures for lightwater nuclear power reactors for normal operation,” imposes fracture toughness and

material surveillance program requirements, which are set forth in 10 CFR Part 50, Appendices G and H, "Reactor Vessel Material Surveillance Program Requirements."

- Appendix G to 10 CFR Part 50 requires that a facility's P-T limits for the RPV be at least as conservative as those obtained by following the methods of analysis and the margins of safety in Appendix G to Section XI of the American Society of Mechanical Engineers *Boiler and Pressure Vessel Code* (ASME Code).

The most recent version of Appendix G to Section XI of the ASME Code which has been endorsed in 10 CFR 50.55a, and therefore by reference in 10 CFR Part 50, Appendix G, is the 2013 Edition of the ASME Code. Calculations of P-T limits are based, in part, on the nil-ductility reference temperature (RT_{NDT}) for the material, as specified in the ASME Code, Section XI, Appendix G. The RT_{NDT} is the critical parameter for determining the critical or reference stress intensity factor (fracture toughness, K_{IC}) for the material. As required by 10 CFR Part 50, Appendix G, RT_{NDT} values for materials in the RPV beltline region shall be adjusted to account for the effects of neutron irradiation. Regulatory Guide (RG) 1.99, Revision 2, "Radiation Embrittlement of Reactor Vessel Materials," contains methodologies for calculating the adjusted RT_{NDT} (ART) due to neutron irradiation.

Appendix G to 10 CFR Part 50 defines the beltline or beltline region of the reactor vessel as the region of the RPV (shell material including welds, heat affected zones, and plates or forgings) that directly surrounds the effective height of the active core and adjacent regions of the RPV that are predicted to experience sufficient neutron irradiation damage to be considered in the selection of the most limiting material with regard to radiation damage.

Determination of the P-T limits for a plant in accordance with the requirements of Appendix G to 10 CFR Part 50 considers several factors, which include the initial properties and chemical composition of the RPV materials, the accumulated neutron fluence for each material, the stress levels applied to the materials resulting from heatup and cooldown transients (which include internal pressure and thermal gradient loads), and structural discontinuities such as nozzles. Development of P-T limits for the beltline region of the RPV considers not only the RPV shell material but also other RPV materials with structural discontinuities such as nozzles.

3.0 SUMMARY OF THE TOPICAL REPORT

The TR is organized as follows:

Section 1, "Background" – provides a background of why nozzle corners must be considered in evaluations of P-T limits, a summary of the NRC-approved methodologies for development of P-T limits for Westinghouse Electric Company (Westinghouse), Combustion Engineering, Inc., and Babcock & Wilcox Company (B&W) PWR designs, a summary of reports that inform nozzle corner analyses, and a summary of low-temperature overpressure protection.

Section 2, "Flaw Size" – describes the basis for postulating a smaller than quarter-thickness (1/4T) flaw and describes the small flaw size models postulated in the inlet and outlet nozzles.

Section 3, "Fracture Toughness" – provides details of the determination of generic nozzle fracture toughness using the master curve approach and generic embrittlement trend curve.

Section 4, "Stress Intensity Factor Calculation" – provides details of the determining stress intensity factors (SIFs) using the finite element method for the small flaw size models in Section 2 of the TR.

Section 5, "Pressure-Temperature Limit Curves" – describes determination of the P-T limits for nozzle corners with a small flaw (using information from Sections 3 and 4 of the TR) and 1/4T beltline size flaw; compares P-T limits for nozzles corners with those from NRC-approved P-T limits for shell (and associated welds) in the RPV beltline region and for the closure flange regions.

Section 6, "Conclusion" – concludes that the generic P-T limits for nozzles corners developed in the TR in accordance with the requirements of Appendix G to 10 CFR Part 50 are bounded by the P-T limits of the shell (and associated welds) in the RPV beltline region and closure flange regions in the U.S. PWR fleet.

4.0 TECHNICAL EVALUATION

The staff reviewed the TR to determine whether the PWROG's evaluation to demonstrate the P-T limits of shell (and associated welds) in the RPV traditional beltline region bound those of inlet and outlet nozzle corners is acceptable. The staff also reviewed the TR to determine that the technical bases are consistent with the requirements of 10 CFR 50.60.

The staff evaluated eleven major topics of the TR. Each topic is addressed in the subsections of the safety evaluation (SE) that follow. Within each major topic, the staff summarized the relevant content of a subsection of the TR or described the relevant information in the subsection that falls under each major topic. Then the staff provided its findings or determinations on the TR subsection or on the major topic.

4.1 Postulated Flaw Size

In Section 2 of the TR, the PWROG explained that a traditionally postulated 1/4T flaw in the nozzle corner region can result in a depth of approximately 4 to 5 inches as measured at a 45-degree angle from the nozzle corner to the RPV outside surface since the nozzle and RPV are thicker in the vicinity of nozzles per the ASME Code design requirements. Crack driving forces for a postulated 1/4T flaw could lead to overly conservative P-T limits. Therefore, the PWROG opted to postulate smaller flaws as allowed in the 2008 edition of the ASME Code, Section XI, Appendix G, Subarticle G-2120, "Maximum Postulated Defect," which states that flaws less than 1/4T may be used on an individual case basis if a smaller size of maximum postulated defect can be ensured. Additionally, the 2008 edition of the ASME Code, Section XI, Appendix G, Paragraph G-2223(a), "Toughness Requirements for Nozzles," states that examination methods "shall be sufficiently reliable and sensitive to detect these smaller defects." The PWROG created finite element models (FEMs) with a small postulated flaw in the nozzle corner (the flaw penetrates 0.5 inch into the low alloy steel (LAS) from the clad-to-LAS interface) to determine SIFs since closed-form SIF solutions for nozzle corners are typically for 1/4T flaws. Additionally, the PWROG created FEMs with a postulated flaw that penetrates 0.05 inch into the LAS to address the effect of the difference in coefficient of thermal expansion (CTE) between the clad and the LAS.

The PWROG showed a probability of detection (POD) plot for vessels that indicates a POD of 100 percent for a 0.5-inch flaw into the LAS and stated that crack growth analyses have been performed for postulated flaws smaller than 0.5 inch based on their high POD. Although a similar POD for nozzle corners does not exist, the PWROG qualitatively concluded that the POD for nozzle corners would be high because pre-service examination through ultrasonic testing (UT) was performed from the inside surface and presented a conclusion by the Electric Power

Research Institute (EPRI) Nondestructive Examination Center that detecting flaws as small as 0.25 inch by UT located in RPV nozzles is excellent.

The staff reviewed the POD information for vessels in the TR, which the PWROG obtained from Performance Demonstration Initiative (PDI) data from UT performed in accordance with ASME Code, Section XI, Appendix VIII. The staff also reviewed the ASME Code, Section XI, examination requirements for nozzle corners, which requires nozzle corners to be examined by UT through PDI in accordance with ASME Code, Section XI, Appendix VIII. Accordingly, the staff determined that the PWROG's qualitative evaluation of high POD for nozzle corners to be reasonable. Thus, the staff determined that the postulated flaw size of 0.5 inch into the LAS meets the detectability criterion of Paragraph G-2223(a) of the 2013 edition of ASME Code, Section XI, which is the latest NRC-approved version of the ASME Code.

The staff noted that the ASME Code, Section XI, examination volume requirement for nozzle corners specifies a maximum depth of 0.5 inch into the LAS. Thus, the staff determined that the postulated flaw size of 0.5 inch into the LAS meets the required examination volume.

The staff noted that Paragraph G-2223(a) in the 2008 edition is different than in the 2013 edition. In addition to the detectability criterion described in Section 4.1 of this SE, Paragraph G-2223(a) of the 2013 edition states that the postulated smaller flaw must appropriately consider the combined effects of internal pressure, external loading, thermal stresses, and flaw shape, and the postulated smaller flaw shall be no smaller than the applicable inservice inspection criteria in Table IWB-3410-1 of ASME Code, Section XI. The staff reviewed Section 4.7, "Loads," of the TR and determined that the PWROG applied the appropriate loads and flaw shape (evaluated in Section 4.6 of this SE). The staff also reviewed the flaw size requirements in Table IWB-3410-1 of the ASME Code, Section XI, and determined that the flaw size of 0.5 inch into the LAS region that the PWROG postulated meets the requirements of the table. Based on this and the POD information the PWROG provided, the staff finds that a postulated flaw of 0.5 inch into the LAS is acceptable and meets the criteria of Subarticle G-2120 and Paragraph G-2223(a) of the 2013 edition of ASME Code, Section XI.

4.2 Fracture Toughness

Generic Nozzle Forging Master Curve Reference Temperature

In Section 3.1, "Generic Nozzle Forging Master Curve Reference Temperature" of the TR, the PWROG stated that the use of the lower bound plane-strain, static fracture toughness (K_{IC}) curve has inherent margin since RT_{NDT} is a conservative method for locating the K_{IC} curve. RT_{NDT} is based on drop weight testing, which is a crack arrest transition temperature measurement, and the Charpy impact test, which is a blunt notch impact test. These data are conservatively bounded by the K_{IC} curve, which is a lower bound crack initiation fracture toughness curve.

In contrast, the PWROG stated that the master curve method is based on an initiation transition temperature true fracture toughness test technique and the master curve index temperature (T_0) provides a much more accurate measure of the material fracture toughness. The PWROG explained that existing master curve fracture toughness data for A-508 Class 2 type forgings was gathered to establish a generic mean and standard deviation for alternate RT_{NDT} for the U.S. PWR inlet and outlet nozzles. Specifically, the master curve fracture toughness data is used with ASME Section XI Code Case N-629, "Use of Fracture Toughness Test Data to Establish Reference Temperature for Pressure Retaining Materials, Section XI, Division 1,"

which is endorsed by RG 1.147 and incorporated by reference in 10 CFR 50.55a as an alternative to RT_{NDT}.

The staff noted that the 2013 edition of ASME Code Section XI (i.e., the latest edition endorsed by 10 CFR 50.55a) permits the use of an alternate RT_{NDT}, which is consistent with Code Case N-629. Specifically, Subarticle G-2110 in the 2013 edition of ASME Code Section XI states, in part, that if material-specific temperature value, T_0, for ferritic steels in the transition range is available then a reference temperature, RT_{T0}, may be used in place of RT_{NDT}.

Since Code Case N-629 is incorporated by reference (e.g., RG 1.147) in 10 CFR 50.55a, and the use of RT_{T0} in lieu of RT_{NDT} is permitted by ASME Code Section XI, the staff finds the use of a fracture-toughness-based reference temperature, RT_{T0}, acceptable and that an exemption to Appendix G to 10 CFR Part 50 by the licensees is not required.

Master Curve Data Search

In Section 3.1.1, "Master Curve Data Search," of the TR, the PWROG described the approach it used for searching and gathering master curve data relevant to RPV nozzle forgings in U.S. PWRs. The PWROG explained that relevant data was gathered from open literature, the Electric Power Research Institute (EPRI) fracture toughness database, and internal Westinghouse references. Specifically, the PWROG considered thick sections of A-508 Class 2 or similar forgings that were used in RPV fabrication or are representative of the materials used to construct U.S. PWR inlet and outlet nozzles. The purpose was to capture all available transition temperature fracture toughness data to establish a generic master curve transition reference temperature for A-508 Class 2 type forgings. The PWROG explained in its supplement that "representative" means that the forging heats from which master curve data were obtained had material specifications similar to A-508 Class 2 forgings used in U.S. PWR inlet and outlet nozzles. Specifically, the staff noted that the PWROG's selection included alternate forging alloys—22NiMoCr37, 20NiMoCr26, and SFVQ2A (the staff's review regarding the applicability of these alternate forging alloys to U.S. PWR inlet and outlet nozzles is discussed below). The PWROG also stated that the meaning of "bounding" is explained in Section 3.1.2.2 of the TR. The staff noted that the master curve data is considered bounding because it included irradiated materials, fracture toughness data based on K_{IC}, one material with RT_{NDT} greater than 60°F, and a diversity of relevant forgings (as evidenced by the large standard deviation presented in Section 3.1.2.2 of the TR), all of which conservatively impact fracture toughness. Based on its review, the staff finds the scope of materials that the PWROG considered and included into the master curve data is representative and reasonably bounds the fracture toughness of RPV inlet and outlet nozzle forgings in U.S. PWRs.

The PWROG explained that the nozzle forgings used in U.S. PWRs are all ASME SA-508 Class 2 or ASTM A-508 Class 2 with the following exceptions: Prairie Island Nuclear Generating Station Units 1 and 2 nozzles, which are SA-508 Class 3, Palo Verde Nuclear Generating Station Units 2 and 3 nozzles (which are a combination of SA-508 Classes 2 and 3), and R.E. Ginna Nuclear Power Plant nozzles (which are SA-336). The PWROG noted that the Ginna nozzles meet the A-508 Class 2 specification requirements per the Ginna Certified Material Test Reports (CMTRs). With regard to the nozzles forgings that are SA-508 Class 3, the PWROG stated that master curve data was assessed for A-508 Class 3 and showed that the fracture toughness properties were better than A-508 Class 2. Based on its review of the master curve data for A-508 Class 3 materials referenced by the PWROG, the staff finds it reasonable that the A-508 Class 2 generic RT_{T0} developed in this TR is conservative compared to A-508 Class 3 forgings. In addition, the staff finds that the A-508 Class 2 generic RT_{T0}

developed in the TR is appropriate for the SA-336 forgings because plant-specific CMTRs demonstrate that these forgings meet the A-508 Class 2 specification requirements.

The PWROG provided a description of the materials relevant to the U.S. PWR nozzle forgings that were included in its master curve data search. Specifically, the PWROG included in its supplement available master curve data, chemical composition, and mechanical properties of the following materials: 22NiMoCr37, ASTM A-508-64 Class 2, SA-508 Class 2 (1971), SA-508 Grade 2 Class 1 (2007), 20NiMoCr26, and SFVQ2A. The staff reviewed the chemical composition and mechanical properties listed for the different forgings and noted that the differences in the chemical composition limits and mechanical properties between all the different alloys are very minor when compared to the alloys used in U.S. PWR nozzle forgings. The PWROG confirmed that each of these forgings in the master curve dataset was quenched and tempered steel for pressure vessels, and that a similar heat treatment was used to produce the required properties. The PWROG also confirmed that the master curve data was produced from specimens taken from thick section forgings except for the 20NiMoCr26 forging, which was thinner. For this particular forging that was thinner, the PWROG indicated that consideration of the forging in the dataset is conservative (i.e., increases the average generic RT_{T0} in the TR). Based on the impact of the 20NiMoCr26 forging to the average generic RT_{T0} determined in the TR, the staff finds its inclusion into the master curve dataset to be conservative.

Based on its review, the staff considers A-508 and SA-508, Class 2, 22NiMoCr37, 20NiMoCr26, and SFVQ2A forgings are essentially the same alloy because of the minor differences in the chemical composition and mechanical properties, and the PWROG's confirmation regarding the methods used to produce these forgings. Thus, the staff finds the PWROG's inclusion of A-508 and SA-508, Class 2, 22NiMoCr37, 20NiMoCr26, and SFVQ2A materials in its master curve dataset to be acceptable and representative of U.S. PWR nozzle forgings.

Based on its review, the staff finds the scope of materials considered by the PWROG and included into the master curve data is representative and reasonably bounds the fracture toughness of the RPV inlet and outlet nozzle forgings in U.S. PWRs.

Results from Master Curve Data Search

Section 3.1.2, "Results from Master Curve Data Search," of the TR states that master curve data for 22 distinct forgings were identified, and in all cases the heats selected are representative of the forgings used in commercial PWRs and boiling water reactors (BWRs) from Japanese, Swedish, German, and U.S. RPVs. The PWROG confirmed that the references were checked to ensure that all the data collected for the TR was from unique forgings.

The PWROG explained that in some cases the references only reported K_{IC} values; nevertheless, the master curve reference temperature can conservatively be developed from these K_{IC} values. The PWROG stated that the K_{IC} values are always the same or lower than the cleavage-onset fracture toughness (K_{JC}) values from the same test; thus, the T_0 value developed from these K_{IC} values would be conservative. The staff noted that where K_{IC} is used instead of K_{JC}, K_{IC} is defined by ASTM E399, "Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{IC} of Metallic Materials," and is the applied SIF (K) where the load displacement trace deviates from linearity by 5 percent. Whereas in ASTM E1921, "Standard Test Method for Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Region," K_{JC} is K converted from the applied J-integral at cleavage. The staff noted that the K_{IC} curve was established using only data deemed to be "valid" by linear elastic fracture mechanics criteria per ASTM E399; thus, only the lower range of cleavage fracture toughness values were used, whereas K_{JC} is determined from data from specimens in a temperature range where either

cleavage cracking or crack pop-in develops during the loading of specimens and is not limited to the lower range values. Thus, the staff finds it acceptable and conservative that the PWROG included relevant K_{IC} values in determining the master curve reference temperature because these values only include the lower range of cleavage fracture toughness data.

Table 3-2 "All Available Master Curve Data on A-508 Class 2 Type Forgings," of the TR presents the results from the master curve data search performed by the PWROG. The PWROG stated that the range of RT_{NDT} values in Table 3-2 of the TR exceeds the range (i.e., more conservative) of the RT_{NDT} values generally observed in U.S. PWR nozzle forgings utilizing the criteria in NB-2300 of Section III of ASME Code, which typically fall between -34°C and -12°C. Additionally, the PWROG stated that the average RT_{NDT} (-11°C) of the 22 forgings in Table 3-2 of the TR falls above (i.e., more conservative) this typical range of RT_{NDT} values observed for U.S. PWR nozzle forgings based on measured data and ASME Code NB-2300 criteria. The PWROG summarized in its supplement NB-2300-compliant measured RT_{NDT} values for U.S. PWR nozzle forgings developed from a review of original CMTRs. The staff noted that this information is not intended to be a complete list of all U.S. PWR nozzle RT_{NDT} values but contains those readily available to the PWROG, which are representative of approximately half of the U.S. PWR nozzle forgings.

The staff reviewed these NB-2300-compliant RT_{NDT} values and noted an average value of -10.5°F (-23.6°C). The staff noted the average value from the reported RT_{NDT} values in the master curve data search (i.e., Table 3-2 in the TR) is 12.2°F (-11°C). Based on the readily available data from U.S. PWR nozzle forgings and the master data search in the TR, the staff finds the forgings included in the master curve data used to develop the A-508 Class 2 generic RT_{T0} in the TR, on average, is not as tough as the nozzle material in U.S. PWRs and, therefore, conservatively represents the fracture toughness of U.S. PWR nozzle forgings.

Based on the discussion above, the staff finds the PWROG demonstrated that the master curve data presented in the TR is conservatively representative with respect to fracture toughness of U.S. PWR nozzle forgings. Specifically, since RT_{T0} is an acceptable alternate to RT_{NDT}, the staff finds the A-508 Class 2 generic RT_{T0} developed in this TR is also considered conservatively representative of the U.S. PWR fleet of nozzle forgings.

Specimen Geometry Constraint Adjustment

Table 3-2 of the TR provides the details of the specimen geometry of the forgings that were used to determine generic nozzle forging master curve reference temperature. Section 3.1.2.1, "Specimen Geometry Constraint Adjustment," of the TR indicates that, as observed by Tregoning and Joyce (Ref. 45 of the TR), there is a systematic, non-conservative bias toward the Single Edge Notched Bend (SE(B)) specimen of generally 5°C to 10°C relative to the compact tension (CT) specimen geometry due to its lower constraint. Thus, the PWROG elected to address this by adding a 10°C bias to the SE(B) T_0 values to adjust for the lower constraint SE(B) geometry, as shown in Table 3-2 of the TR.

By letter dated August 4, 2005 (ADAMS Accession No. ML052070408), the staff approved the use of a 10°C bias for the lower constraint SE(B) geometry in its SE of BAW-2308, Revision 1. In addition, the staff noted that recent editions of ASTM E1921 included an average difference between the CT and SE(B) of 10°C.

The staff finds the PWROG's use of a 10°C bias to the SE(B) T_0 values acceptable because it is consistent with (1) the data and information available on the differences between SE(B)

specimen and CT specimen test result, and (2) the previous approval of a 10°C bias for the lower constraint SE(B) geometry.

Surface Effect

Section 3.2, "Surface Effect," of the TR describes improved toughness near the surface of a forging material compared to a location deeper in the forging. The PWROG cited references that illustrated the improved toughness near the surface and presented transition temperature data for 24 longitudinal (LT) specimens and seven transverse (TL) specimens. The data consisted of shifts in transition temperature at the surface relative to the 1/4T location and were determined from Charpy V-Notch (CVN) or the master curve measurements. The PWROG stated that specimens without a reported orientation were included in the LT data set. Table 3-3, "Summary of Transition Temperature Shifts for LT and TL Specimens," of the TR showed the average and standard deviation of the transition temperature shifts for the LT and TL data sets. The PWROG selected the conservative set of average and standard deviation (i.e., the LT data set) to take credit for improved fracture toughness for the small flaw models described in Section 4.1 of this SE.

The staff reviewed the information in Section 3.2 of the TR and verified the average and standard deviation of the transition temperature shifts in Table 3-3 of the TR. The staff noted these observations in the LT measurements: five of the measurements were taken at less than the assumed flaw size of 0.5 inch and two measurements had only a small difference in the depths that they were taken. The staff recalculated the average and standard deviation without these LT measurements and determined that they caused a negligible change. Therefore, the staff finds the average and standard deviation of the temperature shifts shown in Table 3-3 of the TR to be acceptable. The staff noted that the inherent scatter in CVN measurements tend to increase the standard deviation in the transition temperature shifts, which is conservative; thus, the staff also finds including CVN measurements to be acceptable.

The PWROG addressed in its supplement the specimens without a reported orientation being included in the LT data set in two aspects. First, the PWROG confirmed that the ten B&W forgings, the Westinghouse Four-Loop Inlet Nozzle, Westinghouse Four-Loop Outlet Nozzle #1, and Westinghouse Four-Loop Outlet Nozzle #2 have CMTRs dated from 1969 and 1970. The PWROG stated that testing of TL specimens was not required until after the issuance of the Summer 1972 Addenda of the 1971 Edition of the ASME Code Section III. Although the staff is unable to confirm that these forgings produced prior to 1972 were tested in the LT direction, the second aspect of how the PWROG addressed specimens with unknown orientation is reasonable. The PWROG stated that in addition to the forgings discussed above, the orientation was not reported for the BethForge forging ID, BethForge forging OD, Forging M1, Forging I, and the French forging. For all of the forgings with unknown orientation identified above, the PWROG illustrated the breakdown of the LT dataset measured transition temperature surface shift between those with a reported LT orientation and those with an *assumed* LT orientation. The PWROG explained that the addition of the assumed LT orientation data biases the average shift value in the conservative direction compared to the dataset with only known LT orientation. Specifically, the staff noted that the "known" LT dataset provides an average shift of 44.7°F; whereas, the "unknown" LT dataset in this second category would only provide an average shift of 33.8°F. Thus, when the "known" and "unknown" LT datasets are both included, the average shift and standard deviation values in the TR (36.5°F and 28.9°F, respectively) result in a more conservative ART compared to the ART value based only on known LT data.

In summary, the staff finds that the PWROG adequately addressed the forgings without a reported orientation and their inclusion with the known LT data is appropriate and conservative, as described above. Thus, the staff finds that the PWROG has selected a conservative dataset set to determine the improved fracture toughness near the surface of a forging material and finds it acceptable when addressing the small flaw models described in the TR.

Underclad Heat-Affected Zone Toughness

Section 3.3, "Underclad HAZ Toughness," of the TR states that a significant portion of the small postulated flaw in this TR would be in the underclad heat-affected zone (HAZ); therefore, the properties of the HAZ relative to the adjoining base metal must be considered. The staff's evaluation of the small postulated flaw is documented in Section 4.1 of this SE.

The PWROG provided information from Oak Ridge National Laboratory (ORNL), in which ORNL conducted Charpy impact testing on a stainless steel cladded plate to determine the effect of clad on the propagation of small surface flaws. This plate was specifically heat treated to produce a high transition temperature but was not quenched and only slightly tempered. The testing performed by ORNL showed that the clad HAZ had significantly better properties (i.e., lower transition temperature) than the 1/4T location in the plate. The PWROG stated that since the plate was not quenched, the improved HAZ transition temperature would not be due to a faster cooling rate from quenching, but the tempering of the cladding operation.

The staff noted that HAZ test results from surveillance specimens have revealed the inhomogeneous nature of the HAZ material, which also resulted in significant scatter of the HAZ Charpy test data. As discussed in "Irradiation Embrittlement of Reactor Pressure Vessels (RPVs) in Nuclear Power Plants" (Soneda, N. ed., 2015), the weld HAZ has been shown to exhibit superior fracture toughness compared to the plate or forging. In addition, the staff also noted that the continued need to include HAZ material in RPV material surveillance programs was more recently investigated in a paper by Koichi Masaki, Jinya Katsuyama, and Kunio Onizawa, "Study on the Structural Integrity of RPV Using PFM (Probabilistic Fracture Mechanics) Analysis Concerning Inhomogeneity of the Heat-Affected Zone." This paper investigated the features of HAZ inhomogeneity in RPV steels to determine the need for surveillance test specimens of HAZ materials in Japan. The authors examined the inhomogeneous distribution of fracture toughness for HAZ materials using a PFM code and determined that the high-toughness coarse grain HAZ caused arrest of postulated cracks. This outcome is expected metallurgically, because the HAZ is a tempered version of the plate or forging and, as such, it should exhibit superior fracture toughness compared to the plate or forging.

Thus, the staff finds that the PWROG has adequately addressed the properties of the HAZ relative to the adjoining base metal and finds the PWROG's conclusion that underclad HAZ in nozzles is as tough, or tougher than, the adjacent forging base metal to be acceptable.

4.3 Neutron Embrittlement

Section 3.4, "Neutron Embrittlement," of the TR states that the copper (Cu) content was not measured for all the nozzles manufactured for the U.S. PWR fleet, however it was measured for a substantial number covering nearly the full range of manufacturing dates and all major U.S. RPV fabricators. Cu measurements were averaged for 178 inlet and outlet nozzles yielding an average of 0.0947 percent with a standard deviation of 0.0319 percent, yielding a best-estimate value, as defined by RG 1.99, Revision 2, of average plus one standard deviation of 0.127 percent. The PWROG explained that for nickel (Ni) content, the upper limit of the SA-508

Class 2 specification during the fabrication time period is used, which was 0.90 percent. The PWROG stated that the Cu and Ni contents discussed above are appropriate for the U.S. PWR nozzles, since the database was established from Cu measurements from PWR nozzle forgings only.

The staff reviewed the information in Section 3.4 of the TR and RG 1.99, Revision 2, regarding the Cu and Ni content. The staff finds the PWROG appropriately determined Cu and Ni contents that are representative of U.S. PWR nozzle forgings consistent with the guidance in RG 1.99, Revision 2.

Using the Cu and Ni contents discussed above and RG 1.99, Revision 2, the PWROG developed an embrittlement trend curve (ETC) that shows the shift in RT_{NDT} (ΔRT_{NDT}) as a function of neutron fluence, applicable to U.S. PWR nozzles. The PWROG then determined the fluence value of 4.28×10^{17} n/cm^2 for a ΔRT_{NDT} of 25°F. The PWROG cited NRC Technical Letter Report TLR-RES/DE/CIB-2013-01, "Evaluation of the Beltline Region for Nuclear Reactor Pressure Vessels," Office of Nuclear Regulatory Research (RES), dated November 14, 2014 (ADAMS Accession No. ML14318A177), as a basis for not considering the shift due to irradiation of RPV beltline materials (including nozzles) if ΔRT_{NDT} is less than 25°F. The PWROG used the fluence value at ΔRT_{NDT} of 25°F as a screening threshold below which embrittlement due to irradiation may be neglected in the calculation of ART (as discussed in Section 4.4 of this SE). Section 3.4.5, "Future Increased Nozzle Fluence Projections," of the TR indicates that as long as the nozzle fluence projections are less than the fluence screening threshold, the nozzle P-T limits developed in the TR is applicable (if the new fluence is greater than the threshold, a plant-specific ΔRT_{NDT} or ART shall be calculated).

The PWROG provided additional justification in its supplement that supports the recommendation in TLR-RES/DE/CIB-2013-01 related to ΔRT_{NDT} of 25°F. The PWROG stated that predictions of ΔRT_{NDT} have inherent scatter due to uncertainty in ΔRT_{NDT} data measurement and uncertainty in ΔRT_{NDT} prediction models. The PWROG's premise is that a ΔRT_{NDT} of 25 °F does not have to be considered because 25°F is a reasonable value that represents the scatter in ΔRT_{NDT} due to these uncertainties. To demonstrate this, the PWROG compared the standard deviation (a measure of scatter) of the ΔRT_{NDT} data in TLR-RES/DE/CIB-2013-01 and from the embrittlement database used to develop the ASTM E900 ETC, which included data from welds, plates, and forgings from tested surveillance capsules. The PWROG determined a standard deviation of ΔRT_{NDT} of 23 °F from the data in TLR-RES/DE/CIB-2013-01 and a standard deviation of ΔRT_{NDT} of 18.6 °F from the ASTM E900 ETC data. The standard deviation from the ASTM E900 ETC data included fluence levels up to 4.28×10^{17} n/cm^2, which is the fluence corresponding to a ΔRT_{NDT} of 25 °F and the fluence threshold the PWROG is proposing in the TR below which embrittlement shifts for nozzles do not have to be considered. The PWROG noted that 18.6 °F is slightly less than 23°F but is consistent with the standard deviation of ΔRT_{NDT} from other ETCs, which included ETCs based on RG 1.99, Revision 2 and 10 CFR 50.61a.

To further demonstrate that 25°F is a reasonable value below which embrittlement shifts do not have to be considered, the PWROG, using the ETC from RG 1.99, Revision 2, determined ΔRT_{NDT} values of 24.5°F, 25.4°F, and 29.6°F—all comparable to 25°F–for RPV materials that have hypothetically high Cu content (i.e., highly embrittled) at a fluence level of 0.99×10^{17} n/cm^2. This fluence level is slightly less than the 1×10^{17} n/cm^2 threshold established in Appendix H to 10 CFR Part 50 for monitoring changes in the fracture toughness properties of ferritic materials in the reactor vessel beltline region. Since 0.99×10^{17} n/cm^2 is less than 1×10^{17} n/cm^2, these ΔRT_{NDT} values for RPV materials having hypothetically high Cu content would not have been considered. Based on the discussion above, the PWROG concluded that

25°F is a reasonable value below which embrittlement shifts do not have to be considered. The staff reviewed the PWROG's justification for using the recommendation in TLR-RES/DE/CIB-2013-01 for not having to consider a ΔRT_{NDT} of 25°F. The staff noted that the ΔRT_{NDT} data from the ASTM E900 embrittlement trend curve (Figure 1 in the supplement) have more positive shifts than negative shifts and shifts could be up to 60°F. However, the staff recognizes that the effect of embrittlement is difficult to distinguish from the data scatter for shifts less than 25°F. Therefore, given the safety significance of RPV components, the staff does not find the justification sufficient to demonstrate generically that embrittlement shifts less than 25°F do not have to be considered. In order to determine whether the recommendation in TLR-RES/DE/CIB-2013-01 of excluding 25°F embrittlement is acceptable specifically for this TR, the staff evaluated the safety significance of the recommendation by identifying if there are any U.S. PWRs in which the nozzles are the limiting material for P-T limits when accounting for an embrittlement shift of 25°F.
For this independent assessment to be focused on those U.S. PWRs in which the nozzle material is more limiting than the traditional beltline for P-T limits, the following criteria were used to screen out U.S. PWRs as not needing any additional review:

- Plants that are already shutdown or not pursuing a renewed operating license
- Plant-specific license amendment requests have been reviewed and approved by the NRC to address irradiation embrittlement of the nozzles
- Plant-specific Pressure-Temperature Limits Report (PTLR) demonstrates that the NRC-approved P-T limit curves are limiting
- Neutron fluence at the nozzle region is less than 1 x 10^{17} n/cm^2 (E > 1 MeV) at the end of 60-years of plant operation (neutron fluence information is publicly available in plant-specific license renewal applications, license amendment requests, or PTLR)
- Reactors with traditional beltline materials with Cu ≥ 0.2 wt. % (information is publicly available in Reactor Vessel Integrity Database (RVID) Version 2.0.1)

The staff determined that reactors with a neutron fluence at the nozzle region less than 1 x 10^{17} n/cm^2 (E > 1 MeV) at the end of 60 years of plant operation are screened out consistent with the threshold established in Appendix H to 10 CFR Part 50 for monitoring changes in the fracture toughness properties of ferritic materials in the RPV beltline region. Furthermore, the staff determined that it is reasonable that U.S. PWRs with traditional beltline materials with Cu ≥ 0.2 wt. % are screened out because this level of Cu content would cause a significant shift due to embrittlement in the P-T limits such that it will continue being the limiting material through the license renewal period (i.e., 40 to 60 years of operation).

Following this initial screening, the staff reviewed the information available in RVID 2.0.1 to identify "candidate" U.S. PWRs based on the following criteria:

- Reactors with a traditional beltline material with low Cu content (i.e., ≤ 0.03 wt. %)
- Reactors with NRC-approved P-T limits based on a limiting material with low Cu content
- Nozzle material information (e.g., initial RT_{NDT}, Cu, Ni, and neutron fluence) is available in ADAMS to generate P-T limit curves

The staff noted that reactors meeting these criteria, particularly those reactors with good beltline material properties (i.e., low initial RT_{NDT}), have the highest likelihood that a shift due to embrittlement of the nozzle could lead to nozzle P-T limits being more limiting than the NRC-approved P-T limits based on a traditional beltline material. Since a data search was being performed for nozzle material property information for the "candidate" reactors, the staff opted to also include any additional reactors at the site since the information was already

available in the source documents (e.g., license renewal application). This resulted in a total of nine U.S. PWRs that the staff further investigated by generating P-T limit curves for the limiting nozzle forging using ART values based on an effective full power year (EFPY) that was available from the appropriate source document or data. These nozzle P-T limit curves are based on a 100°F per hour cooldown rate and a postulated inside corner flaw of depth 1/4T.

For the independent assessment, the staff determined applied SIFs for nozzles due to pressure loading (K_{IP}) and thermal gradients (K_{IT}) consistent with those published in the ORNL study, ORNL/TM-2010/246, "Stress and Fracture Mechanics Analyses of Boiling Water Reactor and Pressurized Water Reactor Pressure Vessel Nozzles -Revision 1, June 2012." The staff noted that these SIF solutions are also consistent with those in the 2013 edition of the ASME Code, Section XI, Paragraph G-2223(c), which are applicable to postulated nozzle corner flaws, regardless of plant design. The staff used the limiting nozzle location from ORNL/TM-2010/246 (i.e., the nozzle location with the highest stresses) in its independent assessment. As such, the staff finds that the use of the SIF solutions in ORNL/TM-2010/246 for calculating the K_{IP} and K_{IT} values for the nozzles are acceptable and appropriate for use in its independent assessment.

The nozzle P-T limit curves generated by the staff for these "candidate" U.S. PWRs were then compared to their respective NRC-approved P-T limit curves, both of which were based on ART values calculated at the same EFPY. Based on this comparison, the staff determined that for these nine "candidate" reactors, the limiting traditional beltline NRC-approved P-T limit curves were bounding compared to the nozzle P-T limit curves generated by the staff.

For the remaining U.S. PWRs, the staff noted that nozzle material information (e.g., initial RT_{NDT}, Cu, Ni, and neutron fluence) was not readily available. Thus, for the staff to determine if the nozzle P-T limit curve is limiting, a generic screening ART value for the nozzle was calculated and then compared against the ART values from the traditional beltline. The staff noted that if the ART value for the traditional beltline materials (information available in RVID 2.0.1) is less than this screening generic nozzle ART value, there is a potential that the nozzle P-T limit curve may be more limiting. Since the plant-specific nozzle information was not available, the staff used the generic mean alternate RT_{NDT} value determined in the TR for U.S. PWR nozzle forgings. As discussed in Sections 4.2 and 4.4 of this document, the staff determined the generic mean alternate RT_{NDT} value (i.e., RT_{T0}) in the TR is relevant and conservatively representative of U.S. PWR nozzle forgings.

The generic screening nozzle ART value was determined in the following manner:

- Generic Nozzle $ART_{screening}$ = $RT_{T0\ Inital}$ + $\Delta RT_{NDT\ Stress}$ + $\Delta RT_{NDT\ Embrittle}$ + $margin_{Embrittle}$
- $margin_{Embrittle} = 2(\sigma_i^2+\sigma_\Delta^2)^{½}$ – Per RG 1.99, Revision 2
- $RT_{T0\ Inital}$ = -66.4°F – Per Section 3.5 of the TR
- $\Delta RT_{NDT\ Stress}$ = 25°F – Bounding shift due to stress based on review of P-T limit curves
- $\Delta RT_{NDT\ Embrittle}$ = 25°F – Maximum shift due to embrittlement
- σ_i = 54.5°F – Per Section 3.5 of the TR
- σ_Δ = 12.5°F – Per RG 1.99, Revision 2, σ_Δ cannot be more than ½ of $\Delta RT_{NDT\ Embrittle}$
- Generic Nozzle $ART_{screening}$ = 95.4°F

As noted above, $\Delta RT_{NDT\ Stress}$ represents the shift of the nozzle P-T limit curve resulting from the stress levels due to the structural discontinuities in the nozzle region as compared to the P-T limits curve generated for the traditional beltline. Based on its observations and previous reviews of License Amendment Requests for P-T limits curves, the staff noted that a value of 25°F is appropriate and bounding to account for the increased stress levels due to the structural

discontinuity in the nozzle. Based on this screening generic nozzle ART value, the staff identified four U.S. PWRs that needed a detailed assessment. The staff determined that two of these U.S. PWRs are governed by the P-T limit curve from the bounding unit at the site, which was previously screened out because the ART value for a traditional beltline material was greater than the screening generic nozzle ART value. For the remaining two PWRs, the staff generated P-T limit curves for a generic nozzle ART value, consistent with the methods described above, for comparison with the traditional beltline NRC-approved P-T limit curves. However, to generate these nozzle P-T limit curves, $\Delta RT_{NDT\ Stress}$ = 25°F was not included in the ART value because $\Delta RT_{NDT\ Stress}$ was only for the purpose of screening in PWRs for assessment. The resulting generic nozzle ART value used for generating the P-T limit curves is 70.4°F.
The staff generated nozzle P-T limit curves for the two remaining PWRs using the generic ART value of 70.4 °F and compared them to the NRC-approved P-T limit curves. Based on this comparison for the two U.S. PWRs, the staff noted the following:

- The NRC-approved P-T limit curve was limiting for one reactor
- The NRC-approved P-T limit curve coincided with the P-T limit curve generated with the generic nozzle ART value of 70.4 °F for the other reactor

For the case in which the two curves coincided, the staff noted that the NRC-approved P-T limit curve was based on 36 EFPY (i.e., 40 years of plant operation); whereas, the generic nozzle ART value is based on a neutron fluence in the nozzle region that is conservatively expected after 60-years of plant operation. The staff noted that if the comparison of the NRC-approved P-T limit curve and the P-T limit curve generated with the generic nozzle ART value for the subject reactor was at the same EFPY, the nozzle material would not be limiting. In addition, as discussed in Section 4.2 of this document, the generic nozzle ART value, which is based on RT_{T0} and σ_i developed in the TR, is conservatively representative of the U.S. PWR nozzle forgings. The staff noted that the generic screening nozzle ART value included the shift of 25°F due to embrittlement and that the nozzle-specific shift can be less than this value. Thus, the staff noted that if the plant-specific nozzle material properties for the subject reactor are used, it is reasonable to expect that the nozzle would be tougher than the “generic nozzle” addressed in this TR and would make the NRC-approved P-T limit curve more limiting than the nozzle P-T limit curve.

In summary, based on its assessment of the PWROG’s justification and the staff’s independent assessment, as described above, the staff finds that for a neutron fluence less than 4.28 x 10^{17} n/cm^2 (E > 1 MeV) in the nozzle region, the NRC-approved P-T limit curves are limiting for 60 years of plant-operation when compared to the nozzle P-T limit curves. In addition, even though the PWROG did not consider the shift due to irradiation of the nozzles if ΔRT_{NDT} is less than 25°F, the staff demonstrated in its independent assessment that this assumption is unlikely to cause the P-T limit curves for inlet or outlet nozzle corners of U.S. PWRs to be more limiting than those of the shell (and associated welds) of the traditional beltline region (and closure flange regions, as applicable) of the RPV for a neutron fluence less than 4.28 x 10^{17} n/cm^2 (E > 1 MeV) in the nozzle region.

<u>Fluence Location Relative to the Postulated Flaw Location and Fluence Methodology</u>

Section 3.4.1, “Calculated Fluence Location Relative to the Postulated Flaw Location,” of the TR states that nozzle fluence values are typically assumed to be equal to the RPV upper-shell-to-nozzle forging weld fluence value or the lowest extent of the nozzle forging, and thus the nozzle fluence values are conservative. The PWROG stated that since the postulated flaws in the TR are at the nozzle corners, which are at a higher elevation and therefore further away from the

active core, the fluence value is expected to be significantly lower than the fluence at the lowest extent of the nozzle forging or weld. The staff reviewed the discussion of fluence location relative to the postulated flaw location in Section 3.4.1 of the TR and finds it acceptable.

Section 3.4.2, "Fluence Calculational Methodology," of the TR states the use of new fluence evaluation methods can more accurately determine the nozzle fluence reducing the needed conservatisms. The PWROG showed a comparison of nozzle fluence values between three methods of fluence evaluations. The staff reviewed the information in Section 3.4.2 of the TR and noted that the fluence methods approved by the NRC staff are unique to the individual licensee's current licensing basis. Thus, plant-specific fluence calculations performed by the individual licensee in a manner consistent with the NRC-approved methodology will be necessary to determine whether the use of the TR is applicable.

Neutron Streaming

Section 3.4.3, "Neutron Streaming," of the TR states that neutron streaming up the cavity to the nozzle region from the beltline region is an existing phenomenon. As such, the traditional fluence attenuation equation used in the beltline (i.e., in RG 1.99, Revision 2) is not appropriate in the nozzle region when only considering fluence calculated at the inside surface. The PWROG indicated that the fluence at the outside diameter lowest extent of the nozzles can be higher than the fluence at the lowest extent of the nozzle forging at the RPV inside surface due to cavity neutron streaming. The PWROG investigated the stresses at the inlet and outlet nozzles due to pressure and the thermal cooldown transient. The stresses are shown in Section 4.8 "Stresses at Limiting Locations" of the TR, specifically in the figures from the 3D finite element analysis. The PWROG states that these figures demonstrate that the stresses at the lowest extent outside diameter of the nozzles are significantly lower than at the nozzle inside corner, and when pressure stress and thermal stress are considered together, the combined stress is likely compressive. As is discussed in Section 4.8 of the TR, the flaw is postulated at the nozzle inside surface corner at a geometric discontinuity where the highest stresses exist. As a result, the nozzle inside corner is the limiting location, and this location is where the fluence is considered for embrittlement.

Based on its review, the staff finds the neutron streaming effect is applicable to the 3/4T postulated flaw and that the PWROG's exclusion of the 3/4T postulated flaw in the development of the P-T limits in the TR for the nozzles is appropriate, as described below. Specifically, the staff noted that the pressure stress decreases as a function of distance from the inside corner along the through-wall nozzle corner path, as shown in Figure 24 of ORNL/TM-2010/246. Therefore, the applied SIF due to pressure for a 3/4T postulated flaw at the outside corner of the nozzle would be lower than that for the 1/4T flaw postulated for the inside corner region. The linear elastic fracture mechanics analyses in ORNL/TM-2010/246 do not address 3/4T postulated flaws for this reason. It should be noted that, based on the analysis of the 1/4T location and the smaller postulated flaw from the inside corner region, the nozzle P-T limits for a heatup transient would be less restrictive than those calculated for a cooldown transient because the thermal stresses for a postulated inside corner flaw are compressive for heatup. Therefore, the staff determined that analyses of the 1/4T location and the smaller postulated flaw at the nozzle inside corner during a cooldown transient generates the most bounding P-T limits for the nozzles.

4.4 Calculation of ART

In Section 3.1.2.2, "Calculation of Generic Mean Alternate RT_{NDT}," and Section 3.5, "Adjusted Reference Temperature," of the TR, the PWROG calculated ART with and without the surface effect using the RT_{T0} (evaluated in Section 4.2 of this SE) as the initial reference temperature. The ART value with the surface effect is to be used for the postulated small flaw and the ART

value without the surface effect is to be used for the traditional, postulated 1/4T flaw in the nozzle P-T limits developed in Section 5.1, "Generation of Nozzle P-T Limit Curves," of the TR (evaluated in Section 4.10 of this SE). Both ART calculations do not consider an embrittlement shift of 25°F (which the staff evaluated in Section 4.3 of this SE) since the PWROG developed a fluence threshold screening criterion of 4.28 x 10^{17} n/cm^2. The staff noted that this fluence threshold screening criterion corresponds to a ΔRT_{NDT} of 25°F below which embrittlement shifts may be neglected.

The staff verified the ART calculations in Sections 3.1.2.2 and 3.5 of the TR consistent with the guidance in RG 1.99, Revision 2, and finds the ART values of 43°F for the 1/4T flaw and 21°F for the shallow flaw are acceptable for the A-508 Class 2 generic RT_{T0} developed in this TR.

4.5 Selection of Inlet and Outlet Nozzle Model Geometry

In Section 4.1 of the TR, the PWROG considered several geometric parameters that affect the stress due to pressure and thermal transient in the nozzle corner region. The PWROG stated that "important characteristics that affect nozzle corner stress and SIF were assessed to ensure representative or bounding models were chosen for the whole U.S. PWR fleet." The PWROG considered nozzle radius-to-thickness (R/t) ratio, nozzle diameter, nozzle corner geometry, and clad thickness as the important geometric parameters that affect the nozzle corner stress and SIF. Table 4-1, "Model Geometry Comparison," pictorially depicted in Figure 4-3, "Diversity of Nozzle Geometries Modeled," of the TR summarizes the inlet and outlet geometries that were modeled.

The staff finds the PWROG's approach for selecting nozzle model geometries acceptable since it is not practical to model the unique geometry of each inlet and outlet nozzle design in the U.S. PWR fleet. It is reasonable to consider only the parameters that are most relevant, with respect to the stress that can extend a postulated flaw in the nozzle corner. The staff considers that the thickness of the nozzle section and the sharpness of the nozzle corner radius are the most relevant parameters that can extend a postulated flaw in the nozzle corner. The staff finds that the PWROG adequately addressed the effects of these two parameters by considering the nozzle R/t ratio, nozzle diameter, nozzle corner geometry, and clad thickness. Considering the nozzle R/t ratio (and nozzle diameter which accounts for the radius) addresses the section thickness effect on stress. Considering the nozzle corner geometry addresses the effect of the nozzle corner radius, which causes high stresses on the inside surface of the corner. Considering the clad thickness addresses the effects of clad welding residual stress on the small flaw models described in Section 2.

Furthermore, the staff determined that selecting a nozzle section thickness that bounds all U.S. PWR fleet inlet and outlet nozzle is challenging for two reasons: (1) the effect of thickness on stress due to internal pressure counterbalances the effect of thickness on stress due to thermal transients: a thinner section would generate a higher stress due to internal pressure, but a lower stress due to thermal transient; and (2) the time at which the maximum stress due to internal pressure occurs does not occur at the same time the maximum stress due to thermal transient occurs. Therefore, the staff determined that the PWROG's selection of a nozzle geometry for modeling that is representative of the U.S. PWR fleet nozzle geometry is a practical and reasonable approach.

Based on the discussion above, the staff finds the four nozzle geometries listed in Table 4-1 of the TR acceptable for representing the inlet and outlet nozzle designs in the U.S. PWR fleet.

4.6 Finite Element Model and Analyses

Model Creation

The PWROG described the FEMs of the inlet and outlet nozzles in Section 4.2, "Model/Mesh," Section 4.3, "Flaw Modeling Methodology," and Section 4.6, "Material Properties," of the TR. The three-dimensional FEMs of the inlet and outlet nozzles included flaws in the nozzle corner with depths of 0.05 inch and 0.5 inch into the LAS and with length-to-depth aspect ratios of 2:1 and 6:1. The mesh in the vicinity of the modeled flaws included very fine elements that have features for handling the sharp edges around the flaw tip. The PWROG summarized the FEM cases in Table 4-2, "Flaw Case List," of the TR.

The staff reviewed the descriptions of the FEMs in Sections 4.2, 4.3, and 4.6 of the TR and finds the methods (selection of element types, meshing, and definition of material properties) acceptable.

Boundary Conditions

The PWROG described the boundary conditions applied to FEMs of the inlet and outlet nozzles in Section 4.4, "Thermal Boundary Conditions," and Section 4.5, "Structural Boundary Conditions," of the TR. Thermal boundary conditions included temperature coupling of the coincident nodes of the modeled flaw, an assumption of infinite heat transfer coefficient on the wetted surfaces, and insulated conditions on the surfaces of the FEMs where the models are "cut" from the un-modeled structure. The structural boundary conditions included displacement restraints, internal pressure on the wetted surface and on the crack face, end-cap pressure loads on the modeled RPV shell and nozzle safe-end, and mechanical loads on the modeled nozzle safe-end. Additionally, the temperature field from the thermal FEMs are applied to the structural FEMs.

The staff reviewed the descriptions of the thermal and structural boundary conditions in Sections 4.4 and 4.5 of the TR. One thermal boundary condition of the note is the assumption of infinite heat transfer coefficient on the wetted surface. The staff determined that this assumption produces a large temperature gradient across the nozzle section thickness due to a cooldown transient, which generates conservative tensile stresses on the inside surface of the nozzle corner. The staff, therefore, finds the assumption acceptable. The staff noted that the application of the temperature field from the thermal FEMs into the structural FEMs is actually a structural load in the structural FEMs and is therefore acceptable.

Based on the discussion above, the staff finds that the PWROG applied the proper boundary conditions to the inlet and outlet nozzle FEMs, and therefore finds the boundary conditions acceptable.

Loads

The PWROG described the loads applied to FEMs of the inlet and outlet nozzles in Section 4.7, "Loads," of the TR. The applied loads are the residual stress due to clad welding (clad residual stress), mechanical piping loads, and cooldown transient. The internal pressure load is treated as a boundary condition, which the staff evaluated in the "Boundary Conditions" section.

The staff reviewed the descriptions of the applied loads in Sections 4.7 of the TR. One applied load of note is the clad residual stress. The staff reviewed the PWROG's modeling approach that accounts for clad residual stress. The PWROG cited the review of the Sweden Nuclear Power Inspectorate of programs that measured the effects of cladding on structural integrity of cladded RPVs. Specifically, the PWROG referenced the residual stress profile measured across the cladding of an RPV specimen. Then, using this residual stress profile as a reference

stress distribution and the FEM described in Section 4.2 of the TR, the PWROG determined, through an iterative process, the average stress in the clad by adjusting the CTE reference temperature of the clad material that would produce a similar effect at the flaw tip as the measured clad residual stress profile. Given that the availability of residual stress measurements due to clad welding is limited, the staff determined that this approach to address the effect of clad residual stress is reasonable since the reference residual stress is based on measured data. The staff also reviewed open literature and verified that the method of adjusting the CTE reference temperature is a common approach to simulate a stress between two adjacent materials. The staff, therefore finds the load due to clad residual stress acceptable.

The piping loads included those due to deadweight and thermal expansion loads at normal operating conditions. The staff finds the piping loads acceptable. The cooldown transient included one with composite rates (100°F/hour, then 50°F/hour, then 20°F/hour) and one with 100°F/hour for the limiting outlet nozzle FEM. The staff reviewed PWR systems manuals and previous P-T limit curves for cooldown and determined that both cooldown transients are acceptable.

Based on the discussion above, the staff finds the loads applied to the FEMs of the inlet and outlet nozzle acceptable.

4.7 Stresses

The PWROG presented stresses for the inlet and outlet nozzle in Section 4.8, "Stresses at Limiting Locations," of the TR. The staff reviewed the stress contour plots due to internal pressure and cooldown transient for the inlet and outlet nozzle FEMs and determined that the stress values are within the expected values for these nozzles.

4.8 Stress Intensity Factors

The PWROG presented SIFs for the outlet nozzle in Section 4.9, "Stress Intensity Factor Results," of the TR and stated that it performed evaluations for both inlet and outlet nozzles, but showed SIF results only for the outlet nozzle in the TR. The staff determined that showing SIF results only for the outlet nozzle is sufficient for its review since the SIF results for the inlet nozzle would show similar trends because it was subject to the same loads as the outlet nozzle. The staff reviewed the SIF plots due to internal pressure and cooldown transient (which includes the effect of clad residual stress) and determined that the SIF values are reasonable compared to those calculated from a closed-form SIF solution for a nozzle corner crack.

4.9 Constraint and Cladding Effect

The staff reviewed the discussion of T-stress in Section 4.10.1, "Constraint," of the TR, which is commonly used as a measure of constraint and is correlated to toughness. The staff determined that not taking credit for the increased toughness for a nozzle corner flaw (due to lower constraint compared to the constraint on an SE(B) specimen, the data from which fracture toughness is determined) is acceptable.

The staff also reviewed the discussion of cracking restraint due to cladding in Section 4.10.2, "Cladding," of the TR and determined that not taking credit for the ability of cladding to restrain crack growth is acceptable.

4.10 Generic Nozzle P-T Limit Curves

The PWROG developed generic nozzle P-T limit curves in Section 5.1.1, “Generation of Nozzle P-T Limit Curves with Postulated Small Flaw,” and Section 5.1.2, “Generation of Nozzle P-T Limit Curves with Postulated with 1/4T Beltline Thickness Size Flaw,” of the TR based on the methodology in Appendix G to Section XI of the ASME Code.

The PWROG presented the nozzle P-T limits for the postulated small flaws in Section 5.1.1 of the TR with the ART determined in Section 3.5 of the TR, and the nozzle P-T limits for the postulated 1/4T flaws in Section 5.1.2 of the TR with the ART determined in Section 3.1.2.2 of the TR. The nozzle P-T limits for the small postulated flaws were based on SIFs developed in Section 4 of the TR and included the effect of clad residual stress. The nozzle P-T limits for the 1/4T flaws were based on stresses determined from unflawed nozzle FEMs and SIFs from ORNL/TM-2010/246 (Ref. 18 of the TR).

The staff reviewed the nozzle P-T limit curves in Sections 5.1.1 and 5.1.2 of the TR and compared the limiting curves with known nozzle P-T limit curves. The staff finds the nozzle P-T limit curves in the TR acceptable.

4.11 Comparison of Generic Nozzle P-T Limit Curves to RPV Shell P-T Limit Curves

In Section 5.2, “Comparison of Nozzle to Traditional NRC Approved Pressure-Temperature Limit Curves,” the PWROG selected the limiting nozzle P-T limit curves developed in Sections 5.1.1 and 5.1.2 of the TR and compared them to the NRC-approved P-T limits of the shell (and associated welds) in the RPV beltline region. The PWROG determined that eleven NRC-approved P-T limits of Westinghouse plants (identified in the TR as A through K) do not bound the generic limiting nozzle P-T limits developed in this TR and evaluated them separately in Figures 5-10 through 5-14 of the TR. For these eleven plants, plant-specific nozzle RT_{NDT} values were used instead of the generic nozzle RT_{T0} value developed in the TR, using the P-T limit methodologies in Sections 4 and 5.1.2 of the TR. The staff reviewed the generic bounding nozzle P-T limit curves compared to the NRC-approved P-T limit curves to determine whether the PWROG adequately addressed that the NRC-approved P-T limit curves are bounding when compared to bounding generic nozzle P-T limit curves. The PWROG provided additional information in its supplement that aided the staff’s review of the eleven plants in which the NRC-approved P-T limit curves did not bound the generic bounding nozzle P-T limits developed in the TR.

The staff reviewed Figure 5-15 of the TR, which provided a comparison of the bounding nozzle P-T limit curves compared to NRC-approved P-T limit curves for CE and B&W PWRs. Based on this comparison, the staff finds the PWROG adequately addressed that the NRC-approved P-T limit curves for CE and B&W PWRs bounds the generic nozzle P-T limit curves developed in this TR, as shown in Figure 5-9 of the TR. The staff reviewed Figure 5-9 of the TR, which provided a comparison of the Westinghouse bounding generic nozzle P-T limit curves compared to the NRC-approved P-T limit curves for Westinghouse PWRs, except for the eleven plant-specific cases which are further discussed below (i.e., Plants “A” through “K”). Based on this comparison, the staff finds the PWROG adequately addressed that the NRC-approved P-T limit curves for Westinghouse PWRs (except for Plants “A” through “K”) bound the generic Westinghouse nozzle P-T limit curves developed in this TR, as shown in Figure 5-9 of the TR. The staff’s review of Plants “A” through “K” identified in the TR is provided below.

For Plant “A,” the PWROG explained in its supplement that WCAP-18191-NP, which was previously submitted to the NRC, contains a calculation of nozzle P-T limit curves using the standard 1/4T nozzle corner flaw and the methods in ORNL/TM-2010/246, as well as the determination of the initial RT_{NDT} values for the nozzle forgings. The staff reviewed WCAP-

18191-NP, Appendix B, and verified that the licensee performed confirmatory P-T limit curve calculations of the RPV inlet and outlet nozzles. The staff noted that the Cu and Ni contents of the nozzles were based on plant-specific CMTRs and that the unirradiated RT_{NDT} values are based on drop-weight data, TL CVN test data and NUREG-0800 Branch Technical Position (BTP) 5-3, "Fracture Toughness Requirements," Positions 1.1(3)(a) and (b), with the more limiting unirradiated RT_{NDT} value being selected. The staff noted that the methodology in BTP 5-3 paragraph 1.1(3)(b) was determined to be acceptable in closure memorandum dated April 2017 (ADAMS Accession No. ML16364A285). The staff noted that the licensee performed these nozzle calculations solely to verify that the P-T limits for the RPV "traditional" beltline is bounding compared to any P-T limit curves for the RPV inlet and outlet nozzles. The staff verified that the licensee used the staff-developed methodology in ORNL/TM-2010/246 to generate the P-T limits of the nozzles. Based on its review of the pertinent information in WCAP-18191-NP, for the purposes of this TR, the staff finds the PWROG adequately addressed that the NRC-approved P-T limit curve for Plant "A" bounds the nozzle P-T limit curves, as shown in Figure 5-14 of the TR.

For Plant "B," the PWROG confirmed that the NRC-approved P-T limit curves were previously shown to not be impacted by the nozzle P-T limits curves using the 1/4T flaw, as documented in letter dated January 22, 2015 (ADAMS Accession No. ML15029A417). The staff's review of this comparison is documented in SE dated April 29, 2016 (ADAMS Accession No. ML16081A333). The staff finds the PWROG has adequately addressed that the NRC-approved P-T limit curve for Plant "B" is bounding.

For Plant "C" through Plant "H," the staff noted the nozzle RT_{NDT} values were measured to the requirements of post-1973 ASME Subarticle NB-2300, and the uncertainty associated with an RT_{NDT} estimation method does not affect these RT_{NDT} values. The staff also noted that the PWROG used the FEM with postulated flaws in the TR to generate the nozzle P-T limit curves. The staff's review of the FEM with postulated flaws in the TR are documented in Sections 4.5 through 4.9 of this SE. Based on its review, the staff finds it acceptable that the PWROG used plant-specific nozzle RT_{NDT} values instead of the A-508 Class 2 generic RT_{T0} developed in this TR, along with the FEM with postulated flaws in the TR to generate the nozzle P-T limit curves. Thus, the staff finds the PWROG has adequately addressed that the NRC-approved P-T limit curves for Plant "C" though Plant "H" bound the nozzle P-T limit curve, as shown in Figures 5-10, 5-11, and 5-12 of the TR.

For Plant "I," the PWROG indicated in its supplement that the actual design dimension of the cladding (5/8 inch after machining) was utilized with the postulated 0.5-inch deep LAS flaw, which resulted in a flaw depth of 0.99 inch from the wetted surface. The SIFs for this 0.99-inch flaw in the FEM were developed using the same methodologies that were used for the other nozzle flaws in the TR. The staff's review of the FEM with postulated flaws in the TR are documented in Sections 4.5 through 4.9 of this SE. For Plant "I," the staff noted the nozzle RT_{NDT} values were measured to the requirements of post-1973 ASME Subarticle NB-2300, and the uncertainty associated with an RT_{NDT} estimation method does not affect these RT_{NDT} values. The staff finds it acceptable that the PWROG used plant-specific nozzle RT_{NDT} values instead of the A-508 Class 2 generic RT_{T0} developed in this TR, to generate the nozzle P-T limit curves. Based on the use of the plant-specific nozzle RT_{NDT} values and the PWROG's confirmation that the flaw size for Plant "I" is based on the plant-specific design dimension of the cladding thickness, the staff finds the PWROG adequately addressed that the NRC-approved P-T limits curve for Plant "I" bounds the nozzle P-T limit curve, as shown in Figure 5-13 of the TR.

For Plants "J" and "K," the PWROG confirmed in its supplement the initial RT_{NDT} values for the reactor vessel nozzle forging materials were determined using the methodology in BTP 5-3

paragraph 1.1(3)(b). The staff noted that the methodology in BTP 5-3 paragraph 1.1(3)(b) was determined to be acceptable in closure memorandum dated April 2017 (ADAMS Accession No. ML16364A285). Based on the PWROG's confirmation regarding the source of the initial RT_{NDT} values for Plants "J" and "K," the staff finds the PWROG adequately addressed that the NRC-approved P-T limits curve for Plants "J" and "K" bounds their respective nozzle P-T limit curve, as shown in Figure 5-11 of the TR.

Based on the staff's review of the comparison for the NRC-approved P-T limit curves and the nozzle P-T limits developed in this TR, as described above, the staff finds that the PWROG has adequately demonstrated that the nozzle P-T limit curves developed in the TR are bounded by the NRC-approved P-T limit curves for U.S. PWRs.

5.0 USE AND REFERENCING OF THE TR

As addressed in the TR and in this SE, the use and referencing of this TR is only applicable to U.S. PWR inlet and outlet nozzles with a projected nozzle corner neutron fluence, as calculated by an NRC-approved method of fluence evaluation consistent with the plant licensing basis, or another NRC-approved method of fluence evaluation, of less than 4.28×10^{17} n/cm^2 (E > 1 MeV). As noted in the TR, if the nozzle fluence is greater than 4.28×10^{17} n/cm^2 (E > 1 MeV), the shift (ΔRT_{NDT}) may be calculated for those nozzles on a plant-specific basis using an NRC-approved method; as long as the shift remains below 25°F or the plant-specific ART values remain below the ART determined in the TR, then the analysis in the TR is applicable.

6.0 CONCLUSION

The staff has reviewed the TR including the supplemental information, and based on the evaluation in Section 4 of this SE, finds the TR as modified by this SE, provides an acceptable means for addressing the potential for P-T limit curves for inlet or outlet nozzle corners of U.S. PWRs to be more limiting than the current NRC-approved P-T limits (as of the time of issuance of this SE) of the shell (and associated welds) in the traditional beltline region (and closure flange regions, as applicable) of the RPV. The staff's independent safety assessment in Section 4.3 of this SE of the TR's use of the recommendation in TLR-RES/DE/CIB-2013-01 of excluding 25°F embrittlement is specific only to the TR, and as such, should not be construed as a generic safety assessment. Thus, other applications that use the recommendation in TLR-RES/DE/CIB-2013-01 must be sufficiently justified and shall be subject to NRC review and approval on a case-by-case basis. Accordingly, PWROG-15109-NP, as modified by this SE, is acceptable for referencing to satisfy the fracture toughness requirements in Appendix G to 10 CFR Part 50 for U.S. PWR inlet and outlet nozzles only, which provide adequate margins of safety during any condition of normal operation, including anticipated operational occurrences and system hydrostatic tests, to which the pressure boundary may be subjected over its service lifetime.

Attachment: Comment Resolution Table

Principal Contributors: On Yee
David Dijamco

Date: October 31, 2019

TOPICAL REPORT PWROG-15109-NP, REVISION 0					
Comment #	**DSE Page No.**	**DSE Line No.**	**Comment Type**	**PWROG Comment**	**NRC Response**
1	1	20	Editorial comment	Please revise the text to add: "and closure flange regions" after "(RPV)"	Comment acceptable
2	2	47	Editorial comment	Please revise the text to add: "beltline size" after "1/4T"	Comment acceptable
3	2	49	Editorial comment	Please revise the text to add: "and closure flange regions" after "region"	Comment acceptable
4	3	1	Editorial comment	Please revise the text to add: "and closure flange regions" after "region"	Comment acceptable
5	8	23	Clarification; the PWROG data and experience show that this conclusion is reasonable.	Please revise the text: "Although the staff does not find it reasonable that these forgings…" to: "Although the staff is unable to confirm that these forgings…"	Comment acceptable
6	8	50	Revises text to reflect correct section in the DSE	Please revise the text from: "Section 2" to "Section 4.1"	Comment acceptable
7	12	28, 38, 46	No change is being requested; this is only a comment	The value of the $\Delta RT_{NDT\ Stress}$ = 25°F has not been verified by the PWROG.	Comment noted
8	13	31	Editorial comment	After "beltline region" please add "(and closure flange regions, as applicable)".	Comment acceptable
9	16	4	Revises text to reflect correct section in the TR	Please revise the text from: "Section 4.3" to "Section 4.4" and "Section 4.4" to "Section 4.5".	Comment acceptable
10	16	15	Revises text to reflect correct section in the TR	Please revise the text: "Sections 4.3 and 4.4" to "Sections 4.4 and 4.5".	Comment acceptable
11	20	5	Clarification; this change makes it consistent with the text on DSE page 13, lines 48-52	Please revise the text after "NRC-approved method of fluence evaluation" adding "consistent with the plant licensing basis, or another NRC-approved method of fluence evaluation".	Comment acceptable
12	20	9	Editorial comment	Please add the text "then" after "TR,"	Comment acceptable
13	20	17	Editorial comment	Please add the text "(and closure flange regions, as applicable)" after "beltline region".	Comment acceptable