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DRAFT SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

FOR THE PRESSURIZED WATER REACTOR OWNERS GROUP

TOPICAL REPORT PWROG-18068-NP, REVISION 1,

“USE OF DIRECT FRACTURE TOUGHNESS FOR EVALUATION OF RPV INTEGRITY”

PROJECT NO. 694; DOCKET NO. 99902037

EPID: L-2021-TOP-0027

1.0 INTRODUCTION

By letter dated July 27, 2021 (Ref. 1), the Pressurized Water Reactor Owners Group (PWROG) submitted Topical Report (TR) PWROG-18068-NP, Revision 1, “Use of Direct Fracture Toughness for Evaluation of RPV [Reactor Pressure Vessel] Integrity” (Ref. 2, hereinafter referred to as the TR), to the U.S. Nuclear Regulatory Commission (NRC) for review and approval. By email dated March 30, 2022, the NRC staff transmitted requests for additional information (RAIs) (Ref. 3). The TR was supplemented by letters dated March 8, 2024, and July 24, 2024 (Ref. 4). The enclosures to the March 8, 2024, letter included: (1) responses to RAIs, and (2) the markup of revisions to the TR (hereinafter referred to as the TR markup). The attachment to the July 24, 2024, letter included additional changes to the TR.

The TR proposes an alternative methodology to the structural integrity requirements for RPV materials specified in Title 10 of the *Code of Federal Regulations* Part 50, “Domestic Licensing of Production and Utilization Facilities.” (10 CFR Part 50). The proposed alternative methodology is based on the use of the ductile-brittle reference temperature (T_0) in lieu of the nil-ductility reference temperature (RT_{NDT}) for RPV material integrity evaluations. The details of the alternative methodology are discussed in Section 4.0 of this safety evaluation (SE).

2.0 REGULATORY EVALUATION

The NRC has established requirements in 10 CFR Part 50 to protect the integrity of RPV materials. The regulations relevant to the TR are summarized below.

- 10 CFR 50.12, “Specific exemptions,” specifies criteria for which the NRC may grant exemptions from the requirements of the regulations of 10 CFR Part 50. Exemptions from 10 CFR 50.61 and 10 CFR Part 50, Appendices G and H, accordance with 10 CFR 50.12 will be needed in order for an applicant to implement the TR methodology because the methodology uses an approach to RPV integrity evaluations that is different than the requirements for RPV integrity evaluations in 10 CFR Part 50. The details of such exemptions are described in Section 5.1 of this SE.

- 10 CFR 50.55a, “Codes and standards,” incorporates by reference applicable codes and standards and specifies conditions on the use of the codes and standards.

- 10 CFR 50.60, “Acceptance criteria for fracture prevention measures for light water nuclear power reactors for normal operation,” specifies fracture toughness and embrittlement surveillance program requirements for RPV materials during normal operation events; these requirements are set forth in Appendixes G and H to 10 CFR Part 50.

- 10 CFR 50.61, “Fracture toughness requirements for protection against pressurized thermal shock [(PTS)] events,” requires reference temperature of the RPV materials be within specific values to protect RPV materials against PTS events.

- 10 CFR Part 50, Appendix G, “Fracture Toughness Requirements,” specifies fracture toughness requirements for RPV materials to provide adequate margins of safety against fracture during normal operation events. The regulation in 10 CFR Part 50, Appendix G, refers to Appendix G to Section XI of the American Society of Mechanical Engineers (ASME) *Boiler and Pressure Vessel* Code (ASME Code). Section XI of the ASME Code is incorporated by reference in 10 CFR 50.55a.

- 10 CFR Part 50, Appendix H, “Reactor Vessel Material Surveillance Requirements,” specifies surveillance program requirements for monitoring RPV embrittlement due to neutron irradiation.

- ASME Code Case (CC) N-830, “Direct Use of Master Fracture Toughness Curve for Pressure-Retaining Materials of Class 1 Vessels, Section XI,” is a conditionally approved CC in Regulatory Guide (RG) 1.147, Revision 20, “Inservice Inspection Code Case Applicability, ASME Section XI, Division 1” (Ref. 5). This CC specifies an alternative fracture toughness curve that may be used in lieu of the curve specified in Appendix G of Section XI of the ASME Code, subject to the conditions specified in Table 2 of RG 1.147, Revision 20. RG 1.147, Revision 20, is incorporated by reference in 10 CFR 50.55a.

3.0 TECHNICAL EVALUATION

3.1 Overview of Topical Report PWROG-18068-NP, Revision 1

The TR covers the following major topics:

Section 1 of the TR discusses the “Purpose” and summarizes the proposed methodology that uses direct (i.e., T_0-based) fracture toughness data at the ductile-brittle transition temperature as an alternative to the RPV integrity requirements of 10 CFR 50.61 and 10 CFR Part 50, Appendix G, both of which use RT_{NDT}-based fracture toughness.

Section 2 of the TR presents the “Background” of the document and describes the current approach for evaluating fracture toughness in 10 CFR 50.61 and 10 CFR Part 50, Appendix G, the advantages of using T_0-based fracture toughness, and precedents for the use of T_0-based fracture toughness.

Section 3 of the TR addresses “U.S. Nuclear Regulatory Commission Regulations” and discusses the regulatory requirements affected by the proposed methodology in the TR.

Section 4 of the TR discusses “Methodology For Application of Master Curve Test Data” and provides the details of the methodology proposed in the TR for using the T_0-based fracture toughness data at the ductile-brittle transition temperature to evaluate RPV fracture toughness.

Section 5 of the TR presents the “Overall Summary” and summarizes the content contained in Sections 1 through 4 of the TR.

Appendix A of the TR includes details about “Mini-C(T) Specimen Geometry” and describes use of mini-compact tension (C(T)) specimen geometry compared with standard size C(T) specimen geometry.

Appendix B of the TR contains information on “Irradiated Data Generation Using Mini-C(T) Specimens” and describes the generation of irradiated data from mini-C(T) specimens.

Appendix C of the TR discusses “Example Applications” and provides examples that show the applicability of the TR methodology.

4.0 STAFF EVALUATION OF THE PROPOSED METHODOLOGY

This section documents the NRC staff's evaluation of the TR against the relevant criteria described in Section 2.0 of this SE.

The NRC staff evaluated the proposed methodology described in Section 4 of the TR for the application of T_0 data from irradiated specimens or unirradiated specimens of RPV material (irradiated or unirradiated T_0 data”) for the evaluation RPV material integrity in lieu of the current approach that is based on RT_{NDT} in 10 CFR 50.60, 10 CFR 50.61, and Appendix G to 10 CFR Part 50. In particular, the NRC staff evaluated Equation 1 of the TR for PTS evaluations and Equations 2 and 3 of the TR for development of pressure-temperature (P-T) limit curves, or P-T limits. The NRC staff also evaluated the specific procedures and criteria described in Sections 4.1 through 4.6 of the TR for using the equations to determine T_0-based fracture toughness for ferritic RPV shell materials, which include base metals and welds. In these equations, the parameter, T_0, is the reference temperature that characterizes the fracture toughness of ferritic steels at the onset of cleavage crack initiation, as defined in the testing method in American Society for Testing and Materials (ASTM) E1921-20. This testing method is sometimes referred to as the “master curve method” as discussed below. The current approach to determine fracture toughness is based on RT_{NDT} which is derived from drop-weight tests and Charpy V-notch impact tests.

In Section 2.1 of the TR, the PWROG explained that since RT_{NDT} is determined from drop-weight tests and Charpy impact tests that are based on impact energy, the fracture toughness resulting from the use of RT_{NDT} is not a true (i.e., not a direct) measure of the fracture toughness transition temperature for crack initiation. The PWROG stated that the use of the master curve method (i.e., ASTM E1921-20) is based on true transition temperature fracture toughness tests, and that the master curve method provides a more accurate index of the material fracture toughness transition temperature as compared to RT_{NDT}. The PWROG further stated that the use of T_0 removes the uncertainty in the use of RT_{NDT} and, in turn, establishes a more robust statistical basis for indexing the fracture toughness of the RPV material. Hence fracture toughness based on T_0 is often referred to as direct fracture toughness.

The NRC staff conducted a two-day regulatory audit from January 17 to January 18, 2024, to clarify its understanding of the particular aspects associated with the proposed TR methodology. The regulatory audit plan and audit summary report (Ref. 6) are publicly available.

The NRC staff notes that PWROG has extensively revised Section 4 of the original TR dated July 27, 2021, to align with NRC staff's RAIs dated March 20, 2022. As such, in the SE, the original submittal is denoted as "TR" and the revised TR dated March 8, 2024, is denoted as "TR markup" as stated in Section 1.0 of this SE. The NRC staff discusses the technical basis in the original TR with the understanding that some of the technical basis has been revised or deleted in the TR markup.

Section 4 of the TR describes the proposed methodology, which uses irradiated or unirradiated T_0 data for the evaluation of RPV material integrity in lieu of the current approach in the regulations that is based on RT_{NDT}.

For PTS evaluations, the PWROG proposes the use of TR Equation 1. For P–T limits curve development, the PWROG proposes the use of either Equation 2 or Equation 3 of the TR. The TR equations are reproduced below. The TR markup provided clarifications on Equations 1 and 2 of the TR by defining RT_{T0} to be T_0 + 35°F, consistent with the 2017 Edition of the ASME Code, Section XI, Appendix G. The units are °F for Equation 1, and the units are ksi√in and °F for Equations 2 and 3.

$$RT_{PTS} = RT_{T0} + \textit{adjustment} + \textit{margin} \qquad \text{[Equation 1]}$$

$$K_{Ic} = 33.2 + 20.734 \exp[0.02\,(T - \{RT_{T0} + \textit{adjustment} + \textit{margin}\})] \qquad \text{[Equation 2]}$$

$$K_{Jc\text{-}lower95\%} = 22.9 + 33.3 \exp[0.0106\,(T - \{T_0 + \textit{adjustment} + \textit{margin}\})] \qquad \text{[Equation 3]}$$

Where RT_{PTS} is the nil-ductility reference temperature for PTS evaluations as defined in 10 CFR 50.61; K_{Ic} is the linear-elastic, plain-strain crack initiation fracture toughness, which is referred to in Appendix G to Section XI of the ASME Code as the critical or reference stress intensity factor; and $K_{Jc\text{-}lower95\%}$ is the 95 percent lower tolerance bound master curve fracture toughness as defined in CC N-830.

Equation 2 of the TR is based on the 2017 Edition of the ASME Code, Section XI, Appendix G. Equation 3 of the TR is based on ASME Code Case N-830 as modified by the NRC condition in RG 1.147, "Inservice Inspection Code Case Acceptability, ASME Section XI, Division 1," and 10 CFR 50.55a. The "adjustment" and "margin" terms in Equations 1 to 3 of the TR are defined and evaluated in Sections 4.3 and 4.4 of this SE. Generation and validation of irradiated data for the proposed TR methodology are discussed in Section 4.1 of this SE. Specimen test data and an approach for determining a T_0 value if only unirradiated T_0 data are available are discussed in Section 4.2 of this SE; uncertainty due to material variability is discussed in Section 4.5 of this SE; flowcharts for applying the TR methodology are discussed in Section 4.6 of this SE; implementation of the TR methodology and TR sample calculations are discussed in Section 4.7 of this SE; and exemption needed for implementing the TR methodology are discussed in Section 5.1.

4.1 Generation and Validation of Irradiated Data

Section 4.1 of the TR discusses the generation and validation of irradiated data for the proposed methodology. The PWROG stated that ideally, the RPV material to be evaluated would be obtained from a surveillance capsule irradiated in the RPV. The PWROG further stated that only a small portion of the U.S. PWR plants have their P–T limits curve-limiting and near-limiting materials included in their RPV material surveillance programs because inclusion of all near-limiting materials is not a requirement for RPV material surveillance program design. In addition, the RPV limiting material can change depending on Charpy shift measurements, credibility determination, and embrittlement projection methods. According to the PWROG, it is advantageous to have T_0-based fracture toughness test data for all RPV materials that are limiting or might become limiting. Most plants have their P–T curve limiting and near-limiting materials in unirradiated archive storage. Therefore, the PWROG stated that it is advantageous to be able to irradiate specimens at a high flux to produce relevant fluence data in a reasonable time period. In Appendix B.2 of the TR, the PWROG stated that Material Test Reactor (MTR) irradiations typically produce representative or conservatively biased results. The PWROG defines “high flux” as a flux greater than that experienced by any surveillance capsule in commercial pressurized water reactors (PWRs). ASTM E900-15, “Standard Guide for Predicting Radiation-Induced Transition Temperature Shift in Reactor Vessel Materials,” ASTM International, 2015, identifies the maximum flux for a PWR irradiation included in the database which formed the basis of the embrittlement trend correlation (ETC) as 5×10^{12} n/cm^2/s (E > 1 MeV). Therefore, the NRC staff evaluated the generation and validation of irradiated T_0 data for the proposed methodology.

In Appendix B of the TR, Figures B-1 and B-2 show plots of the effect of flux on RPV welds and forgings. The NRC staff noted that the correlation between the shift in RT_{NDT} due to neutron irradiation (ΔRT_{NDT}, which is equivalent to ΔT_{41J}) and the shift in T_0 due to neutron irradiation (ΔT_0) in Figures B-1 and B-2 does not appear to be close to the nearly 1-to-1 general correlation illustrated in TR Figure 6. The data in Figures B-1 and B-2 seem to imply that ΔT_0 is higher than ΔT_{41J} and that this disparity increases with increasing fluence. In response to RAI No. 22 Part (a), the PWROG stated that the ΔT_{41J} and ΔT_0 measurements shown in Figures B-1 and B-2 are a relatively small sample size and are within the same distribution of data as shown in Figure 6 and new Figure 7 of the TR markup. The PWROG also indicated that Section 5.3 in MRP-462, “Methods to Address the Effects of Irradiation Embrittlement in Section XI of the ASME Code (MRP-462): Estimation of an Irradiated Reference Temperature Using Either Traditional Charpy Approaches or Master Curve Data,” EPRI, Palo Alto, CA: 2021, 3002020911 (as addressed in Ref. 4, March 8, 2024 responses to RAI No.13) and Section 4.3.5 of the TR markup (evaluated in Section 4.3.5 of this SE) contain a more detailed analysis of the correlation of ΔT_{30} (i.e., ΔT_{41J}) to ΔT_0 with larger data populations than what is shown in Appendix B, Figures B-1 and B-2 of the TR.

The NRC staff also noted that Figures B-1 and B-2 of the TR contain limited high-flux data, especially at high fluences (i.e., above 1E+20 n/cm^2). The NRC staff requested information on how this relative lack of high-fluence data, and the associated larger uncertainties have been addressed in the TR methodology (i.e., in both the testing requirements and analysis methods) to properly account for flux effects. The NRC staff further requested information regarding the conditions in the MTR and PWR irradiations that need to be met to assure that these conditions are representative, or conservative, with respect to the intended evaluation conditions. In response to RAI No. 22 Part (b), the PWROG stated that the validation material will be exposed in the same irradiation campaign and will have a similar fluence to the other materials in the same MTR. For each copper (Cu) grouping discussed in the paragraph below and identified in the TR, the comparison of the data obtained from the validation material exposed in an MTR to the data obtained from samples of the same material exposed in a PWR ensures that the results are representative or conservative. The MTR irradiated validation material fluence must be within 50 percent of the PWR reactor irradiated validation material used for comparison ensuring representativeness at the fluence of interest, although the TR does not quantify the maximum allowed adjustment of the Adjusted $T_{0\text{high flux VM}}$ term in Equation 9 of the TR markup (formerly Equation 7). The PWROG revised the last paragraph in Section 4.1 of the TR as discussed in the response to RAI No. 01 and as shown in the TR markup.

The PWROG stated that the effect of flux on embrittlement shift is dependent on the Cu level and neutron fluence. The PWROG stated that depending on where in the Cu-related hardening regime the material is during irradiation, the effect can vary. The PWROG categorized Cu as "low Cu," "medium Cu," and "Cu saturated" to determine RPV embrittlement. The PWROG stated that the low Cu level and the level at which Cu saturation occurs is included in the ASTM E900-15 ETC Cu term. Therefore, validation materials are grouped based on three Cu weight percent (wt. %) categories as follows: (a) Low Cu is defined as Cu wt. % ≤ 0.053; (b) Medium Cu is defined as 0.053 < Cu wt. % < 0.28; and (c) High Cu is defined as Cu wt. % ≥ 0.28. The PWROG indicated that each material irradiated in a high flux test reactor must have at least one validation material in the corresponding Cu grouping to provide a quantitative evaluation of any neutron flux effects. Materials in the same Cu group would be expected to behave similarly with respect to any flux effect, especially at high fluence (60-year RPV core region fluence) when Cu precipitation has already occurred. The PWROG stated that the validation material results are used in the overall methodology to ensure conservatism of the test results.

In response to RAI No. 01, the PWROG clarified that when MTR data are used, each Cu grouping must have at least one validation material heat which is also being or has been irradiated in a PWR, and, as mentioned above, the MTR validation material fluence has to be within 50 percent of the PWR validation fluence (i.e., 0.5 x PWR validation fluence < MTR validation material fluence < 1.5 x PWR validation fluence) to provide a quantitative evaluation of any flux effects. For example, the PWROG stated that if specimens from two heats were irradiated in an MTR within the same Cu group, a specimen from one of those heats must also be irradiated in a PWR and used as the validation material for the other heat, as discussed in Section 4.3.4.2 of the TR. The PWROG added this clarification as shown in the TR markup.

The NRC staff noted that the PWROG's discussion on the generation and validation of irradiated MTR data in Section 4.1 of the TR as summarized above centers on two aspects: (a) the discussion in Appendix B.2 of the TR to show that higher flux irradiation data from MTRs is representative or conservative compared to low flux irradiation data from PWRs; and (b) MTR irradiation data is appropriately validated against PWR irradiation data. The acceptability of the first aspect depends on the acceptability of the correlation between ΔT_{41J} and ΔT_0 (i.e., the correlation between ΔT_{30} and ΔT_0), which is discussed in Section 4.3.5 of this SE. The acceptability of the second aspect depends on the acceptability of the validation of MTR irradiation data against PWR irradiation data, which is discussed in Section 4.3.4.2 of this SE. Therefore, based on the NRC staff's evaluations of these two aspects in Sections 4.3.4.2 and 4.3.5 of this SE, the NRC staff finds the generation and validation of irradiated MTR data for the proposed TR methodology acceptable because (a) the correlation between ΔT_{30} and ΔT_0 as used in the proposed TR methodology is acceptable; and (b) the approach for validating the MTR-irradiated T_0 data against the PWR-irradiated T_0 data validation material is acceptable.

4.2 Specimen Test Data

Section 4.2 of the TR discusses the evaluation of the specimen test data used for determining T_0 for the proposed methodology. The PWROG requires that test data from material from the same heat as the RPV material of interest be used to evaluate the RPV fracture toughness. The RPV material of interest, which would typically be the limiting and/or near-limiting material(s). In response to RAI No. 02, the PWROG provided additional information on the use of generic unirradiated T_0 data and added the information in the TR, as shown in Sections 4.2 and 4.3.1 of the TR markup. The PWROG clarified that the TR methodology cannot be used for development of generic irradiated T_0 values nor for the application of measured irradiated T_0 data on a different heat number than the heat number of the RPV material of interest.

The PWROG added a methodology for determining an unirradiated T_0 value from generic unirradiated T_0 values. This methodology is based on the statistical method described in Section 9.12 of NUREG-1475, Revision 1 (Ref. 7) to determine a generic unirradiated T_0 value based on the mean T_0 value, standard deviation (S) about the mean T_0, and the 95/95 one-sided tolerance limit factor ($k1$), which is a function of the number of measured heats (n). The PWROG specified using at least four measured heats (i.e., n = 4 or more) with valid unirradiated T_0 for forgings, plates, and welds based on common manufacturer, material class, or flux types. In Attachment 1 of the July 24, 2024, letter (Ref. 4), the PWROG clarified that “forgings, plates, and welds based on common manufacturer, material class, or flux types” means that the material purchase or welding fabrication specification and heat treatment must be consistent with the RPV material of interest. The PWROG stated that the basis for the generic grouping must be documented (i.e., included) with the document implementing the methodology. The PWROG also defined a margin term, Equation 5 of the TR markup, that uses the $k1$ and S values from NUREG1475, Revision 1. In Attachment 1 of the July 24, 2024, letter (Ref. 4), the PWROG clarified that the second term under the square root sign of Equation 5 of the TR markup is $\{2 \bullet \text{Equation 12}\}^2$. The NRC staff finds this clarification acceptable because Equation 12 of the TR markup ensures a minimum of 9°C margin to account for adjustment uncertainty. The Equation 5 margin term is to be used when determining an unirradiated T_0 value from generic unirradiated T_0 values. The NRC staff finds the application of the statistical method in Section 9.12 of NUREG-1475, Revision 1, for determining an unirradiated T_0 value from generic unirradiated T_0 values of similar materials to be acceptable because the method would ensure that the resulting generic unirradiated T_0 value would bound greater than or equal to 95 percent of the measured unirradiated T_0 values with 95 percent confidence level. The NRC staff noted that “similar materials” means the unirradiated materials available for T_0 data are similar and they are similar to the RPV material of interest.

The PWROG stated that specimens must be removed from approximately the 1/4 or 3/4 wall thickness (T) (1/4T or 3/4T) location in a plate or forging, and weld specimens can be removed from any depth location except near the surfaces. ASTM E185-82, “Standard Practice for Conducting Surveillance Tests for Light-Water Cooled Nuclear Power Reactor Vessels, E 706,” provides additional details on specimen location with reference to the source material. Plate and forging specimens are to be oriented in the transverse (weak) direction, while weld specimens are to be oriented with crack growth parallel to the weld seam (i.e., welding direction).

The PWROG stated that the T_0 test data must meet the requirements of ASTM E1921-20. If T_0 test data was produced in accordance with another version of ASTM E1921 or another test standard (e.g., ASTM E399), the user of the TR must review the data and revise the analysis to ensure compliance with ASTM E1921-20. According to the PWROG, extra specimens are recommended to be tested to ensure that a valid T_0 is obtained. The dataset will be screened for inhomogeneity as discussed in paragraph 10.6 of ASTM E1921-20. Datasets that fail the screening criterion will be evaluated in accordance with Appendix X5, “Treatment of Potentially Inhomogeneous Data Sets,” of ASTM E1921-20 with T_0 set equal to T_{0IN} (T_{0IN} is a biased T_0 accounting for data screened as inhomogeneous as defined in Appendix X5.2 of ASTM E1921-20) for all subsequent calculations and validations in this methodology. Alternatively, the procedures of Appendix X5.3.2 or X5.3.3 of ASTM E1921-20 may be used for large inhomogeneous datasets exhibiting bimodal or multimodal behavior, respectively.

Section 3.2 of the TR explains the use of ASTM E1921-20 in the TR methodology, which is a version of the ASTM standard that has not been referenced in the latest edition of Section XI of the ASME Code incorporated by reference in 10 CFR 50.55a. The PWROG states that ASTM E1921-15 is incorporated by reference in 10 CFR 50.55a through the 2017 Edition of ASME Code, Section XI and that the use of ASTM E1921-20 is specified in the TR methodology because ASTM E1921-15 does not have a homogeneity screening procedure. The PWROG further stated that in addition to the homogeneity screening procedure, ASTM E1921-20 includes minor updates to specimen and testing requirements and a slightly different equation due to coefficient rounding as compared to ASTM E1921-15, and that otherwise, the 2015 and 2020 versions of the ASTM standard are equivalent with respect to the TR methodology. The NRC staff reviewed ASTM E1921-15 and ASTM E1921-20 and confirmed that there is nothing in the noted updates and differences between the two versions of the ASTM standard that would have a significant impact on the determination of T_0 for homogenous datasets.

In response to RAI No. 03, the PWROG stated that the requirement for the size of the dataset is defined in ASTM E1921-20, paragraph 10.3, which is based on the judgment of the industry consensus body of the ASTM E08 committee that the dataset size requirements provide sufficient accuracy to determine T_0. For datasets meeting the minimum requirement, the standard deviation of a valid T_0 is defined in ASTM E1921-20, paragraph 10.9 and is a function of the number of uncensored test specimen. The NRC staff reviewed paragraphs 10.3 and 10.9 of ASTM E1921-20 to ensure their consistency with the corresponding paragraphs in ASTM E1921-15 that is incorporated by reference in 10 CFR 50.55a. The NRC staff noted that ASTM E1921-20 provides a clearer definition of the confidence level for the standard deviation of a valid T_0 test value because it includes a specific definition of this confidence level, whereas ASTM E1921-15 states that the confidence level is based on engineering judgment. Therefore, the NRC staff finds that with regards to dataset size, ASTM E1921-20 is acceptable because it provides clarity to the confidence level for the standard deviation with regard to the valid T_0 test value.

Section 3.2 of the TR states that for inhomogeneous datasets, the resulting T_0 determined from ASTM E1921-20 would be more conservative than the T_0 determined in accordance with ASTM E1921-15. In responses to RAIs nos. 04 and 16, the PWROG provided additional explanation regarding inhomogeneous datasets. In response to RAI No.16, the PWROG clarified that if a dataset does not satisfy the homogeneity screening criterion in ASTM E1921-20 (i.e., the dataset is inhomogeneous) the data will be evaluated in accordance with Appendix X5 of ASTM E1921-20. The PWROG revised Section 4.2 of the TR (as shown in TR markup) to state that the procedures of Appendix X5.3.2 or X5.3.3 of ASTM E1921-20 may be alternatively used for large inhomogeneous datasets ($N \geq 20$) exhibiting bimodal or multimodal behavior, respectively. In response to RAI No. 04, the PWROG removed the allowance for modification of the ASTM E1921-20 T_{0IN} by (1) positioning $K_{Jc\text{-}lower95\%}$ curve through the least tough data point and (2) modification of the specimen test standard deviation (described in Section 4.4.1 of the TR) as shown in the TR markup. The NRC staff finds that removal of the above allowance acceptable because it removes the potential non-conservatism in the determination of the ASTM E1921-20 T_{0IN} value and associated specimen test standard deviation.

The PWROG stated that test data from specimens of any ASTM E1921 standard geometry include the mini-compact tension [C(T)] size (0.16 inch thick), and that significant experience has shown that the mini-C(T) specimen size produces results that are indistinguishable from larger C(T) specimens as discussed in TR Appendix A. The PWROG indicated that test data from the three-point bend (3PB) Charpy 10×10 mm size specimen is applicable if a bias correction addition of 18°Fahrenheit (°F) (equivalent to a bias correction of 10°Celsius [°C]) is included. If there is a mixture of Charpy 3PB and mini-C(T) specimens, the bias can be prorated based on the proportion of Charpy 3PB specimens. In response to RAI 10, the PWROG stated that, instead of a prorated value, the bias correction of 18°F (10°C) due to the use of Charpy 3PB is added to the test temperature of each Charpy 3PB specimen when calculating T_0. The PWROG added this revision in Section 4.2 of the TR markup. The PWROG explained that the uncertainty for the mini-C(T) specimen T_0 measurement is treated the same as for larger C(T) specimens, as described in Appendix A of the TR. The NRC staff finds the treatment of specimen test data acceptable because a bias value is added to each Charpy datapoint instead of adding a prorated value to the T_0 measured value when Charpy 3PB specimens are used. The NRC staff determined that adding the bias value to the Charpy 3PB datapoint adequately addresses the test specimen uncertainty when using Charpy 3PB specimens. Additionally, Appendix A of the TR adequately demonstrates that there is no significant bias or uncertainty associated with the use of mini-C(T) specimens to determine T_0.

Based on the discussion above, the NRC staff finds that evaluation of the specimen test data used for determining T_0 for the proposed TR methodology is acceptable because PWROG stated that: (a) the method for determining a generic unirradiated T_0 value would ensure that the generic unirradiated T_0 value would bound greater than or equal to 95 percent of the measured unirradiated T_0 values with 95 percent confidence level; (b) the T_0 test data must meet the requirements of ASTM E1921-20 that includes treatment of small and large inhomogeneous datasets; and (c) the uncertainty or bias due to test specimen type used for determining T_0 is adequately accounted for in the methodology.

4.3 Adjustment Term in Equations 1, 2, and 3 of the Topical Report

Section 4.3 of the TR describes the determination of the *adjustment* term used in Equations 1, 2, and 3 of the TR. The PWROG stated that irradiated specimens will rarely reflect the exact same irradiation conditions and chemistry as the represented RPV shell material. The TR further states that adjustments are necessary to compensate for differences between test samples (i.e., specimens) and the actual RPV shell material in the field. According to the PWROG, the ETC contained in ASTM E900-15 is the most recent internationally accepted consensus standard for predicting RPV embrittlement. ASTM E900-15 is used to account for the difference between the embrittlement of the specimens and actual RPV embrittlement. ASTM E900-15 ETC is based on a Charpy 30 ft-lb transition temperature shift (ΔT_{30}) database comprised of 1,878 power reactor surveillance program shift measurements. The TR markup stated that average ΔT_{30} is not exactly the same as ΔT_0 and that there is a clear relationship between the two values (see Figure 6 and Figure 7 in TR markup) and the average differences can be accounted for using the adjustment of 1.0 for welds or 1.1 for base metals (BM) as shown in Equation 6 in the TR markup.

The PWROG stated that in the case of the ASTM E900-15 ETC, none of the adjustments can be made using data outside the calibration range of the shift prediction model as shown in Table 1 of the TR. The PWROG noted that flux may be outside the calibration range in the case of an MTR; however, flux is not used to determine data adjustments and whether the data is representative is validated as discussed in Section 4.1 of the TR. The calibration range for the ASTM E900-15 ETC is reproduced in Table 1 of the TR.

The NRC staff evaluated specific aspects of the adjustment methodology in the following subsections. The NRC staff notes that the specific use of ASTM E900-15 in the TR methodology does not constitute generic approval of ASTM E900-15. The NRC staff evaluated the specific use of ASTM E900-15 in the TR methodology based on its evaluation of the ΔT_{30} and ΔT_0 correlation in Section 4.3.5 of this SE and the adjustment uncertainty, i.e., $\sigma_{adjustment}$ in Section 4.4.2 of this SE.

4.3.1 Chemistry (Copper, Manganese, Nickel, and Phosphorous)

Section 4.3.1 of the TR states that irradiated test materials must be from the same heat as the RPV materials of interest; therefore, chemistry adjustments should be relatively small. The PWROG further stated that for RPV base metals, no chemistry adjustment is typically required, because the test samples are removed from the same RPV base material and there is typically no difference between the best-estimate chemistry in the tested specimen material and the RPV base metal. For welds, there generally is a chemistry difference between the test material source (usually the surveillance weld) and the RPV weld best estimate. The PWROG indicated that the test specimen material source chemistry and heat best-estimate chemistry for the RPV weld should be used when determining the adjustment calculation for welds.

The NRC staff finds the adjustment term on chemistry for welds acceptable because the adjustment procedure specified in the TR accounts for the differences between the chemistry for the test specimen material source and the best-estimate chemistry for the heat of the RPV weld. The NRC staff further finds the adjustment term on chemistry for base metal acceptable because the test samples are removed from the same RPV base material and there is typically no difference between the best-estimate chemistry in the tested specimen material and the RPV base metal.

4.3.2 Temperature

Section 4.3.2 of the TR states that the time-weighted average temperature for the RPV thickness location that corresponds to the fluence projection should be used for the RPV, and the test sample irradiation time-weighted average temperature should be used in the adjustment calculation. The PWROG stated that for P–T limit calculations the temperature at the 1/4T or 3/4T crack tip can be used in the ETC calculation. Alternatively, if a simplified conservative approach is used, the value of average cold leg temperature (T_{cold}) can be used in the ETC, which will over-estimate the effect of embrittlement on ΔT_{30}. Gamma heating of the RPV in the beltline region increases the RPV wall temperature relative to T_{cold} at the wetted surface during normal operation, and a lower embrittlement shift occurs at higher irradiation temperatures. T_{cold} should be used for PTS calculations that are performed for the clad/low alloy steel interface where the irradiation temperature would be very close to T_{cold}.

In response to RAI No. 06, the PWROG clarified that the reason for using T_{cold} for PTS calculations is that it would be at a lower temperature value (thus higher embrittlement shift) compared to the temperature toward the insulated outside RPV surface because of gamma heating. The PWROG included the clarification in TR markup, Section 4.3.2. The NRC staff finds the clarification acceptable because the use of T_{cold} temperature for PTS calculations would ensure a higher embrittlement shift compared to the embrittlement shift resulting from a higher temperature due to gamma heating. Based on this discussion, the NRC staff finds the adjustment term on temperature acceptable.

4.3.3 Fluence

Section 4.3.3 of the TR states that the best-estimate fluence (E > 1 MeV) at both the RPV thickness location of interest and the test specimens must be determined to make the necessary adjustments. The RPV and test material fluence shall be determined using an NRC-approved methodology of fluence evaluation consistent with the plant licensing basis, or another NRC-approved methodology for fluence evaluation. RPV wall neutron attenuation to the postulated flaw tip location can be determined by one of three ways using an NRC-approved fluence calculation methodology:

1. Consistent with RG 1.99, Revision 2 (Ref. 8),

2. The ratio of displacement per atom (dpa) at the postulated flaw depth to dpa at the inner surface may be substituted for the exponential attenuation factor in Equation 6 of the TR, or

3. Directly calculated E > 1 MeV neutron fluence at the desired RPV thickness location.

With regard to the bulleted item No. 2 above, the NRC staff noted that either the dpa or fluence at crack depth location is required to predict the other, unknown variable (from a single equation). In response to RAI No. 18, the PWROG stated that the exponential attenuation factor in the revised Equation 7 of the TR markup is "$e^{-0.24x}$". Substituting (flaw depth dpa)/(inner surface dpa) would reduce the surface fluence to the flaw depth fluence. For example: $fluence_{1/4T} = fluence_{surface} * dpa_{1/4T} / dpa_{surface}$. PWROG stated that this is consistent with the guidance provided in Section 1.1 of RG 1.99, Revision 2. The PWROG added Equation 8 in the TR markup to clarify how the dpa ratio can be used to directly calculate the fluence at a given distance (x) from the inner surface.

$$fluence_X = fluence_{surface} \bullet e^{-0.24x} \qquad \text{[Equation 7 of TR markup]}$$

$$fluence_X = fluence_{surface} \bullet (dpa\ at\ x\ /\ dpa\ at\ inner\ surface) \qquad \text{[Equation 8 of TR markup]}$$

Where,

$fluence_X$ = the fluence at x depth of the RPV wall thickness
$fluence_{surface}$ = the fluence at the inner wetted surface of the RPV
x = the depth into the RPV wall measured from the inner wetted surface of the RPV

The NRC staff finds that the use of the fluence parameter in the equation to derive the adjustment term is acceptable because the TR methodology specifies that an NRC-approved methodology for fluence evaluation should be used and the fluence attenuation equation (item no. 2 above), must therefore, be consistent with the guidance of RG 1.99, Revision 2.

4.3.4 Flux

Section 4.3.4 of the TR discusses two sources of flux, typical PWR flux and the high flux of an MTR, for adjustments related to the irradiation fluence rate (i.e., flux). The PWROG stated that flux is the fluence divided by effective full power years. The NRC staff evaluated these two sources of neutron flux in the following subsections.

4.3.4.1 Power Reactor Flux

Section 4.3.4.1 of the TR states that specimens irradiated in a power reactor at a flux not considered "high" (i.e., a flux less than 5 ×10^{12} n/cm^2/s, E > 1 MeV) generally are considered to have a flux that is representative of the flux received by the RPV material. The ASTM E900-15 ETC used for the adjustment term has no flux term, because the flux does not have a statistically significant effect within the power reactor irradiation flux range. The NRC staff reviewed Section 4.3.4.1 of the TR and finds that specimens irradiated in a power reactor flux need no further adjustment because the flux in a power reactor is representative of the flux that is received by the RPV material.

4.3.4.2 Material Test Reactor Flux

Section 4.3.4.2 of the TR states that for high flux irradiations, a set of validation specimens must be irradiated and tested to validate that the high flux irradiated specimens are representative or conservative compared to PWR flux specimens. In Attachment 1 of the July 24, 2024 letter (Ref. 4), the PWROG clarified that high flux irradiations mean, for example, MTR irradiations used in an MTR campaign. The PWROG stated that T_0 data obtained from a PWR flux irradiation must be available to provide a comparison for the same RPV material heat to the high flux validation specimens from the MTR. The PWROG clarified in Section 4 of the TR markup and in the response to RAI No. 07 that if multiple datasets for the heat of interest include both MTR and PWR irradiations, the MTR irradiations will not be used. The NRC staff noted that this is the case for the two examples in Appendix C of the TR markup, in which the MTR irradiated T_0 data was not used in the final irradiated T_0 value.

The PWROG indicated that after adjusting for differences in exposure using the ASTM E900-15 ETC, the high flux and PWR-irradiated T_0 values determined must be compared to validate that the high flux irradiation produced representative or conservative T_0 results. The PWROG implemented this comparison as an inequality, Equation 7 of the TR (Equation 9 in the TR markup), that must be determined true or false. The left side of the inequality is the high flux irradiated T_0 value, and the right side of the inequality is the PWR irradiated T_0 value. The PWROG stated that if the inequality in Equation 7 of the TR is met (i.e., the inequality is true), the T_0 values in the corresponding material grouping ("low Cu", "medium Cu", or "high Cu") for the high flux irradiation are considered representative of, or conservative, compared to the irradiation of the PWR RPV material of interest. The PWROG stated that if the inequality in Equation 7 of the TR is not met (i.e., the inequality is false), the T_0 values of the high flux materials in the corresponding material grouping ("low Cu", "medium Cu", or "high Cu") will be increased to ensure the T_0 results are representative of the PWR RPV material of interest. In this case, the difference in T_0 results between the high flux and PWR irradiations is assumed to be a result of differences in embrittlement shift due to irradiation in the MTR. Therefore, the increase in T_0 for the materials in the corresponding material grouping are a proportion of the predicted embrittlement shift as shown in Equation 8 of the TR (Equation 10 in the TR markup).

The PWROG provided additional explanation and clarifications on Equations 7 and 8 of the TR and revised them as Equations 9 and 10, respectively, in the TR markup and in the responses to RAI Nos. 11 and 12. The NRC staff reviewed the explanation and clarifications, especially noting the removal of the term "$2 \cdot \sqrt{(\sigma_{test\ high\ flux\ VM}^2 + \sigma_{test\ PWR\ VM}^2)}$" in Equation 7 of the TR (revised as Equation 9 as shown in the TR markup), where $\sigma_{test\ high\ flux\ VM}$ is the standard deviation of the test data for the high flux validation material and $\sigma_{test\ PWR\ VM}$ is the standard deviation of the PWR validation material, the revised subscripts in Equation 8 (revised as Equation 10), and the explanation of handling of multiple datasets.

The removal of the term "$2 \cdot \sqrt{(\sigma_{test\ high\ flux\ VM}^2 + \sigma_{test\ PWR\ VM}^2)}$" from Equation 7, resulting in Equation 9 of the TR markup, adds conservatism in the parameter on the left side of the equation because it results in a higher T_0 value compared to the T_0 value obtained from the equation with the "$2 \cdot \sqrt{(\sigma_{test\ high\ flux\ VM}^2 + \sigma_{test\ PWR\ VM}^2)}$" term. The revised subscripts in Equation 8 clarify the meaning of the terms in the equation. The NRC staff also noted that Equation 8 ensures that when the T_0 value of the MTR-irradiated validation material is less than the T_0 value of the PWR-irradiated validation material, the T_0 value of the MTR-irradiated validation material is increased based on the T_0 value of the PWR-irradiated validation material to ensure that the MTR-irradiated data is representative of PWR-irradiated data. The NRC staff verified the example application of Equation 8 in the revised Table C-3 in the TR markup. The NRC staff determined that handling of multiple datasets (multiple MTR-irradiated T_0 data and/or multiple PWR-irradiated T_0 data) is adequate because the weighting method in Section 4 of the TR markup is used to validate the MTR-irradiated T_0 data to the PWR-irradiated T_0 data. The NRC staff finds the weighting method acceptable because the TR used weighting factors that ensure the MTR data that are closer to the PWR validation data have more weight. The NRC staff also determined that the handling of the case when there is separate independent MTR-irradiations is adequate because the MTR-irradiated T_0 data that is closest to satisfying Equation 7 (revised as Equation 9) will be used.

The NRC staff finds the approach for adjusting the MTR-irradiated T_0 data described in Section 4.3.4.2 of the TR to be acceptable because the adjustment is based on PWR-irradiated T_0 data validation material.

4.3.5 Correlation between ΔT_{30} and ΔT_0

The NRC staff notes that during nuclear plant operation, neutron irradiation embrittles the RPV material. The RPV embrittlement is measured or calculated based on the shift of the reference temperature. The TR methodology uses ΔT_{30} for embrittlement shift of the RPV material because the ASTM E900-15 ETC model is based on ΔT_{30} data. Section 4.3.5 of the TR states that in some cases, there is a measured difference between the embrittlement shift ΔT_{30} and ΔT_0. Since the ETC model uses ΔT_{30}, and the TR methodology uses ΔT_0, the difference between ΔT_{30} and ΔT_0 should be considered and correlated. There is no commonly accepted ETC model based on ΔT_0.

The PWROG stated that on average, the ratio of ΔT_0 to ΔT_{30} embrittlement shift for welds is 0.99 and 1.1 for plates. The PWROG further stated that due to lack of forging embrittlement shift data, a value of 1.1 has previously been used for forgings matching the plate value, as shown in NUREG-1807, "Probabilistic Fracture Mechanics — Models, Parameters, and Uncertainty Treatment Used in FAVOR [Fracture Analysis of Vessels Oak Ridge] Version 04.1" (Ref. 9). The PWROG indicated that additional forging data (approximately 30 points) from literature confirmed that a value of 1.1 for forging materials is appropriate. The PWROG suggested that for simplicity and conservatism, 1.0 be used for welds and 1.1 be used for plates and forgings. NUREG-1807, Section 4.2.3.4.2 provides justification for adding no uncertainty when converting from ΔT_{30} to ΔT_0 (or vice versa). The NRC staff finds that the justification for not considering uncertainty is adequate because when ΔT_0 and ΔT_{30} are better defined, their values would have less scatter. The PWROG stated that when measured ΔT_0 values are determined from a large number of specimens, there is less scatter.

The NRC staff noted that the discussion in the TR of the correlation between ΔT_{30} and ΔT_0, as shown in TR Figure 6, does not include model uncertainty (i.e., uncertainty in the correlation). In response to RAI No. 13 Part (a), the PWROG stated that the uncertainty (standard deviation) of a T_0 measurement tested in accordance with ASTM E1921 typically ranges from approximately 10°F to 14°F when testing the minimum number of 6 or 7 specimens. The uncertainty of a typical T_{30} measurement can range from approximately 6°F to 18°F. Each ΔT_{30} and ΔT_0 data point has four measurements associated with its initial T_0, initial T_{30}, irradiated T_0, and irradiated T_{30}. Therefore, there are four uncertainties associated with each point in the revised Figure 6 and new Figure 7 in the TR markup. Markup Section 4.3.5 of the TR summarizes the fitting statistics of the ΔT_{30} - ΔT_0 correlation in Figures 6 and 7 of the TR markup. The NRC staff finds that Figure 6 (for welds) and Figure 7 (for base metal) present appropriate relationships of the embrittlement shift between ΔT_{30} and ΔT_0 for welds and base metal, respectively, based on statistical study of the measured data.

In response to RAI Nos. 13 Part (b) and 13 Part (c), the PWROG stated that the TR methodology allows for adjustment of both unirradiated and irradiated T_0 measurements. Unirradiated measurements use the same reference state, and therefore, there is no difference. For the adjustment of irradiated T_0 values, in most cases the adjustments are small and any deviation in the slope due to the different (irradiated) reference state would have a minimal impact on the adjustment. The ΔT_0 /ΔT_{30} slope is the same with the reference state for unirradiated vs. irradiated measurements, as discussed below. There is no change in failure mechanism, only a shift in the ductile-to-brittle transition curve due to irradiation.

In response to RAI No.13 Part (d), PWROG stated that Section 5.3 of MRP-462, "Methods to Address the Effects of Irradiation Embrittlement in Section XI of the ASME Code (MRP-462): Estimation of an Irradiated Reference Temperature Using Either Traditional Charpy Approaches or Master Curve Data," EPRI, Palo Alto, CA: 2021, 3002020911, provides a more detailed analysis of larger data populations than what is presented in NUREG-1807. The MRP-462 methods yield, for welds, a mean of 0.99 with a standard error on the slope of 0.02. For plates, the mean is 1.11 with a standard error on the slope of 0.03. For forgings, the mean is 1.09 with a standard error on the slope of 0.06. For plates and forgings combined, the mean is 1.10 with a standard error on the slope of 0.03. These results are consistent with that presented in the response to RAI No. 13 (a) and the revision to Section 4.3.5 of the TR. The PWROG stated that the conclusion in MRP-462 is the same as the TR with a slope of 1.0 for welds and 1.1 for base metals recommended for use in converting from ΔT_{30} to ΔT_0 with no uncertainty added, since the uncertainty is largely due to measurement and material variability, which are explicitly addressed in the TR. The 95 percent confidence level (2σ) on the ΔT_0 / ΔT_{30} slope for the welds is 0.95 to 1.02 and for base metal is 1.03 to 1.13. The NRC staff determined that the confidence level on the ΔT_0 / ΔT_{30} slope provides adequate coverage for uncertainties, and therefore, is acceptable.

The PWROG stated that both the ASTM E23 Charpy impact specimens tested in the ductile-brittle transition temperature (DBTT) region (and fit with a hyperbolic tangent curve to determine the reference temperature at 30 (foot-pounds (ft-lbs)) and the ASTM E1921 T_0 reference temperature are both measuring the location of the DBTT. A cleavage event initiates in both the Charpy test as well as the E1921 fracture test after a plastic zone is formed at the notch or precrack tip. The PWROG stated that the absolute value of the two DBTT measurements is different, however, the change (shift) due to neutron irradiation is caused by the same mechanism (initiation of the cleavage event); therefore, the underlying physics is the same. The absolute values of each metric are different due to differences in the test such as: geometry, loading rate, notch tip, etc. The PWROG stated that the available data with the same material having both ΔT_0 and ΔT_{30} at multiple fluence levels is limited and likely would not produce statistically significant results due to the small sample size. The NRC staff finds that when the sample size is small for the same material having embrittlement shift at multiple fluence levels, the embrittlement results would not be statistically significant.

The PWROG indicated that a recent collection of weld and plate data of absolute T_0 vs. T_{30} showed a linear relationship between T_0 and T_{30} including unirradiated and irradiated data to high fluence with a similar slope as shown in Figure 6 and new Figure 7 of the TR markup. The PWROG stated that the preponderance of data shows a linear relationship between ΔT_0 and ΔT_{30} with no significant deviation in trend at higher shifts (which tends to represent a high fluence). The PWROG showed a best-fit line for the error in the linear fits (residual) of ΔT_0 and ΔT_{30} starting from a midshift (fluence) to a higher fluence to demonstrate that the error trend is statistically insignificant. The NRC staff determined that based on the data in Figures 6 and 7 from mid-shift fluence to high fluence, the error between ΔT_0 and ΔT_{30} values is statistically insignificant.

The PWROG stated that NUREG/CR-6609 "Comparison of Irradiation-Induced Shifts of K_{Jc} and Charpy Impact Toughness for Reactor Pressure Vessel Steels" (Ref. 10) shows a linear 1:1 relationship between absolute T_0 (shown as T100 in the figure) and T_{41J} (Charpy 30 ft-lb temperature) with an $R^2 = 0.90$. K_{Jc} is the stress intensity factor for elastic-plastic fracture mechanics, describing fracture toughness up to cleavage instability in terms of J-integral, J_C. R^2 is the correlation coefficient.
The PWROG stated that the reported one standard deviation residual uncertainty is 20°C and does not appear to change with T_{41J} and that this absolute residual is similar to the residuals determined for the shift comparison shown in Table 2 of the TR markup of 17°C for welds and base metal. Therefore, the PWROG stated that the scatter in individual measurements is due to measurement uncertainty, material variability and the conversion of T_{41J} to T_0. The correlation is linear and the uncertainty on the correlation (long dashed lines) is small similar to those shown in Figures 6 and 7 of the TR. The PWROG concluded that using the overall linear slope with no added uncertainty to adjust the irradiated data is appropriate. The NRC staff determined that the uncertainty is not needed to adjust the irradiated data because the correlation as shown in Figures 6 and 7 is linear and uncertainty on the correlation is small.

The NRC staff determined that Section 4.3.5 of the TR markup has presented data demonstrating that correlation between ΔT_0 and ΔT_{30} is acceptable based on statistical analysis of embrittlement shift data as discussed above. Based on the discussion above, the NRC staff finds the correlation between ΔT_{30} and ΔT_0 as used in the proposed TR methodology acceptable because of the following PWROG actions: (a) provided an adequate basis for not including model uncertainty associated with the correlation between ΔT_{30} and ΔT_0; and (b) adequately justified a ΔT_0 / ΔT_{30} linear correlation slope of 1.0 for welds and 1.1 for base metals.

4.4 Margin Term in Equations 1, 2, and 3 of the Topical Report

The NRC staff notes that Equations 1, 2, and 3 as shown in Section 4.0 of the TR contain a margin term to account for various uncertainties. Section 4.4 of the TR states that this margin term accounts for uncertainties in the test measurement of T_0, the adjustment uncertainty (if required), irradiation temperature uncertainty of the test specimens and of the RPV, and neutron fluence uncertainty of the test specimens and RPV. The PWROG stated that these uncertainties are independent; therefore, they are combined using the square root of the sum of the squares (SRSS) as shown in Equation 9 of the TR.

In the TR markup, the margin term has been revised to Equation 11, where σ_{test} is changed to σ_{E1921}, and $\sigma_{additional}$ is changed to $\sigma_{adjustment}$. The uncertainties are defined and evaluated below.

4.4.1 Determination of Testing Uncertainty

Section 4.4.1 of the TR discusses the determination of the uncertainty due to specimen testing, σ_{test}. In response to RAI 19 (a) and as shown in the TR markup, the PWROG removed the use of σ_{test} for inhomogeneous materials from the TR and replaced it with σ_{E1921} which is consistent with the ASTM E1921-20 definition. Also, PWROG revised TR Section 4.4.1 as shown in the TR markup to state that: "…σ_{E1921} is calculated in accordance with paragraph 10.9 of ASTM E1921 (with standard calibration practices, $\sigma_{exp} = 4°C$). Alternatively, if the Procedures of X5.3.2 or X5.3.3 of ASTM E1921-20 are used for large inhomogeneous data sets ($N \geq 20$), then the associated σ will be substituted with σ_{E1921}, as the number of samples will ensure that there is a sufficient population of low toughness data included in the result…"

As indicated above, the NRC staff confirmed that no difference between ASTM E1921-15 and ASTM E1921-20, including the updates in the latter version, would have a significant impact on the determination of T_0 for homogenous datasets. Further, as discussed in Section 4.2 of this SE, ASTM E1921-15 is incorporated by reference in 10 CFR 50.55a through the 2017 Edition of ASME Code, Section XI. As such, the NRC staff finds that ASTM E1921-20 provides an adequate standard test method for determination of reference temperature, T_0, for ferritic steels in the transition range for the purposes of this TR. The NRC staff reviewed Section 4.4.1 of the TR markup and determined that the method for determining σ_{test} (revised to σ_{E1921}) is acceptable because the method follows ASTM E1921-20. The NRC approval of the TR does not imply or infer the NRC approval of generic use of ASTM E1921-20. The NRC staff notes that the use of ASTM E1921-20 is limited to the use of the TR methodology.

4.4.2 Determination of Adjustment Uncertainty

Section 4.4.2 of the TR states that if adjustments exceed the standard deviation of the ETC, an additional margin, $\sigma_{additional,}$ is required to be included in the margin term for the test measurement of $T_{0,}$ i.e., $\sigma_{additional,}$ Equation 10 of the TR provides the derivation of $\sigma_{additional,}$. If adjustments do not exceed the standard deviation of the ETC, $\sigma_{additional}$ is set equal to zero.

The PWROG stated that the intent of $\sigma_{additional}$ is to include the uncertainty of the adjustment due to the underlying uncertainty of the ETC trend. SD_{ETC} is based on the standard deviation of the measured T_0 data relative to the ETC TTS [TTS = E900-15 predicted shift in 30 ft-lb transition temperature (°C)] which represents the uncertainty in making a single prediction, which includes measurement and input uncertainties. The margin term in Equation 9 of the TR independently accounts for uncertainties in measurement, temperature, and fluence. Furthermore, any chemistry variation is considered indirectly through the homogeneity screening, which identifies atypical toughness variation. The PWROG stated that use of $\sigma_{additional}$ double counts several of the uncertainties that are explicitly included in the margin term. The PWROG indicated that the uncertainty of the ASTM E900-15 prediction within a specific heat (after the heat bias has been compensated for) is less than SD_{ETC}. The PWROG stated that for the same heat σ_{ETCRPV} (the standard deviation of the ETC prediction for the RPV material of interest) and $\sigma_{ETCspecimens}$ (the standard deviation of the ETC prediction for the test specimens) are not independent and do not need to be combined using the square root sum of squares (SRSS). The PWROG further stated that instead, these uncertainties are combined as a simple difference in Equation 10 of the TR, implying that the uncertainties are fully dependent. The PWROG explained that although σ_{ETCRPV} and $\sigma_{ETCspecimens}$ are neither fully dependent nor fully independent, the approximation of being fully dependent is appropriate, because some uncertainties are being double counted in this methodology. Using Equation 10 of the TR with unirradiated test specimens, $\sigma_{ETCspecimens}$ = 0°F and, therefore, $\sigma_{additional} = \sigma_{ETCRPV} = SD_{ETC}$. The PWROG noted that this approach is similar to the approach in BAW-2308, Revision 1-A, “Initial RT_{NDT} of Linde 80 Weld Materials,” B&W Owners Group, August 2005, where unirradiated data is used with the full σ_{ETC} and is combined with σ_{To} and $\sigma_{Monte\ Carlo}$ (a measure of material variability).

In regard to the adjustment described above, and similar to the development and use of Equation 5 of the TR (and RAI No.17) for calculating SD_{ETC}, the NRC staff noted that any additional margin should be a function of the amount of ETC shift between the test data and RPV application and not solely a function of the standard deviation of the ETC. The NRC staff noted that a bigger shift between the RPV and specimen should have more uncertainty and that Equation 10 of the TR would not account for the amount of shift. The NRC staff also noted that the additional margin should be exactly equal to the ETC standard deviation if one of the conditions is the unirradiated state.

In response to RAI No. 20 Part (a), the PWROG removed the allowance to set the adjustment uncertainty term to 0 as shown in Section 4.4.2 of the TR markup. As the adjustment gets larger due to the difference in TTS between the RPV material and the test specimens, so does $\sigma_{additional}$ (revised to be $\sigma_{adjustment}$ in the TR, as discussed in the response to RAI No. 5 Part (a) and discussed below). With an unirradiated T_0, the $adjustment = \Delta T_{30\ RPV}$, making the $\sigma_{adjustment}$ = SD of ASTM E900-15 or 9°C whichever is larger. The PWROG has added the 9°C minimum to account for material variability and other uncertainties with small adjustments. The NRC staff determined that including the 9°C to account for material variability is acceptable as discussed further in Section 4.5 of the SE. The PWROG has revised Equation 9 of the TR to Equation 11 and Equation 10 of the TR to Equation 12 as shown in the TR markup.

The PWROG stated that $\sigma_{adjustment}$ is required to account for the uncertainty of adjusting the measured T_0 to the RPV condition of interest as determined by Equation 12. The $\sigma_{adjustment}$ is the simple ratio of the adjustment magnitude to $\Delta T_{30\ RPV}$ and cannot be smaller than 9°C. For unirradiated T_0 data, the $\sigma_{adjustment}$ becomes the ETC uncertainty. The NRC staff determined that Equation 12 is acceptable because it provides an adjustment sufficient to address the uncertainty for the measured T_0 to the RPV material of interest.

In RAI No. 20 Part (b), the NRC staff questioned differences in chemistry between test data and the RPV of interest. In response to RAI No. 20 Part (b), the PWROG stated that the TR methodology adjusts for the difference in the best estimate chemistry of the test material and the best estimate of the RPV material (typically the heat best estimate) in Section 4.3 of the TR.

There is still variation in chemistry about the best estimate. If this chemistry variation were to significantly affect the fracture toughness distribution (e.g., the Cu variation in an irradiated weld, if not saturated, could affect the toughness distribution), the inhomogeneity screen in Section 4.2 of the TR conservatively addresses this scenario. This is demonstrated in practice on the WF-70 Midland Beltline weld shown in Table C-9 and Figure C-2 of the TR (see the response to RAI No. 4 Part (c)). The PWROG proposed to revise Section 4.4.2 of the TR to state that "...Furthermore, any local chemistry variation is considered indirectly through the homogeneity screening, which identifies atypical toughness variation..." The NRC staff determined that any local chemistry variation would be accounted for in the homogeneity screening and, is therefore, acceptable.

Section 4.4.2 of the TR states: "The uncertainty of the ASTM E900-15 prediction within a specific heat (after the heat bias has been compensated for) is less than SD_{ETC}." The NRC staff noted that it is reasonable to suggest that a smaller standard deviation of the ETC curve exists within a specific heat of material. However, that doesn't imply that the standard deviation should be simply equal to the standard deviation differences between the RPV and test specimens as proposed in Equation 10. The implication is that if σ_{ETCRPV} and $\sigma_{ETCspecimen}$ are the same, then $\sigma_{additional}$ is zero. The NRC staff was not clear regarding why the TR does not evaluate both σ_{ETCRPV} and $\sigma_{ETCspecimen}$ and then choose the greatest uncertainty value in this situation. Therefore, in RAI No. 20 Part (c), the NRC staff asked about whether Equation 10 is appropriate for calculation $\sigma_{additional}$ for a specific heat of material and why σ_{ETCPRV} and $\sigma_{ETCspecimen}$ are not evaluated, and then $\sigma_{additional}$ set to the maximum uncertainty value. In response to RAI No. 20 Part (c), the PWROG stated the methodology in the TR markup now has a minimum $\sigma_{additional}$ adjustment of 9°C and for larger adjustment is defined in the new Equation 12.

The NRC staff noted that Section 4.4.2 of the TR stated that $\sigma_{additional}$ double counts several of the uncertainties that are explicitly included in the margin term (Equation 9), but the TR is not clear about what other terms in Equation 9 of the TR associated with the $\sigma_{additional}$ term double counts for and why or how it double counts. The NRC staff requested additional information regarding the double counting of margin terms in the $\sigma_{additional}$ term to understand if the uncertainties are reasonably accounted for. In response to RAI No. 20 Part (d), the PWROG revised Section 4.4.2 of the TR as follows: "The minimum value of 9°C also addresses other unidentified uncertainties such as material variability. The ASTM E900-15 standard deviation (SD) is based on the SD of the measured data relative to the ETC ΔT_{30} prediction which represents the uncertainty in making a single prediction, and which includes uncertainties associated with unirradiated and irradiated T_{30} measurements, material differences between the unirradiated and irradiated T_{30} measurements, and ETC input uncertainties including irradiation temperature, fluence and chemical composition… When using [TR markup] Equation 12 with unirradiated test specimens, $\sigma_{adjustment}$ becomes the ASTM E900-15 SD." The NRC staff determined that the TR has addressed the uncertainty adequately because the TR has adequately considered the uncertainties associated with unirradiated and irradiated T_{30} measurements and a minimum of 9°C for the adjustment.

The NRC staff finds the method for determining $\sigma_{additional}$, which is revised to be $\sigma_{adjustment}$, acceptable because the TR markup has adequately addressed the measurement uncertainties and input uncertainties for the unirradiated and irradiated T_{30} measurements.

4.4.3 Determination of Temperature Uncertainty

Section 4.4.3 of the TR defines the margin terms, $\sigma_{tempspecimen}$ and $\sigma_{tempRPV}$. $\sigma_{tempspecimen}$ is defined as the effect of uncertainty of the specimen irradiation temperature on T_0 embrittlement using the ETC **x** (ΔT_0 / ΔT_{30} Slope) at the specimen best estimate condition. The term $\sigma_{tempRPV}$ is defined as the effect of the uncertainty of the RPV irradiation temperature on embrittlement using the ETC **x** (ΔT_0 / ΔT_{30} Slope) at the RPV best estimate condition.

The PWROG stated that the total PWR instrument loop temperature is measured often and averaged over many cycles; therefore, the standard error of the time weighted average temperature (standard error = standard deviation / √ N) is small. The PWROG stated that therefore, the uncertainty of the average (standard error) irradiation temperature is less than or equal to 2°F after averaging at least data from four plant operation cycles. The PWROG explained that there may be some unique situations (i.e., short irradiation time), but 2°F for the uncertainty in the time weighted average irradiation temperature can be used conservatively for surveillance capsule and RPV wall irradiations. For MTR irradiations, the PWROG stated that the temperature uncertainty should be provided by the irradiation facility. If the specimens were irradiated in a surveillance capsule contained in the assessed RPV, the temperature of both are largely controlled by the coolant in the downcomer region. The PWROG stated that, therefore, the capsule irradiation temperature uncertainty is addressed in the RPV irradiation temperature uncertainty term and $\sigma_{tempspecimen}$ can be set to zero.

The PWROG noted that these σ values are the effect on the ETC prediction as a result of the temperature uncertainty, explaining that a 2°F irradiation temperature uncertainty does not necessarily correlate to a 2°F embrittlement shift because, for example, changing the irradiation temperature by 2°F can result in a 6°F embrittlement shift. The PWROG stated that the effect of a change in irradiation temperature equal to the uncertainty must be assessed by changing the input to the ASTM E900 ETC from the best-estimate conditions to determine the σ value in terms of embrittlement shift.

In response to RAI No.14, the PWROG clarified how the irradiation temperature uncertainty of 2°F is derived. The NRC staff finds the clarification on the derivation of 2°F uncertainty on temperature acceptable because temperature is measured often and averaged over many operational cycles, and thus, uncertainty is expected to be small compared to 2°F. Further, the NRC staff noted that using the temperature uncertainty as an input to the methodology rather than as an adjustment to calculated embrittlement shift fully accounts for the uncertainty. Based on this discussion, the NRC staff finds the method for determining $\sigma_{tempspecimen}$ and $\sigma_{tempRPV}$ acceptable.

4.4.4 Determination of Fluence Uncertainty

Section 4.4.4 of the TR defines the margin terms, $\sigma_{fluencespecimen}$ and $\sigma_{fluenceRPV}$. $\sigma_{fluencespecimen}$ is defined as the effect of uncertainty of the specimen fluence on embrittlement using the ETC **x** (ΔT_0 / ΔT_{30} Slope) at the specimen best estimate condition. $\sigma_{fluenceRPV}$ is defined as the effect of uncertainty of the RPV fluence on embrittlement using the ETC **x** (ΔT_0 / ΔT_{30} Slope) at the RPV best estimate condition.

The PWROG stated that the fluence uncertainty may not be completely captured in the variation of the test specimen fluence and toughness. Therefore, the fluence uncertainty is based on the NRC-approved methodology used to calculate fluence. The RPV fluence uncertainty may be one standard deviation of the methodology uncertainty. The PWROG further stated that dosimetry activity measurements can be used to reduce the uncertainty in the calculated fluence values; therefore, use of a least squares evaluation considering in-capsule dosimetry measurements is acceptable for determining the specimen fluence uncertainty. PWROG further stated that if ex-vessel dosimetry measurements are available, use of a least squares evaluation considering the dosimetry measurements is acceptable for determining the RPV fluence uncertainty.

The PWROG noted that these σ values are the effect on the ETC prediction as a result of the fluence uncertainty. For example, a 6% fluence uncertainty does not necessarily correlate to a 6% change in embrittlement shift. The PWROG stated that the effect of an increase in fluence equal to the uncertainty must be assessed by changing the input to the ASTM E900 ETC from the best-estimate conditions to determine the σ value(s) in terms of embrittlement shift.

In response to RAI No. 15, the PWROG confirmed the NRC staff's understanding of the fluence uncertainties defined in Section 4.4.4 of the TR. Accordingly, the NRC staff finds the method for determining $\sigma_{fluencespecimen}$ and $\sigma_{fluenceRPV}$ acceptable because fluence uncertainty is based on the NRC approved methodology used to calculate fluence, not on the variation of test specimen fluence and toughness, and the fluence uncertainties are used as input to the methodology rather than as a correction to the calculated embrittlement shift.

4.5 Material Variability Uncertainty

Section 4.5 of the TR states that the existing approach for accounting for the material variability in RPV embrittlement relies on the uncertainty of the prediction model which is based on many embrittlement shift measurements of many materials. Thus, empirical ETCs inherently reflect uncertainty related to material variation and chemistry uncertainties in the predicted standard deviation. The PWROG stated that when measuring the fracture toughness reference temperature (i.e., T_0) in the irradiated condition, an embrittlement prediction is not used (except to make adjustments). The PWROG indicated that the variation in the chemistry in the product that affects embrittlement shift, and any initial fracture toughness variation must be considered to ensure an appropriate level of conservatism.

The PWROG stated that paragraph 10.6 of ASTM E1921-20 describes the homogeneity screening procedure to detect if the dataset may be representative of a macroscopically inhomogeneous material. The PWROG explained that inhomogeneity in fracture toughness could be the result of at least two effects: initial properties or variation in embrittlement effects. Datasets that fail the homogeneity screening criterion in ASTM E1921-20 are evaluated in accordance with Appendix X5 of ASTM E1921-20.

According to the PWROG, variability in the entire RPV material population may be undetected in the tested material as a result of macroscopic variation (i.e., macro segregation) which may not occur in the tested material. However, this scenario could also be present using current methods in which qualification samples are removed from only a small portion of the component. PWROG stated that ASME Code safety factors such as a 1/4T flaw size, a safety factor of two on pressure stress, and the use of material properties from the 1/4T location ensure that sufficient conservatism is included.

The PWROG stated that 10 CFR 50.61 contains inherent conservatism as shown in NUREG-1874, "Recommended Screening Limits for Pressurized Thermal Shock (PTS)" (Ref. 11). The PWROG further stated that an RPV ring forging containing macro segregation had toughness at the inside surface no lower than the 1/4T toughness of the acceptance ring even when considering the reduced toughness in the macro segregated region. The PWROG indicated that the TR methodology does not change the safety factors in the ASME Code, 10 CFR Part 50 Appendix G, or 10 CFR 50.61. Thus, no explicit uncertainties are needed to consider material variability aside from those associated with the homogeneity screening. The PWROG contended that measurement of T_0-based fracture toughness reduces the uncertainty associated with the correlation of RT_{NDT} to fracture toughness and that measurement of irradiated fracture toughness near the condition of interest removes the uncertainty associated with embrittlement prediction.

The NRC staff noted that if all limiting materials could be completely tested, there would be no epistemic uncertainty due to material variability, and it would be appropriate not to consider additional uncertainty to address possible material variability. However, because only a relatively small number of representative (and not the actual) limiting materials can be evaluated using the TR methodology, the uncertainty in whether the limiting material condition has been evaluated increases. The NRC staff also noted that the ASME Code addresses some of these uncertainties for plates and forgings by requiring, for example, testing at the quarter-wall thickness locations, but no such stipulation exists for the weld materials. The TR did not provide sufficient information to demonstrate that material variability does not need to be considered. As such, the NRC staff asked PWROG to justify why material variability does not need to be considered in the TR methodology for RAI no. 21.

In response to RAI No. 21 Part (a), the PWROG provided additional justification and explanation on material variability. The PWROG stated that all product forms have material variability to different degrees. The PWROG stated that the ASTM E1921-20 method has been demonstrated to represent the product tested from a small set of sampled material. For example, in the response to RAI No. 4 Part (c), the PWROG showed that worst case small sample subsets were evaluated from large specimen populations removed from RPV forgings, plates, and welds, in which large portions were tested with some exhibiting significant variability in fracture toughness. The conclusion was that ~95 precent of data from any test temperature was bounded for the least conservative subset assessed. PWROG stated that if all subsets were considered from the ten large datasets, the data bounded is considerably more than 95 percent. PWROG stated that in addition, the ASME Code Section XI, Appendix G includes safety factors such as a 1/4T flaw size and a safety factor of two on pressure stress. The detectable flaw size during the pre-service and periodic in-service inspections is much smaller than the 1/4T size flaw.

The PWROG stated that the toughness measured in a fracture toughness test occurs as the plastic zone develops at the crack tip with the applied load and produces sufficient local stress coinciding with a local stress concentrator that would be sufficient to cause cleavage initiation in the metal matrix. Therefore, the volume of material tested is a function of the crack front length and stressed region/plastic zone size along the crack front and would be different for each specimen tested. Regardless of the size and number of specimens tested, the sampled volume of material is relatively small even relative to the specimen volume. The principal is the same with a Charpy impact specimen tested in the ductile to brittle transition temperature (DBTT) regime in which a plastic zone forms at the notch tip and grows and/or tears until a cleavage initiator is encountered with sufficient local stress. The NRC staff's concern was whether the small size specimens will provide similar results as from the larger size specimens. The NRC staff determined that the fracture toughness measurements of a small Charpy specimen is similar to that of large size specimen.

The PWROG stated that cleavage fracture typically initiates at grain triple points, carbides, or other microscopic stress concentrators. If there is a sufficient density of such sufficiently sized cleavage initiators within the critical region of a test specimen, then the expected weakest-link behavior is experienced as reflected in the ASTM E1921 methodology. The typical base metal ASTM grain size ranges from 6-8, which is a grain diameter of 0.022 mm to 0.045 mm. PWROG stated that for a mini-CT specimen with a 4 mm thickness (crack front length), approximately 100 grains or more are sampled. With ~10 specimens tested in accordance with ASTM E1921 to measure a T_0, 1000 or more grains are sampled in the plastic zone ahead of the pre-crack tip. PWROG indicated that for a macroscopically homogeneous material, the consistency of the small 4 mm test specimen results with larger size test specimens, as shown in Appendix A of the TR, demonstrates that sufficient microscopic initiators are being sampled by the crack front. The NRC staff noted that for a homogeneous material, testing of small specimens should provide adequate data result as compared to the data results from the larger size test specimens.

The PWROG stated that for macroscopically inhomogeneous materials, T_{0IN} resulting from the ASTM E1921 inhomogeneous screening procedure conservatively addresses the identified lower toughness material.

The PWROG stated that it is possible that a flaw could be associated (correlated) with low toughness inhomogeneity, however, the peak fluence location (most embrittled region) is unlikely to be associated with an unidentified flaw in a low toughness region of a large forging or plate. First, the peak RPV fluence is at the inside surface where PTS is evaluated. Thick section RPV plates and forgings have improved toughness at the surface versus deep locations due to the higher cooling rate at the surface during tempering. The ASME Code, Section III, Division 1, NB-2300 qualification specimens and T_0 test specimens are removed at the 1/4T location from the surface. PWROG stated that the T_0 for specimens developed in accordance with the TR methodology are from the 1/4T locations. The average improvement in surface toughness for RPV forgings is 36.5°F relative to the 1/4T location. Therefore, the peak fluence will inherently occur in material which has better fracture toughness than the tested specimens. PWROG stated that this conclusion also considers the potential impact of carbon macro-segregation, which can cause lower toughness at the surface in large forgings. The NRC staff noted that it is possible that the peak fluence location where embrittlement is highest is at the inside surface of the RPV. However, the toughness of the RPV inside surface is higher than the inside the wall thickness location. The NRC staff noted that the fluence at the inner surface of the RPV is higher than the tested specimens which are taken at the 1/4 location from the RPV inner surface.

The PWROG stated that the peak fluence is only experienced in limited angular locations around the RPV circumference, further reducing the likelihood that the peak fluence will be experienced in a location that is on the lower end of the material fracture toughness property variation/scatter.

In addition, the PWROG stated that a large database of Carbon (C) values was compiled on plates and forgings used in US RPV beltline construction to assess the variation in C and potential for the C macro-segregation impact on toughness. The PWROG further stated that the C standard deviation of the difference from the average measurement is 0.0121% for plates and 0.0074% for forgings. PWROG stated that the effect of 0.0121% change in C on the transition temperature T_{30} is approximately 434°F/ΔC wt% to 540°F/ ΔC wt% which is approximately an effect of a 5°F to 6°F variation due to C variability. This effect is insignificant relative to the T_{30} measurement uncertainty and would be considered Part of the material variability discussed in the response to RAI No. 13 Part (a) above. This magnitude of the potential uncertainty due to C macro-segregation is bounded by the minimum value established for $\sigma_{adjustment}$ of 16°F (9°C).

The PWROG stated that a large amount of measured fracture toughness and T_0 data have demonstrated the conservativeness of the approach. The PWROG further stated that many datasets include at least two sets of specimen tests from which T_0 can be calculated from the same heat of RPV steel. One T_0 measurement is used as the direct fracture toughness measurement and the second measurement (or additional measurements) of T_0 is assumed to be from an irradiated RPV represented by the irradiated ductile-brittle transition temperature fracture toughness test results. One T_0 measurement is adjusted to the condition of the second (or more) measured datasets, which provides the margin needed to ensure an evaluation of the RPV would be bounding. PWROG stated that greater than 95 percent of measured T_0 values and fracture toughness values are bounded by the TR methodology. This is consistent with the level of safety in ASME Code Section III NB-2300, ASME Code Section XI, Appendix G and ASME Section XI Code Case N-830.

The NRC staff transmitted RAIs regarding the criteria and/or limitations that ensure that the condition in the measurement of irradiated fracture toughness is sufficiently “near the condition of interest.” In response to RAI No. 21 Part (b), the PWROG stated that the adjustment in Section 4.3 of the TR uses the latest industry consensus ETC (ASTM E900-15) to adjust the test data to the condition of interest at the RPV, which ensures that the tested material represents the condition of interest in the RPV. The uncertainty of this adjustment is $\sigma_{adjustment}$, which could be zero if there were no adjustment (a minimum of 16°F (9°C) is conservatively used), and the full SD_{ETC} term if the tested material were unirradiated in accordance with Equation 12 of the TR (formerly Equation 10). PWROG stated that in addition, the chemistry adjustments are limited, since the adjustment between the tested specimens and the RPV material best estimate is limited to the chemistry variation within the heat. Also, the PWROG stated that as discussed in response to RAI No. 20 Part (b), the inhomogeneity screening identifies atypical toughness variation, and that the TR contains a methodology to treat the data for inhomogeneity.

Table 2 of the TR markup discusses that the standard deviation of the combination of measurement uncertainty, material variability and the uncertainty of the fit (standard error on the slope) (collectively, the residuals) is 17°C (30.6°F) for welds and base metals. The PWROG explained that these uncertainties are independent, and that the average material uncertainty can be approximated by removing the measurement uncertainties and standard error on the fit. The PWROG calculated a measurement uncertainty of 14°C (26°F) in Section 4.3.5 of the TR markup and standard error on the fit of 4.5°F in its response to RAI No.13 Part (a). Removing the measurement uncertainty and the fit standard error from the fit residual of 17°C (30.6°F) resulted in 16^{o}F (9°C). The NRC staff finds that the 9°C (16^{o}F) value is acceptable because it is the minimum uncertainty to account for the uncertainty of adjusting measured T_0 to the RPV condition of interest.

The PWROG concluded that the material variability portion of the uncertainty is approximately 16°F (9°C) based on the above discussion. In response to RAI No. 13 Part (a), the PWROG explained that the ASTM E900-15 ETC standard deviation term also includes material variability as a portion of the standard deviation. The ΔT_{30} values used as a basis for the ASTM E900-15 ETC were composed of T_{30} unirradiated and T_{30} irradiated, which were measured using specimens machined from different portions of the material. This material variability would be expected to be similar to the material variability of that determined above, since both are fits to RPV materials. The PWROG stated that because the ASTM E900-15 ETC standard deviation, $\sigma_{adjustment}$, (or a portion thereof when adjusting from irradiated data) includes this material variability, a minimum value for this term is used because the RPV material of interest is always different than the tested material regardless of the magnitude of the adjustment. The PWROG explained that this material variability should not be another term in the margin term since it is not independent of $\sigma_{adjustment}$. The PWROG indicated that application of this 9°C minimum for $\sigma_{adjustment}$ demonstrates the conservativeness of the approach for datasets which are adjusted from irradiated measured T_0 where this 9°C (16°F) value is the maximum value in accordance with Equation 12 of the TR markup. Section 4.3.5 of the TR markup summarizes the reasons for treating the material variability as being included in the $\sigma_{adjustment}$ term.

The NRC staff finds the treatment of material variability uncertainty described in Section 4.5 of the TR acceptable because of the following: (a) the margins currently required by the ASME Code, Section III, incorporated into 10 CFR 50.55a are sufficient to account for uncertainties, in combination with the following; (b) evaluating RPV material within the 1/4T location provides structural margin compared to a location near the RPV surface because the crack driving force at the 1/4T location is larger than that at the location near the RPV surface; (c) the proposed TR methodology provides additional conservatism because it is based on evaluation of a large amount of measured fracture toughness and T_0 data; and (d) material variability uncertainty is accounted for in the $\sigma_{adjustment}$ term, because the TR uses conservative methods for subtracting the measurement uncertainty and standard deviation of the fit from $\sigma_{adjustment}$ (leaving material variability uncertainty), and therefore, an additional uncertainty term to account for material variability is not needed. Accordingly, the NRC staff concludes that that a 9°C(16°F) term as proposed by the TR is acceptable to account for material variability.

4.6 Applying the Methodology

The NRC staff noted that, given the complexity of applying the master curve approach described in Section 4 of the TR, the process by which the final calculated irradiated T_0 value, including adjustment and margin, is determined starting from a dataset or multiple datasets of T_0 values (irradiated and/or unirradiated) is not clear for all cases. The NRC staff also noted that while the examples in Appendix C of the TR show how the TR methodology is applied, the examples do not provide a clear guidance on the process steps. As such, the NRC staff asked for a detailed description of the process by which the final calculated irradiated T_0 value is determined starting from a dataset or multiple datasets of T_0 values (irradiated and/or unirradiated). In response to RAI No. 24, the PWROG provided flowcharts in applying the TR methodology and included the flowcharts in Section 4.6 of the TR markup. In Attachment 1 of the July 24, 2024, letter (Ref. 4), the PWROG provided clarifications on the "Data Adjustments" flowchart. The NRC staff examined the flowcharts and determined that they define an adequate method for implementing the TR methodology for all cases. Accordingly, the NRC staff finds that the flowcharts in Section 4.6 of the TR markup adequately reflect and clarify the detailed steps of the TR methodology.

4.7 Implementation and Sample Calculations

In Section 4 of the TR, with clarifications in the TR markup and in the responses to RAI Nos. 07, 08, 09, and 23, the PWROG stated that if multiple datasets are available for the heat of interest (i.e., the same heat of the material as in the RPV base metal or weld), the dataset with the irradiation and material conditions most similar to the RPV has a higher weight. The "T_0 (or RT_{T0}) + adjustment + margin" values will be averaged using the respective adjustment and margin for each dataset available with a weighting factor.

In response to RAI No. 07, the PWROG described a weighting method for handling the case when multiple datasets are available for the heat of interest. The PWROG added this weighting method as shown in the Section 4 of the TR markup. The PWROG stated that for this case, the dataset with the irradiation and material conditions most similar to the RPV would have a higher weighting and provided Equations 4a and 4b for calculating the weighting factors. The PWROG calculated weighting factors for the examples in Appendix C of the TR markup (Tables C-6, C-6a, and C-14). The NRC staff verified the calculated weighting factors in the examples and confirmed that they were appropriately applied to determine the final "T_0 (or RT_{T0}) + adjustment + margin" value that would be used in Equations 1 to 3 of the TR.

In response to RAI No. 08, the PWROG explained how the condition in 10 CFR 50.55a(b)(2)(xxxvi) shown below will be met when using the TR methodology with respect to the use of irradiated T_0 and the need to submit a proposed alternative to the above condition under the provision of 10 CFR 50.55a(z). As of the date of this SE, an application to use the TR methodology will need to address the requirement in 10 CFR 50.55a(b)(2)(xxxvi). The response to RAI no. 08 explains how an applicant seeking to apply the TR could satisfy the criteria of sec. 50.55a(z)(1) and (2).

In response to RAI No. 09, the PWROG proposed changes to Section 4.3 of the TR for the case if only unirradiated T_0 data is available and clarified the individual uncertainty terms to be used in the margin equation in Section 4.4 of the TR. Further discussion on the use of unirradiated data is discussed in Section 4.2 of this SE. The NRC staff finds that the proposed methodology adequately addresses the case if only unirradiated T_0 data is available because appropriate adjustment and margin are applied to the data as described in sections 4.2 and 4.3 of this SE.

In response to RAI No. 23, the PWROG clarified that the TR methodology is not an alternative for calculating the parameter RT_{MAX} in 10 CFR 50.61a (alternate PTS rule) and that Code Case N-830-1 is outside of the scope of the methodology. The TR markup includes this clarification. The NRC staff finds the clarifications acceptable because PWROG confirmed that the TR methodology does not interface with other regulations related to the use of T_0 that were not specifically discussed in the TR.

Appendix C of the TR provides examples on the use of the proposed methodology. In its response to RAI No. 25, the PWROG provided additional information on the examples and how the TR methodology is formulated. In response to RAI No. 25 Part (a), PWROG stated that different datasets have different amounts of uncertainty in the exposure conditions, test sample size and magnitude of adjustment, which can have a significant impact on the margin (combined uncertainty terms). These uncertainties are all addressed explicitly. In PWROG's response to RAI No. 4 it is stated that $T_0 + 2\sigma_{E1921}$ bounds greater than 95 percent of data from large datasets as discussed in the responses to RAI No. 21 above.

In response to RAI No. 25 Part (b), PWROG stated that σ_{E1921} is a function of r (the number of uncensored data per ASTM E1921-20) as shown in Table 2 of the TR markup (Table 3 of the original TR), which uses ASTM E1921-20 paragraph 10.9. Table C-9 of the TR markup shows the various values that are calculated including “N, r” and “T_0 Basis.” The values have been determined using the revision to the TR methodology discussed in the response to RAI No. 10 in Section 4.2 of this SE, where the Charpy bias is added to the test temperature and all other changes to the TR discussed in the RAI responses above and shown in the TR markup.

The NRC staff finds that the proposed methodology described in Section 4 of the TR is acceptable because the PWROG adequately clarified how the TR methodology is implemented with regard to the use of multiple datasets, the fulfillment of the condition in 10 CFR 50.55a(b)(2)(xxxvi) about the use of irradiated T_0 values, the individual uncertainty terms to be used in the margin equation in Section 4.4 of the TR, and the interface of the TR methodology with other regulations related to the use of T_0 that were not specifically discussed in the TR. Moreover, the NRC staff finds the proposed methodology in Section 4 of the TR acceptable because the PWROG provided appropriate sample calculations to demonstrate how the TR methodology should be used.

4.8 Summary of Staff Evaluation

As described in detail in the foregoing NRC staff SE, with respect to the proposed TR methodology, i.e., as applied through Equations 1, 2, and 3 of the TR, the NRC staff determined that the PWROG has adequately:

- defined the “adjustment” and “margin” terms in Equations 1, 2, and 3 of the TR;
- defined provisions for generating and validating irradiated T_0 data, including MTR-irradiated T_0 data;
- specified requirements for specimen test data and defined an approach for determining a bounding T_0 value if only unirradiated T_0 data is available;
- considered uncertainty due to material variability;
- generated flowcharts adequate to apply the TR methodology; and
- demonstrated how the TR methodology is used by sample calculations.

Therefore, the NRC staff finds that Equation 1 of the TR is acceptable for use to evaluate PTS in PWRs. The NRC staff further finds that either Equation 2 or Equation 3 of the TR is acceptable for use to develop P–T limit curves in PWRs.

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Equation 1 of the TR is acceptable for use to evaluate PTS in PWRs. Either Equation 2 or Equation 3 of the TR is acceptable for use to develop P–T limit curves in PWRs. Section 4 of the TR as modified by this SE provides details of the use of these equations.

5.1 Required Exemptions

Exemptions in accordance with 10 CFR 50.12 are needed for implementing the TR methodology because the methodology uses an approach to RPV integrity evaluations that is different than the requirements for RPV integrity evaluations in 10 CFR Part 50.

The regulations at 10 CFR 50.61 and 10 CFR Part 50, Appendix G require the use of RT_{NDT} while the TR methodology specifies the use of T_0. In Section 5 of the TR, the PWROG stated that exemptions to 10 CFR 50.61 (for use of Equation 1 of the TR) or 10 CFR Part 50,

Appendix G (for use of Equations 2 or 3 of the TR) are required to implement the TR methodology.

The regulation at 10 CFR Part 50, Appendix G requires the effects of neutron radiation to be taken into account, including the results of the surveillance program of 10 CFR Part 50, Appendix H, which refers to ASTM E185-82, "Standard Practice for Conducting Surveillance Tests for Light-Water Cooled Nuclear Power Reactor Vessels." This ASTM standard requires testing of Charpy impact specimens. In Section 3.3 of the TR, the PWROG discussed three options for performing fracture toughness testing of 10 CFR Part 50, Appendix H irradiated material. The PWROG stated that the first two options that involve the modification of Charpy specimens and testing them in a three-point bending configuration (or another configuration) require an exemption to 10 CFR Part50, Appendix H. For the third option, the PWROG stated:

> Small fracture toughness specimens from broken Charpy specimens or untested heat-affected zone (HAZ) specimens can be tested in accordance with ASTM E1921-20 to provide useful test data that could be used for RPV integrity evaluations in accordance with the methodology discussed in this topical report. This approach does not require an exemption to the requirements of 10 CFR [Part] 50 Appendix H, because all the requirements would be met, and only tested or unused specimens would be used.

The NRC staff noted that since only specimens that have been tested or unused specimens will be used to obtain ASTM E1921-20 T_0 data and all requirements would be met, an exemption to 10 CFR Part 50, Appendix H is not required for the third option.

6.0 SUMMARY AND CONCLUSIONS

Based on its evaluation, the NRC staff finds that the proposed methodology in the TR for using irradiated or unirradiated T_0 data for RPV material integrity evaluations in lieu of the current approach in the regulations that is based on RT_{NDT} is acceptable because the proposed methodology has adequate provisions for adjustment and margin applied to the T_0 data that ensure the final T_0 value is sufficiently representative or conservative to perform the structural integrity evaluation of the RPV shell material in the field. Accordingly, the TR, as modified by this SE, is acceptable for referencing for the use of T_0 for the evaluation of RPV structural integrity as defined in the TR.

7.0 REFERENCES

1. Letter from M. Powell (PWROG) to NRC, Transmittal of Topical Report PWROG-18068-NP, Revision 1, "Use of Direct Fracture Toughness for Evaluation of RPV Integrity" July 27, 2021 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML21209A932).

2. Pressurized Water Reactor Owners Group Topical Report PWROG-18068-NP, Revision 1, “Use of Direct Fracture Toughness for Evaluation of RPV Integrity,” July 2021 (ADAMS Accession No. ML21209A933 (Non-Proprietary (NP)).

3. Email from L. Fields (NRC) to C. Holderbaum and J Andrachek (PWROG), “Email Transmittal for Requests for Additional Information for Topical Report, PWROG-18068-NP Rev. 1”, March 30, 2022, (ADAMS Accession No. ML22084A390), and the enclosed Requests for Additional Information (ADAMS Accession No. ML22084A246).

4. Letter (Supplement) from J. Lynde (PWROG) to NRC, “Transmittal of the Responses to a Request for Additional Information, RAIs Associated with PWROG-18068-NP, Revision 1, “Use of Direct Fracture Toughness for Evaluation of RPV Integrity”, March 8, 2024 (ADAMS Package Accession No. ML24068A101), and Enclosure 1: Responses to NRC RAIs associated with PWROG-18068-NP Revision 1 (ADAMS Accession No. ML24068A102), and Enclosure 2: Markup of Topical Report PWROG-18068-NP, Revision 1 (ADAMS Accession No. ML24068A103), and supplemental letter from J. Lynde (PWROG) to NRC, “Transmittal of Additional Changes to PWROG-18068-NP, Revision 1, “Use of Direct Fracture Toughness for Evaluation of RPV Integrity”, July 24, 2024 (ADAMS Package Accession No. ML24206A042).

5. NRC RG 1.147, Revision 20, Inservice Inspection Code Case Acceptability, ASME Section XI, Division 1, December 17, 2021 (ADAMS Accession No. ML21181A222.

6. NRC Audit Report Summary Package For The Review Of Topical Report Pwrog-18068-NP, Revision 1, “Use Of Direct Fracture Toughness For Evaluation Of Reactor Pressure Vessel Integrity,” Docket No. 99902037; (EPID L 2021-TOP-0027), January 17-18, 2024 (ADAMS Pkg Accession No. ML24060A313).

7. NRC NUREG-1475, Revision 1, “Applying Statistics,” March 31, 2011 (ADAMS Accession No. ML11102A076).

8. NRC RG 1.99, Revision 2, “Radiation Embrittlement of Reactor Vessel Materials”, May 31, 1988 (ADAMS Accession No. ML031430205).

9. NUREG-1807, “Probabilistic Fracture Mechanics — Models, Parameters, and Uncertainty Treatment Used in FAVOR Version 04.1,” June 2007 (ADAMS Accession No. ML072010411).

10. NRC NUREG/CR-6609 “Comparison of Irradiation-Induced Shifts of K_{Jc} and Charpy Impact Toughness for Reactor Pressure Vessel Steels,” November 2000 (ADAMS Accession No. ML003774072).

11. NUREG-1874, “Recommended Screening Limits for Pressurized Thermal Shock (PTS).” March 1, 2007 (ADAMS Accession No. ML070860156).