NUCLEAR REGULATORY COMMISSION'S

DRAFT REQUEST FOR ADDITIONAL INFORMATION

BY THE OFFICE OF NUCLEAR REACTOR REGULATION ON

TOPICAL REPORT PWROG-18068-NP, REVISION 1,

"USE OF DIRECT FRACTURE TOUGHNESS FOR EVALUATION OF RPV INTEGRITY,"

FOR THE PRESSURIZED WATER REACTOR OWNERS GROUP

PROJECT NO. 99902037; EPID: L-2021-TOP-0027

BACKGROUND

By letter dated July 27, 2021 (Agencywide Documents Access and Management System Accession (ADAMS) No. ML21209A932), the Pressurized Water Reactor Owners Group (PWROG) submitted Topical Report (TR) PWROG -18068-NP, Revision (Rev.) 1, "Use of Direct Fracture Toughness for Evaluation of [Reactor Pressure Vessel] RPV Integrity" (ADAMS No. ML21209A933), for U.S. Nuclear Regulatory Commission (NRC) staff review and approval. The TR provides an alternative methodology to the RPV material integrity requirements presented in the "Fracture Toughness Requirements" of Appendix G to Part 50 Section 61 of Title 10 of the *Code of Federal Regulations* (10 CFR).

As a result of the review of TR PWROG -18068, Rev. 1, the NRC staff has determined that the request for additional information (RAI) questions provided below are needed to complete the next phase of the review.

REGULATORY BASES

The NRC has established regulatory requirements under 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," to protect the structural integrity of the reactor coolant pressure boundary in nuclear power plants as follows:

10 CFR 50.60, "Acceptance Criteria for Fracture Prevention Measures for Lightwater Nuclear Power Reactors for Normal Operation," states that fracture toughness requirements for RPV materials, which are set forth in Appendix G to 10 CFR Part 50 and "Reactor Vessel Material Surveillance Program Requirements," in Appendix H to 10 CFR Part 50.

10 CFR 50.61, "Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock," requires that the reference temperature of the RPV materials be within specific values to prevent pressurized thermal shock of the RPV materials.

Therefore, the regulatory basis for the following RAI questions is directly related to reasonable assurance for structural integrity of RPV materials in accordance with the regulations listed in this section.

REQUESTS FOR ADDITIONAL INFORMATION

RAI 01 – Section 4.1 of TR – Generation and Validation of Irradiated Data

NRC Comment

Section 4.1 of the TR states that each material irradiated in a high flux test reactor must have at least one validation material in the copper grouping shown in the section. The NRC staff is not clear on what steps will be taken if the material irradiated in a high flux test reactor does not have at least one validation material in the copper grouping.

NRC Request

Clarify/provide the steps that will be taken if the material irradiated in a high flux test reactor does not have at least one validation material in the copper grouping.

Response to RAI 01:

There has to be at least one validation material within the copper grouping. This is a condition for the use of high flux test reactor (MTR) irradiated data. The following text has been added to the Appendix C.1 Kewaunee example comparing the validation material fluence values:

> The 0.5*PWR validation material fluence is slightly less than the MTR validation material fluence (0.5*6.11 < 3.15 < 1.5*6.11) in this example and therefore can be used as a validation material for this MTR irradiation campaign in accordance with Section 4.1.

The 3rd paragraph of Section 4.1 of the TR will be revised as follows:

> When MTR data is used, ~~E~~each Cu grouping of interest ~~material irradiated in a high flux test reactor~~ must have at least one validation material ~~in the corresponding Cu grouping~~ heat which is also being or has been irradiated in a PWR (0.5*PWR validation material fluence < MTR validation material fluence < 1.5*PWR validation material fluence) to provide a quantitative evaluation of any neutron flux effects. For example, if 2 heats were irradiated in an MTR within the same Cu group, one heat must also be irradiated in a PWR and used as the validation material for the other heat (see subsection 4.3.4.2).

RAI 02 – Section 4.0 of the TR – Data Adjustments

NRC Comment

Various subsections in Section 4 of the TR, state that irradiated materials must be from the same heat as the RPV materials of interest. For example, Section 4.3.1 states that irradiated materials must be from the same heat as the RPV materials of interest; therefore, chemistry adjustments should be relatively small.

NRC Request (a, b)

a. If irradiated materials must be from the same heat as the RPV materials of interest, describe whether or not the proposed alternative to the methodology can be used or needs to be modified for use if irradiated materials are not from the same heat as the RPV materials of interest.

Response to RAI 02.a:

Generic values can only be developed for unirradiated data and then adjusted using the methods in the TR. Generic values cannot be developed using irradiated data and applied to other heats of irradiated data.

Section 4.2 of the TR will be revised as shown below to allow the use of materials other than the tested heat:

> Test data from the same heat of material is required to evaluate the RPV material of interest, which would typically be the limiting and/or near-limiting material(s), however, generic unirradiated values can be used as discussed below.
>
> Generic T_0 or RT_{T0} values that bound ≥ 95% of the measured unirradiated T_0 heat values with a 95% confidence level can be determined for forgings, plates, and welds based on a common manufacturer, class, or flux types if at least 4 heats have a measured valid T_0 to establish the basis. The basis for the generic grouping must be documented with the document implementing this methodology. The method discussed in Section 9.12 of NUREG-1475, Rev. 1 [41] will be used to determine the generic T_0 based on the mean T_0, standard deviation of the mean T_0 (S), and the 95/95 one-sided tolerance limit factor (k_1) which is a function of the number of measured heats (n) which is used in NUREG-1475, Revision 1 to calculate k_1 and S.
>
> The generic unirradiated T_0 values can be used subject to the following:
>
> - If heat-specific valid T_0 data is available, the generic value cannot be used for that heat.
> - If there is any irradiated data available for a heat within the generic grouping, the generic value will be adjusted using the adjustment method in Section 4.3 and the adjusted generic value must bound 95% of the measured irradiated K_{Jc1T} data.
> - The adjustment discussed in Section 4.3 of the TR will be used to adjust the generic mean T_0 to the RPV material condition. For unirradiated data, $\sigma_{ETCspecimen}$, $\sigma_{tempspecimen}$ and $\sigma_{fluencespecimen}$ are = 0. The $\sigma_{adjustment}$, $\sigma_{tempRPV}$ and $\sigma_{fluenceRPV}$ still apply and are calculated as discussed in Section 4.4. Since k_1 would likely be different than the value of 2 used in Equation 11, Equation 5 below will be used in lieu of the Equation 11 margin term (°F) in Section 4.4. The C and D factors are consistent with ASTM E900-15 and defined in Table 3. The base metal (BM) adjustment is included as discussed in Section 4.3.5.

$$\text{Margin} = 1.8\frac{°\text{F}}{°\text{C}} \bullet \sqrt{(k_1 \text{S})^2 + \{\mathbf{2} \bullet \boldsymbol{C}([If\ BM, 1.1] \bullet \Delta T_{30RPV})^{\boldsymbol{D}}\}^2 + (2\sigma_{tempRPV})^2 + (2\sigma_{fluenceRPV})^2}$$

[Equation 5]

41. NUREG-1475, Revision 1, “Applying Statistics,” U.S. Nuclear Regulatory Commission, March 2011.

Section 4.3.1:

Irradiated materials ~~must be~~ from the same heat as the RPV material~~s~~ of interest; ~~therefore,~~ would have chemistry adjustments ~~should be~~ which are relatively small. For base metals of the same heat, no chemistry adjustment is typically required, since the test samples are removed from the same RPV product and there is typically no difference between the best-estimate chemistry in the tested material and the RPV.

b. If the irradiated RPV materials are not from the same heat as the RPV material of interest, describe how the chemistry adjustments are derived.

Response to RAI 02.b:

The TR cannot be used for the development of irradiated generic values nor for the application of measured irradiated data on a different heat than the heat of interest in the RPV.

RAI 03 – Section 4.2 of the TR – Specimen Test Data

NRC Comment

Section 4.2 of the TR states that extra specimens are recommended to be tested to ensure that a valid T_0 is obtained.

NRC Request

Provide information regarding why the minimum specimens required in ASTM E1921 are sufficient to obtain a valid T_0.

Response to RAI 03:

The requirement for the size of the data set is defined in ASTM E1921-20[1] paragraph 10.3. It was the judgement of the industry consensus body of the ASTM E08 committee that the data set size requirements provide sufficient accuracy to determine T_0. For data sets 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 specimens.

RAI 04 – Section 4.2 of the TR – Specimen Test Data

NRC Comment (a, b, c)

a. Section 4.2 of the TR states that for large data sets (20 or more) which are screened as inhomogeneous, regardless of the ASTM E1921-20[1] treatment method used, or the analysis result, the T_0 used does not have to be more conservative than the T_0

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[1] *Standard Test Method for Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range.*

corresponding to the least tough datapoint being on the $K_{Jc\text{-}lower95\%}$ curve plus σ_{E1921} (σ value per ASTM E1921-20 paragraph 10.9). The NRC staff is not clear why the T_0 that is used does not have to be more conservative than the T_0 corresponding to the least tough datapoint.

b. The TR does not provide the technical basis for the statement that T_0 does not have to be more conservative than the T_0 corresponding to the least tough datapoint.

c. The NRC staff noted that larger data sets would more likely result in a datapoint lower than the 5th percentile, especially if the material is determined to be significantly inhomogeneous. However, it is also possible that there may not be a large percentage of the lower toughness material within the data set such that the datapoint may not be representative of the $K_{Jc\text{-}lower95\%}$ curve.

NRC Request (a, b, c)

a. Clarify if the requirement in part a of the comment above means that the analysis T_0 value (i.e., $T_0 + \sigma_{E1921}$) does not have to be greater than a value which would cause the least tough datapoint to fall exactly on the associated $K_{Jc\text{-}lower95\%}$ curve, or if another interpretation is intended by this statement.

Response to RAI 03.a:

This allowance has been removed from the TR.

b. Discuss the technical basis for the statement that T_0 does not have to be more conservative than the T_0 corresponding to the least tough datapoint.

Response to RAI 03.b:

This allowance has been removed from the TR.

c. Provide details on why the proposed treatment of large, inhomogeneous data sets is more appropriate, or more conservative, than the method required in E1921 to characterize both the material toughness and the uncertainty in the toughness value.

Response to RAI 03.c:

The methods detailed in ASTM E1921-20 paragraphs X5.3.2 or X5.3.3 can produce extremely conservative results. For example, the Midland Beltline Irradiated Weld multimodal analysis (X5.3.3) produces a T_m = 22°C with σ_{Tm} = 40°C as shown in Reference [1]. A $K_{Jc\text{-}lower95\%}$ curve positioned using $T_m + 2\sigma_{Tm}$ (22°C + 2*40°C = 102°C) is unrealistically conservative. However, to be conservative, the allowance for modifying the ASTM E1921-20 T_{0IN} by positioning the $K_{Jc\text{-}lower95\%}$ curve through the least tough data point and modification of σ has been removed from the TR.

The following text will be removed from Section 4.2 of the TR:

~~For large data sets (20 or more) which are screened as inhomogeneous, regardless of the ASTM E1921-20 treatment method used or the analysis result, the T_0 that is used does not have to be more conservative than the T_0 corresponding to the least tough datapoint being on the $K_{Jc\text{-}lower95\%}$ curve plus σ_{E1921} (σ per ASTM E1921-20 paragraph 10.9).~~

For inhomogeneous data sets with N ≥ 20, the reference temperature estimate provided by the simplified method, T_{0IN}, was determined to be generally conservative, and in some cases, significantly more conservative, compared to the multimodal approach using the margin-adjusted T_m. Generally, the multimodal method appears to be slightly less conservative than the simplified method (T_{0IN}) [2].

[1] J. B. Hall, E. Lucon, and W. Server, "Practical Application of the New Homogeneity Screening Procedure Added to ASTM E1921-20 and Appendix X5 Inhomogeneous Data Treatment," Journal of Testing and Evaluation 50, no. 4 (July/August 2022): 2190–2208. https://doi.org/10.1520/JTE20210716

[2] E. Lucon, "Assessment of macroscopically inhomogeneous fracture toughness data sets using the simplified and multimodal master curve methods," Theoretical and Applied Fracture Mechanics, Volume 125, 103861, June 2023. https://doi.org/10.1016/j.tafmec.2023.103861

RAI 05 – Section 4.3 of the TR – Data Adjustments

NRC Comment (a, b, c, d)

a. Section 4.3 of the TR states that for adjustments that are within the uncertainty of the embrittlement trend correlation (ETC), because the difference in the ETC prediction of the irradiated test material and the RPV is relatively small, any systemic errors in the ETC model (model uncertainty) would be negligible. The TR does not provide data to show that difference in the ETC prediction of the irradiated test material and the RPV is small. The NRC staff is not clear how small of a difference the systemic errors would need to be in order to be considered negligible.

b. The NRC staff is not clear why the "predicted ΔT_{30} of the irradiated tested material" term within the parentheses in Equation 4 in Section 4.3 of the TR is not called "**measured** ΔT_{30} of the irradiated tested material" instead (emphasis added) because ΔT_{30} values from tested materials should have measured ΔT_{30} values by definition, not predicted ΔT_{30} values.

c. With respect to the Part b question above, if the intent of Equation 4 is to calculate the ΔT_{30} value of the irradiated test material predicted by E900-15, the NRC staff is not clear why the measured ΔT_{30} value of the irradiated test material is not used.

d. The NRC staff is not clear whether the statement after Equation 4 should state "The **predicted** ΔT_{30} above…" (emphasis added).

NRC Request (a, b, c, d)

a. Provide data to show that the difference in the ETC prediction of the irradiated test material and the RPV is relatively small so that any systemic errors in the ETC model (model uncertainty) would be considered negligible.

<u>Response to RAI 05.a:</u>

The TR will be revised to eliminate the discussion that any systemic errors in the ETC model (model uncertainty) would be considered negligible. The term, $\sigma_{additional}$ will be revised to $\sigma_{adjustment}$ for clarity throughout the revised TR and the $\sigma_{additional}$ formula (Eq. 12) will be revised with a minimum value of 9°C imposed. Please see the response to RAI 20 for additional information and revised Equation 12.

The following text will be removed from Section 4.3 of the TR:

> ~~If the calculated adjustment exceeds the prediction model uncertainty (SD$_{ETC}$) shown in Equation 5, then additional margin is added as described in Section 4.4.~~
>
> ~~*SD$_{ETC}$* = the uncertainty (standard deviation) determined by the applicable ETC. The equation for the E900-15 *SD$_{ETC}$* is summarized in Equation 5.~~

~~$SD_{ETC} = C \bullet TTS^{D}$ [Equation 5]~~

> ~~Where,~~
>
> ~~TTS = E900-15 predicted shift in 30 ft-lb transition temperature (°C)~~
>
> ~~C and D are provided in Table :~~

~~Table 2: Coefficients for ASTM E900-15 Embrittlement Shift Model Uncertainty [4]~~

~~Product Form~~	**~~C~~**	**~~D~~**
~~Forgings~~	~~6.972~~	~~0.199~~
~~Plates~~	~~6.593~~	~~0.163~~
~~Welds~~	~~7.681~~	~~0.181~~

> ~~Limiting the adjustment to the ETC uncertainty without additional margin reduces the potential for any error in the uncertainty of the ETC to become significant. For adjustments that are within the uncertainty of the ETC, since the difference in the ETC prediction of the irradiated test material and the RPV is relatively small, any systemic errors in the ETC model (model uncertainty) would be negligible. Any systemic error in the ETC would be expected to be approximately the same for the test material and the actual RPV material since the adjustment is limited and the inputs are similar. Therefore, if the adjustment is less than SD$_{ETC}$ then the ETC uncertainty is negligible.~~

Note, Equation 5 and Table 2, above, have been moved to Section 4.4.2.

The following text in Section 4.4.2 will be removed from the TR:

> ~~If adjustments do not exceed the standard deviation of the ETC, $\sigma_{additional}$ is set equal to zero.~~

b. Clarify why the “predicted ΔT_{30} of the irradiated tested material” term within the parentheses in Equation 4 in Section 4.3 of the TR is called “predicted ΔT_{30} of the irradiated tested material” instead of “**measured** ΔT_{30} of the irradiated tested material.”

Response to RAI 05.b:

Equation 6 (formerly Equation 4) will be revised to delete the word “irradiated” since the TR can be applied to an unirradiated T_0 value. Other than this change, Equation 6 (formerly Equation 4) is correct as written. The test specimen T_0 may or may not have an associated **measured** ΔT_{30} of the irradiated tested material. The purpose of the adjustment is to adjust the condition of the tested material T_0 to the condition of the RPV. Therefore, the embrittlement prediction is calculated for the tested specimens and the RPV. The difference in prediction of both conditions is used to make the adjustment.

c. Clarify why the measured ΔT_{30} value of the irradiated test material is not used in Equation 4.

Response to RAI 05.c:

If there were a bias in the measured ΔT_{30} value relative to the ETC prediction, an adjustment using the measured ΔT_{30} value would include this bias. Since ΔT_0 and ΔT_{30} are correlated, the measured T_0 that is being adjusted includes the bias, therefore including measured T_0 and measured ΔT_{30} would include the bias twice, resulting in an adjustment that is too large.

d. Clarify whether the statement after Equation 4 should state “The **predicted** ΔT_{30} above…”

Response to RAI 05.d:

The cited sentence should begin with “The predicted ΔT_{30} above…”. The TR will be revised to reflect this change.

RAI 06 – Section 4.3.2 – Data Adjustments - Temperature

NRC Comment

Section 4.3.2 of the TR states that for pressure-temperature (P-T) limit calculations the temperature at the ¼ or ¾T 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}. Section 4.3.2 further states that 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. Section 4.3.2 indicates that T_{cold} should be used for PTS calculations which are performed for the clad/low alloy steel interface where the irradiation temperature would be very close to T_{cold}.

NRC Request

Describe why T_{cold} should be used for PTS calculations which are performed for the clad/low alloy steel interface where the irradiation temperature would be very close to T_{cold} regardless of gamma heating. Therefore, T_{cold} is the appropriate temperature for use in the 10 CFR 50.61 evaluation.

Response to RAI 06:

10 CFR 50.61 requires an assessment at the clad/low alloy steel interface where the irradiation temperature is very close to T_{cold}.

Section 4.3.2 of the TR will be revised as follows:

> Gamma heating of the RPV in the beltline region increases the RPV wall temperature toward the insulated outside RPV surface. During normal operation, the wetted surface remains at T_{cold}. ~~relative to T_{cold} at the wetted surface during normal operation, and a~~A lower embrittlement shift occurs at higher irradiation temperatures which occur toward the insulated outside RPV surface. T_{cold} will ~~should~~ be used for PTS calculations which are performed for the clad/low alloy steel interface where the irradiation temperature would be very close to T_{cold}.

RAI 07 – Section 4.0 of TR – Master Curve Set Data

NRC Comment (a, b, c)

a. Section 4 of the TR, page 4-1, states that if multiple data sets are available for the heat of interest, the data set with the irradiation conditions most similar to the reactor vessel may be used alone. The NRC staff is not clear regarding the acceptance criteria that will be used to permit the use of the irradiated data set.

b. Section 4 of the TR further states that alternatively, the "T_0 (or RT_{T0}) + adjustment + margin" values can be averaged using the respective adjustment and margin for each data set available. The NRC staff is not clear how the above values can be averaged to result in an appropriate T_0.

c. Section 4 of the TR states that if unirradiated data is also available, this data does not have to be combined with irradiated data because the irradiated T_0 provides the measured effect of embrittlement without the need for the full prediction of uncertainty. Section 4 indicates that if only unirradiated T_0 is available, the approach discussed can also be used. The NRC staff is not clear whether the adjustment term and margin term in Equations 1, 2 and 3 are needed to calculate T_0, if irradiated and unirradiated data are available.

NRC Request (a, b, c)

a. Describe the acceptance criteria that will be used to decide the irradiation conditions that are most similar to the reactor vessel in question such that the irradiation data could be used alone. Discuss the need for acceptance criteria to demonstrate that a data set is sufficiently representative of the conditions to be evaluated and, if it cannot be demonstrated, that such criteria are not needed, describe the appropriate criteria that could be used to appropriately select data sets.

Response to RAI 07.a:

A weighting method will be added and the last paragraph in Section 4 of the TR will be revised as follows:

> If multiple data sets are available for the heat of interest, the data set with the irradiation and material conditions most similar to the RPV have a higher weighting as discussed below ~~reactor vessel may be used alone~~. If multiple data sets for the heat of interest include both MTR and PWR irradiations, the MTR irradiation(s) will not be used. ~~unless the MTR data quality is significantly superior to the PWR irradiated data~~ ~~Alternatively, t~~The T_0 *(or* RT_{T0}*)* + *adjustment* + *margin* values ~~can~~ will be averaged using the respective adjustment and margin for each data set available with a weighting factor as shown in Equations 4a and 4b. For each measured T_0, the absolute value of the effect of each input to the ASTM E900-15 prediction between the RPV and test material conditions are calculated individually and summed as shown in Equation 4a. Each of the ASTM E900-15 inputs is individually changed to be equal to that of the test material ($\Delta T_{30\ RPV_{1/6TM}}$), while all other inputs are kept at the RPV condition. There are 6 independent inputs (Cu, Ni, Mn, P, fluence, and temperature), therefore, there are 6 ΔT_{30} predictions. Then the absolute value of the differences between the 6 ΔT_{30} and the ΔT_{30} based on the RPV material ($\Delta T_{30\ RPV}$) are summed and divided by the ΔT_{30} for the RPV material. This provides a metric for the representativeness of the test material to the RPV which is used for the weighting factor. This representativeness metric is divided by the ASTM E900-15 prediction of the RPV and subtracted from 1 to determine the weighting factor, w_i ($w_i \geq 0$) as shown in Equation 4a. The weighting factor is multiplied by each T_0 *(or* RT_{T0}*)* + *adjustment* + *margin* value, summed and divided by the sum of the weighting factors as shown in Equation 4b. ~~If unirradiated data is also available, this data does not have to be combined with irradiated data since the irradiated T~~$\sim\sim_0$~~ provides the measured effect of embrittlement without the need for the full prediction uncertainty. If only unirradiated T~~$\sim\sim_0$~~ is available, the approach discussed herein can also be used.~~
>
> $$w_i = \max\left(0, 1 - \sum^{Cu,Ni,Mn,P,fluence,temp} \frac{\left|\Delta T_{30\ RPV} - \Delta T_{30\ RPV_{1/6TM}}\right|}{\Delta T_{30\ RPV}}\right)$$
>
> [Equation 4a]
>
> $$Weighted\ average\ (T_0 + adjustment + margin) = \frac{\sum_1^{no}\left(T_{0,i} + adjustment_i + margin_i\right) w_i}{\sum_1^{no} w_i}$$
>
> [Equation 4b]
>
> Where:
>
> w_i = the weighting factor of each measured T_0 *(or* RT_{T0}*)* + *adjustment* + *margin* value
> *no* = number of measured T_0 *(or* RT_{T0}*)* + *adjustment* + *margin* values.

If only unirradiated data is available, the above procedure will not be used, and all the datasets for a given heat are combined in a single T_0 calculation.

Note that worked examples are provided in Appendix C.

b. Describe how the “T_0 (or RT_{T0}) + adjustment + margin” values can be averaged using the respective adjustment and margin for each data set available.

Response to RAI 07.b:

Appendix C has been revised to include examples of how the “T_0 (or RT_{T0}) + adjustment + margin” values are averaged. Weighted averaging, as the final step, takes into account the different adjustment and margin for each measurement for the RPV condition of interest.

b. (cont.) Discuss why a bounding “T_0 (or RT_{T0}) + adjustment + margin” value from the multiple data is not a more appropriate approach to ensure reasonable conservatism instead of the proposed averaged value.

Response to RAI 07.b (cont.):

The approach is similar to the Regulatory Guide 1.99, Revision 2 least squares fit where the chemistry factor is the best fit to the measured ΔT_{30} data. The TR approach uses all the measured information with each respective margin to ensure that any individual measurement is bounding. Weighted averaging the “T_0 (or RT_{T0}) + adjustment + margin” values ensures that all of the data is used with the most representative measurement given the highest weighting.

b. (cont.) Discuss why the “T_0 (or RT_{T0}) + adjustment + margin” values are not weight-averaged by criteria such as the number of data sets or the similarity of the data set to the evaluated conditions instead of simply averaged.

Response to RAI 07.b (cont.):

As discussed in the response to RAI 07.a. above, the weighting method will be used to focus on the RPV conditions. The sample size was not considered in the weighting as the margin term includes an uncertainty on sample size number (σ_{1921}) and an adjustment uncertainty. Therefore, the weighted average of the “T_0 (or RT_{T0}) + adjustment + margin” values include these uncertainties.

c. Clarify if the adjustment term and margin term in Equations 1, 2, and 3 of the TR are needed to calculate the T_0 (or RT_{T0}) value if unirradiated data for the reactor vessel in question are available in addition to irradiated data.

Response to RAI 07.c:

The methodology can be used with unirradiated data with the margin and adjustments calculated in accordance with the TR. If both unirradiated and irradiated data are available, only the irradiated data is used as it is a closer reflection of the RPV condition. The weighting method discussed in the response to RAI 07 a. above, reduces the weight of unirradiated data to 0.

RAI 08 – Section 4.0 of TR – 10 CFR 50.55a Condition on Use of Irradiated T0

NRC Comment

Section 4 of the TR states that Equation 2 is one of the options for development of Appendix G P-T curves. Equation 2 is based on the K_{IC} equation from Appendix G of Section XI of the 2017 Edition of the ASME Code. G-2212 of Section XI of the ASME Code refers to A-4400 of Section XI of the ASME Code, which is subject to 10 CFR 50.55a condition regarding the use of irradiated T_0 data, as given below:

> (xxxvi) *Section XI condition: Fracture toughness of irradiated materials*. When using the 2013 through 2017 Editions of the ASME BPV Code, Section XI, Appendix A paragraph A–4400, the licensee shall obtain NRC approval under paragraph (z) of this section before using irradiated T_0 and the associated RT_{T0}.

The TR does not explain how this condition will be met when using the methodology described in the TR.

NRC Request

Explain how the referenced 10 CFR 50.55a condition will be met when using the methodology described in the TR.

Response to RAI 08:

The referenced paragraph (z) from 87 FR 73633, dated December 1, 2022 is quoted as follows:

> “(z) *Alternatives to codes and standards requirements*. Alternatives to the requirements of paragraphs (b) through (h) of this section or portions thereof may be used when authorized by the Director, Office of Nuclear Reactor Regulation. A proposed alternative must be submitted and authorized prior to implementation. The applicant or licensee must demonstrate that:
>
> (1) Acceptable level of quality and safety. The proposed alternative would provide an acceptable level of quality and safety; or
> (2) *Hardship without a compensating increase in quality and safety*. Compliance with the specified requirements of this section would result in hardship or unusual difficulty without a compensating increase in the level of quality and safety.”

The methodology in the TR is consistent with paragraph (z) of the ASME Code cited above, which have been approved by the NRC. Additionally, the methodology in the TR includes uncertainties in the margin term, which is more conservative than ASME BPV Code, Section XI, Appendix A paragraph A–4400 and Appendix G-2200 therefore, demonstrating an acceptable level of safety consistent with (z) (1) above. The testing and analysis must be performed in accordance with a 10CFR50, Appendix B quality assurance program, which would ensure the quality of data and analysis consistent with (z) (1) above. Therefore, the referenced 10 CFR 50.55a condition will be met when a licensee uses the methodology described in the TR.

RAI 09 – Section 4.0 of TR – Use of Master Curve Approach When Only Unirradiated T0 Data is Available

NRC Comment

Section 4 of the TR states that “if only unirradiated T_0 is available, the approach discussed herein can also be used.” The TR does not discuss the approach or methodology for determining irradiated T_0 if only unirradiated T_0 data is available.

NRC Request

Describe the approach or methodology for the “adjustment” and “margin” terms in Equations 1, 2, and 3 of the TR if only unirradiated T_0 data is available for determining irradiated T_0.

Response to RAI 09:

The word “irradiated” will be removed from Section 4.3, Equation 6 (formerly Equation 4) in the TR revision as shown below:

~~*adjustment* = (predicted ΔT30 of the RPV material at the fluence of interest – predicted ΔT30 of the irradiated tested material) * average shift difference between ΔT0 and ΔT30~~

$$adjustment = \left(\Delta T_{30\ RPV} - \Delta T_{30\ Specimens}\right) \bullet (If\ BM, 1.1) \bullet 1.8 \frac{°\mathrm{F}}{°\mathrm{C}} \qquad \text{[Equation 6]}$$

where:

For base metal (BM), multiply by 1.1, otherwise use 1.0 for welds

$\Delta T_{30\ RPV}$ = predicted ΔT_{30} of the RPV material at the fluence of interest using the ASTM E900-15 ETC

$\Delta T_{30\ Specimens}$ = predicted ΔT_{30} of the tested specimens using the ASTM E900-15 ETC

If only unirradiated T_0 data is available, the “$\Delta T_{30\ Specimens}$” will be = 0 and the unirradiated T_0 will be adjusted to the RPV condition of interest using the terms of Equation 6 (formerly Equation 4). This approach is similar to the BAW-2308, Revision 1-A methodology.

RAI 10 – Section 4.2 of the TR – Specimen Test Data

NRC Comment

The last paragraph of Section 4.2 of the TR states: “Test data from three-point bend (3PB) Charpy 10 x 10 mm size specimen is acceptable, if a bias correction addition of 18°F (10°C) [3 and 31] is included. If there is a mixture of Charpy 3PB and C(T) specimens, the bias correction can be prorated based on the proportion of Charpy 3PB specimens.” Also, the last paragraph on page A-3 of the TR states: “The uncertainty per ASTM E1921 for the mini-C(T) T_0 values shown in Table A-1 would be expected to range from approximately 4°C through 8°C.” The NRC staff is not clear whether the bias correction and/or the uncertainty for the mini-C(T) specimens are incorporated into the data adjustment or margin terms in Equations 1, 2, and 3 of the TR. The NRC staff also noted that the master curve is essentially a nonlinear fitting method, and data below T_0 have a stronger effect on the T_0 value than data above T_0. Therefore, the weight is a function of the relative test temperatures, and that a more consistent, and simpler, approach would be to shift the test temperature of all 3PB data (even if mixed with C(T) specimens) by +18°F (+10°C) in determining T_0.

NRC Requests (a, b, c)

a. Describe whether a bias correction addition of +18°F (+10°C) is appropriate for adding to all 3PB specimen data when calculating the adjustment or margin terms in Equations 1, 2, and 3 of the TR. If not, provide an explanation for when it is not needed.

Response to RAI 10.a:

It is agreed that adding the 3PB bias to the test temperature of the 3PB specimens is more accurate than the prorated approach described in the TR. The last two sentences in Section 4.2 will be revised as follows:

> Test data from a three-point bend (3PB) Charpy 10 x 10 mm size specimen is acceptable, if a bias correction addition of 18°F (10°C) [3 and 31] is ~~included~~ added to the test temperature of each 3PB specimen when calculating T_0. ~~If there is a mixture of Charpy 3PB and C(T) specimens, the bias can be prorated based on the proportion of Charpy 3PB specimens.~~

The example calculations in Appendix C (Tables C-1 and C-9) of the TR have been revised to reflect this change.

b. Regarding the uncertainty for mini-C(T) of 4°C to 8°C discussed in Appendix A of the TR, clarify if the uncertainty value of 4°C to 8°C is added to the adjustment or margin terms and discuss if additional uncertainty for mini-C(T) specimen data (i.e., uncertainty greater than what would be applied for larger C(T) specimens) would be included in the adjustment or margin terms. If not, provide justification.

Response to RAI 10.b:

Appendix A provides a significant database comparing the T_0 determined from mini-C(T) specimens relative to the T_0 from larger test specimens from the same material. The resulting comparison shows no statistically significant difference, meaning the size adjustment in the industry consensus ASTM E1921 standard is applicable to 0.16TC(T) specimens. The average difference and standard deviation shown in Appendix A are within the results that were expected considering the individual measurement uncertainties. There is no significant bias or additional uncertainty associated with the mini-C(T) test data and no uncertainty is included as a function of the specimen thickness. Dr. Sokolov also concluded: "available data on the use of Mini-C(T) specimens for characterization of the fracture toughness of reactor pressure vessel steels revealed very good correspondence between T_0 derived from Mini-C(T) and larger fracture toughness specimens in both, the unirradiated and irradiated conditions." [3]

The uncertainty for the mini-C(T) specimen T_0 measurement is treated the same as for larger C(T) specimens.

[3] M. Sokolov, “Use of Mini-CT Specimens for Fracture Toughness Characterization of Irradiated Highly Embrittled Weld,” ASME PVP2022-84827, 2022.

c. Justify the proposed method for linearly prorating the bias when there is a mixture of Charpy 3PB and C(T) specimens.

Response to RAI 10.c:

Please see the response to RAI 10.a. above.

RAI 11 – Section 4.3 of the TR – MTR Flux

NRC Comment

The NRC staff is not clear on the derivation, definition of certain terms, or application of Material Test Reactor (MTR) flux validation (i.e., Equation 7 of the TR) and adjustment (i.e., Equation 8 of the TR) as discussed in Section 4.3.4.2 of the TR. First, the NRC staff is not clear how Equation 7 and Equation 8 were derived. With respect to Equation 7, the NRC staff noted that it may not be an appropriately conservative criterion. For example, if the σ terms are equal, Equation 7 only requires that the “$\text{AdjustedT}_{\text{0highfluxVM}}$” value be greater than approximately the 0.2% probability curve of the data (i.e., Z = -2*√(2) or -2.82). Therefore, this criterion appears to be not sufficient to judge that the high-flux data set is representative, or conservatively bound, the T_{0PWRVM} conditions. The NRC staff also noted that a t-test (with classical 5% alpha-acceptance criteria) could be a better criterion to demonstrate that “$\text{AdjustedT}_{\text{0highfluxVM}}$” can be considered to be equivalent to or greater than “T_{0PWRVM}.” With respect to Equation 8, the NRC staff is not clear how it is representative of or conservative compared to PWR flux, as discussed in Section 4.3.4.2. Finally, the NRC staff noted that the numerator within the brackets in Equation 8 should be “$\text{AdjustedT}_{\text{0highfluxVM}} – T_{\text{0PWRVM}}$” or the absolute value of “$\text{AdjustedT}_{\text{0highfluxVM}} – T_{\text{0PWRVM}}$” instead of “$T_{\text{0PWRVM}} – \text{AdjustedT}_{\text{0highfluxVM}}$”.

NRC Requests (a, b, c, d, e, f, g)

a. Provide a clear derivation and description of Equation 7 and Equation 8. Also, clarify, as part of the description of this derivation, if these equations should only be used with T_0 and ΔT_0 data or if T_{30} and ΔT_{30} (along with the $\Delta T_0/\Delta T_{30}$ correction ratio) data can be used in this assessment.

Response to RAI 11.a:

Revised Equation 9 (formerly Equation 7) in Section 4.3.4.2 only uses T_0 and the adjusted T_0. Equation 9 (formerly Equation 7) will be revised as follows:

$$Adjusted\ T_{0high\ flux\ VM} \geq T_{0PWR\ VM} \cancel{- 2 \cdot \sqrt{\sigma_{T0high\ fluxVM}^{2} + \sigma_{T0PWRVM}^{2}}} \qquad \text{[Equation 9~~7~~]}$$

Eliminating the σ terms, increases the conservatism of the high flux T_0. The definition of the $\sigma_{test\ high\ flux\ VM}$ and $\sigma_{test\ PWR\ VM}$ will be removed from Section 4.3.4.2.

Equation 9 (formerly Equation 7) ensures that the high flux T_0 adjusted to the condition of the PWR irradiated T_0 produces a representative or conservative result. If the adjusted high flux T_0 is less than the PWR irradiated T_0 (non-conservative) then all the MTR data in the validated Cu grouping must be increased using Equation 10 to ensure a representative result.

b. Explain why a t-test is not used to infer that "Adjusted$T_{0highfluxVM}$" is equivalent to or greater than "T_{0PWRVM}."

Response to RAI 11.b:

The t-test is not used because the σ term in Subsection 4.4.1, is partially derived from ASTM E1921-20 paragraph 10.9, which is not a simple standard deviation term, and includes experimental uncertainties and β, which is a function of median toughness. The calculation of Z is a function of σ and the number of samples according to NUREG-1475, Rev. 1, Section 15.4. β places a differing weight on n depending on the toughness, which is not addressed in the basic Z calculation discussed in NUREG-1475, Rev. 1. Therefore, it is not a like-for-like comparison. The revision to Equation 9 (formerly Equation 7) shown in the response to RAI 11a. above, ensures that the MTR test data is conservative.

c. Clarify the definition of the "Adjusted$T_{0highfluxVM}$" term that is used in Equation 7. Clarify if only $T_{0highfluxVM}$ that gets adjusted to the PWR VM conditions (i.e., fluence, chemistry, temperature) or if both $T_{0highfluxVM}$ and T_{0PWRVM} get adjusted to the conditions of interest for the limiting material.

Response to RAI 11.c:

Only $T_{0highflux\ VM}$ is adjusted to the PWR validation material conditions. This is only a comparison of the validation material between the MTR irradiation and the PWR irradiation to ensure that sufficient conservatism is included. Therefore, an adjustment is only made to one measurement to the condition of the other material condition for the comparison in Equation 9 (formerly Equation 7).

d. Clarify and justify how Equation 7 should be applied with multiple data sets. Specifically, justify why it is more appropriate for multiple data sets to be considered collectively (i.e., by adding both sides of the inequalities using all that data) rather than to independently judge each data set on its representativeness, such that only data sets which have demonstrated representativeness would be used within the TR methodology.

Response to RAI 11.d:

For multiple validation data sets the following wording has been added to Section 4.3.4.2 after the Equation 9 definition of terms and the Appendix C examples will be revised to reflect this process:

> If multiple data sets (e.g., different fluences) are available from the same MTR irradiation for the validation heat, then the weighting procedure defined in Section 4 will be used to

> determine the weighted average of $Adjusted\ T_{0high\ flux\ VM}$ and used for comparison in Equation 9 and Equation 10 $Adjusted\ T_{0high\ flux\ VM}$, if the Equation 9 inequality is not met.
>
> If there are multiple PWR irradiations for the validation heat, then the material that matches the same source as the MTR irradiated validation material (e.g., the same plant surveillance weld or same nozzle dropout weld) will be used in preference to a different material source and then secondarily the closest fluence to the MTR irradiation will be the one used.

If data is available from two or more separate MTR irradiations, then the MTR irradiation which produced the most representative result will be used. The next to the last paragraph in Section 4.3.4.2 of the TR will be replaced with:

> If the Equation 9 inequality is not met and multiple data sets are available from separate independent MTR irradiations, then only the single adjusted MTR irradiation which resulted in the most representative result (the result which is the closest to satisfying Equation 9) will be used.

e. Clarify how the Equation 8 would lead to an irradiated T_0 value that is representative or conservative compared to a PWR-irradiated T_0 value.

Response to RAI 11.e:

For data sets which have a validation material irradiated in an MTR, which has a lower T_0 relative to the material being irradiated in a PWR, T_0 of the same material is non-conservative if it is not adjusted. Adjusting the MTR data using Equation 10 (formerly Equation 8), increases the T_0 or RT_{T0} in Equations 1 through 3 to produce a representative result using the difference between the $T_{0PWR\ VM}$ and $adjusted\ T_{0high\ flux\ VM}$ as a percentage of the predicted shift of the MTR irradiation. This adjustment is done in addition to the adjustment made in Equation 6 (formerly Equation 4). In addition, the calculated uncertainties are included in the margin term as discussed in Section 4.4 of the TR.

f. Clearly describe how multiple data sets are to be treated within Equation 8 and provide the basis supporting the proposed treatment, including the appropriateness of averaging multiple data sets for the variables contained within the Equation 8 brackets.

Response to RAI 11.f:

See the TR revisions discussed in the in response to RAI 11.d.

g. Clarify the baseline or reference condition for the "$\Delta T_{high\ flux\ VM}$" and "$\Delta T_{high\ flux}$" terms; specifically, explain if these terms are intended to represent the difference between the test condition fluence and the evaluated (e.g., end-of-life) fluence, the predicted ΔT_0 (or ΔT_{30}) value for the "PWR VM" experiments starting from unirradiated or whatever initial state of the material was, or is a different interpretation of these terms intended. If a different interpretation is intended, please clarify their definitions.

Response to RAI 11.g:

Please see the response to RAI 12 below which revises Equation 9 (formerly Equation 7) and clarifies and revises the definition of terms.

RAI 12 – Section 4.3.4.2 of the TR – MTR Flux Adjustment

NRC Comment

Page 4-8 of the TR shows the following definition of $\Delta T_{high\ flux\ VM}$:

> $\Delta T_{high\ flux\ VM}$ = Predicted shift of the PWR flux validation material using the ASTM E900-15 ETC

The NRC staff is not clear whether the definition should be:

> "Predicted shift of the **high flux validation** material using the ASTM E900-15 ETC"

NRC Request

Clarify whether the definition of $\Delta T_{high\ flux\ VM}$ should be:

> "Predicted shift of the high flux validation material using the ASTM E900-15 ETC"

Response to RAI 12:

The PWROG agrees with the Staff comment. Section 4.3.4.2 of the TR will be revised as follows:

> Revised Equation 10 (formerly Equation 8):

$$Adjusted\ T_{0high\ flux} = \left\{\frac{(T_{0PWR\ VM} - \ Adjusted\ T_{0high\ flux\ VM})}{\Delta T_{30highflux\cancel{PWR}\ VM}}\right\} \cdot \Delta T_{30RPV\cancel{highflux}} + T_{0high\ flux}$$

> $\Delta T_{30\ high\ flux\ VM}$ = P~~p~~redicted ΔT_{30} ~~shift~~ of the ~~PWR~~ high flux validation material using the ASTM E900-15 ETC
>
> $T_{0\ high\ flux}$ = The T_0 (T_0 per Section 4.2) determined using the high flux material from the same Cu group as the validation material

RAI 13 – Section 4.3.5 of the TR – Correlation between ΔT30 and ΔT0

NRC Comment

The NRC staff noted that the discussion of the correlation between ΔT_{30} and ΔT_0 (shown in Figure 6 of the TR) does not include model uncertainty (i.e., uncertainty in the correlation). Regardless of the basis as used in NUREG-1807, "Probabilistic Fracture Mechanics – Models, Parameters, and Uncertainty Treatment Used in FAVOR Version 04.1", the NRC staff is not clear that this precedent should apply in the methodology as used in the TR. Therefore, some basis for not considering model uncertainty should be provided. For a given ΔT_0, the NRC staff noted that the spread in observed ΔT_{30} values can easily be greater than 100°F. Thus, there are other factors contributing to this scatter in the ΔT_{30} and ΔT_0 relationship than just measurement uncertainty associated with individual value. Also, the correlation between ΔT_{30} and ΔT_0 is an assumed linear model where all the measurement points come from comparing an irradiated to unirradiated measure, but in the TR, the correlation is used to adjust between two irradiation levels. Further, it appears from Figure 6 of the TR that the R-value associated with the linear fit is not particularly high, which would mean that a linear correlation may not be the best assumption.

NRC Request (a, b, c, d)

Provide additional justification to support the proposed use and treatment of the model uncertainty in the correlation between ΔT_{30} and ΔT_0 as applied in the methodology in the TR. This justification should:

a. Address other sources of uncertainty in this relationship, including the uncertainty associated with individual measurement values.

Response to RAI 13.a:

The uncertainty (standard deviation) of a T_0 measurement tested in accordance with ASTM E1921 typically ranges from ~ 10°F to 14°F when testing the minimum number (6 or 7) of specimens. The uncertainty of a typical T_{30} measurement can range from ~6°F to 18°F [4, 5, and 6]. 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} measurements. Therefore, there are 4 uncertainties associated with each point in the revised Figure 6 and new Figure 7 in the TR revision. Combining the 4 uncertainties using the square root of the sum of the squares and doubling it to approximate the few points at the extremes results in:

$$2\sqrt{T_{0init}^2 + T_{0irr}^2 + T_{30init}^2 + T_{30irr}^2} \approx 2\sqrt{10^2 + 14^2 + 6^2 + 18^2} = 52°\mathrm{F}\ (29°C)$$

Table 2 of the TR discusses that the standard deviation of the residuals to the fit is 17°C for welds and base metals. These residuals are a combination of measurement uncertainty, material variability and the uncertainty of the fit (standard error on the slope). These uncertainties are independent, and the average material uncertainty can be approximated by removing the measurement uncertainties and standard error on the fit. From Table 2 of the TR, the standard error on the slope is 0.02 for welds and 0.03 for base metals. The midpoint of the datasets shown in Figures 1 and 2 of the TR revision is approximately 100°C times the average standard error of 0.025 = 2.5°C (4.5°F). Subtracting the fit standard error and the measurement uncertainties from the fit residual results in:

$$\sqrt{30.6^2 - 4.5^2 - 26^2} = 16°\mathrm{F}$$

Therefore, it is concluded that the material variability portion of the uncertainty is approximately 16°F (9°C). The ASTM E900-15 standard deviation term also includes material variability as a portion of the standard deviation (SD). The ΔT_{30} values used as a basis for the 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 nuclear RPV type materials. Since $\sigma_{adjustment}$ is the E900-15 ETC SD (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. This material variability should not be another term in the margin term since it is not independent of $\sigma_{adjustment}$.

A draft 2024 ASME PVP paper, “An Examination of Margins Needed to Ensure Conservative Application of T_0 to RPV Fracture Toughness,” is included as an Attachment to demonstrate the conservatism of the revised approach that addressed both the ΔT_{30} and ΔT_0 and the material variability question. 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 value is the maximum value in accordance with Equation 12.

[4] B. Marini, “Empirical estimation of uncertainties of Charpy impact testing transition temperatures for an RPV steel,” EPJ Nuclear Sci. Technol. 6, 57, 2020, https://doi.org/10.1051/epjn/2020019

[5] H. Takamizawa, Y. Nishiyama, T. Hirano, “Bayesian Uncertainty Evaluation of Charpy Ductile-to-Brittle Transition Temperature for Reactor Pressure Vessel Steels,” ASME PVP2020-21698, 2020, https://doi.org/10.1115/PVP2020-21698

[6] H. Hein, J. Kobiela, et al., “Addressing of Specific Uncertainties in Determination of RPV Fracture Toughness in the SOTERIA Project,” Fonevraud 9, 2018.

TR Section 4.3.5 will be revised as follows:

> In some cases, there is a measured difference between the embrittlement shift in ΔT_{30} and ΔT_0. Since the ETC model used is based on ΔT_{30}, this difference ~~should be~~ is taken into account. There is no industry accepted ETC model based on ΔT_0. Figure 6 and Figure 7 show a number of shift measurements comparing ~~the two shifts [43]~~ ΔT_0 and ΔT_{30} for welds and base metals, respectively. The linear fit parameters and statistics for the welds, plates and forgings are shown in Table 2. The statistics show that the plate and forging fits are indistinguishable and are therefore combined as base metal. On average, the ~~ratio~~ slope of ΔT_0 to ΔT_{30} ~~shift difference~~ for welds is 0.99 and ~~1.1~~ 1.08 for ~~plates~~ base metals. The linear fit statistics are excellent with a low standard error on the slope and a high R^2, meaning the slope is known with a high confidence level. For simplicity and conservatism, 1.0 is used for welds and 1.1 is used for base metal in several equations. The addition of the 0.01 or 0.02 conservatism in the slope is more conservative than adding the slope standard error of ~0.03 into the margin term of Equation 11 where it would be combined with all the other uncertainties reducing its effect.
>
> There is significant scatter in the individual measurements with a standard deviation of the errors of the measurement relative to the fit (residual) averaging 17°C (30°F). Each ΔT_0 and ΔT_{30} measurement is comprised of an uncertainty of both the unirradiated and irradiated measurements with the typical combined measurement standard deviation using 2 times the square root of the sum of the squares (SRSS) is shown as error bars in Figure 6 and Figure 7 of 20°C (36°F) for both ΔT_0 and ΔT_{30}. If the independent shift measurement uncertainties (10°C for ΔT_0 and 10°C for ΔT_{30}) are combined using the SRSS, the resulting 14°C (26°F)

measurement uncertainty is not as large as the fit residual of 17°C (30°F). The measurements are composed of unirradiated and irradiated T_{30}, unirradiated and irradiated T_0 which were measured using specimens machined from different portions of the material tested, therefore there would be a contribution of the material variability introduced into the scatter seen in Figure 6 and Figure 7. The addition of 9°C (16°F) into the SRSS calculation with the measurement uncertainties produces an uncertainty of 17°C (30°F) consistent with the residual standard deviation and the expected 95% of the plotted data falls within 2 standard deviations, ±34°C (60°F), of the median fit. The 9°C (16°F) material variability is included in the margin term in Equation 12. Since the T_0 measurement uncertainty is included in the Equation 11 margin term, the measurement uncertainty shown in Figure 6 and Figure 7 is not added to the correlation. ~~Due to lack of forging shift data, a value of 1.1 has previously been used for forgings matching the plate value, as shown in NUREG-1807 [14]. A review of additional forging data (approximately 30 points) from other references [44, 45, 46 and 47] confirmed a value of 1.1 for forging materials is appropriate. For simplicity and conservatism, 1.0 may be used for welds and 1.1 may be used for plates and forgings.~~

NUREG-1807 Section 4.2.3.4.2 [14] provides additional justification for not including an~~adding no~~ uncertainty when converting from ΔT_{30} to ΔT_0 (or vice versa) where the author concludes that when measured ΔT_0 values are determined from a large number of specimens, there is less scatter; therefore, the scatter is largely an artifact of the measurement uncertainty.

Table 2: Fitting Statistics for the ΔT_{30} and ΔT_0 Correlations

Product Form	**Number**	**Data Sources**	**Slope**	**Standard Error on Slope**	**Standard Deviation on Fit Residuals (°C)**	**R^2**	**Equation 6 Adjustment**
Weld	86	14, 31, 43, 45	0.99	0.02	17	0.97	1.0
Plate	59*	14	1.08	0.03	17	0.96	1.1
Forging	29	14, 43, 44, 45, 46	1.08	0.06	16	0.93	1.1
Plate & Forging Combined (BM)	88	14, 43, 44, 45, 46	1.08	0.03	17	0.96	1.1

Notes:

*Two VVER and 5 advanced CrNiMoV steel data points were removed as being non-representative.

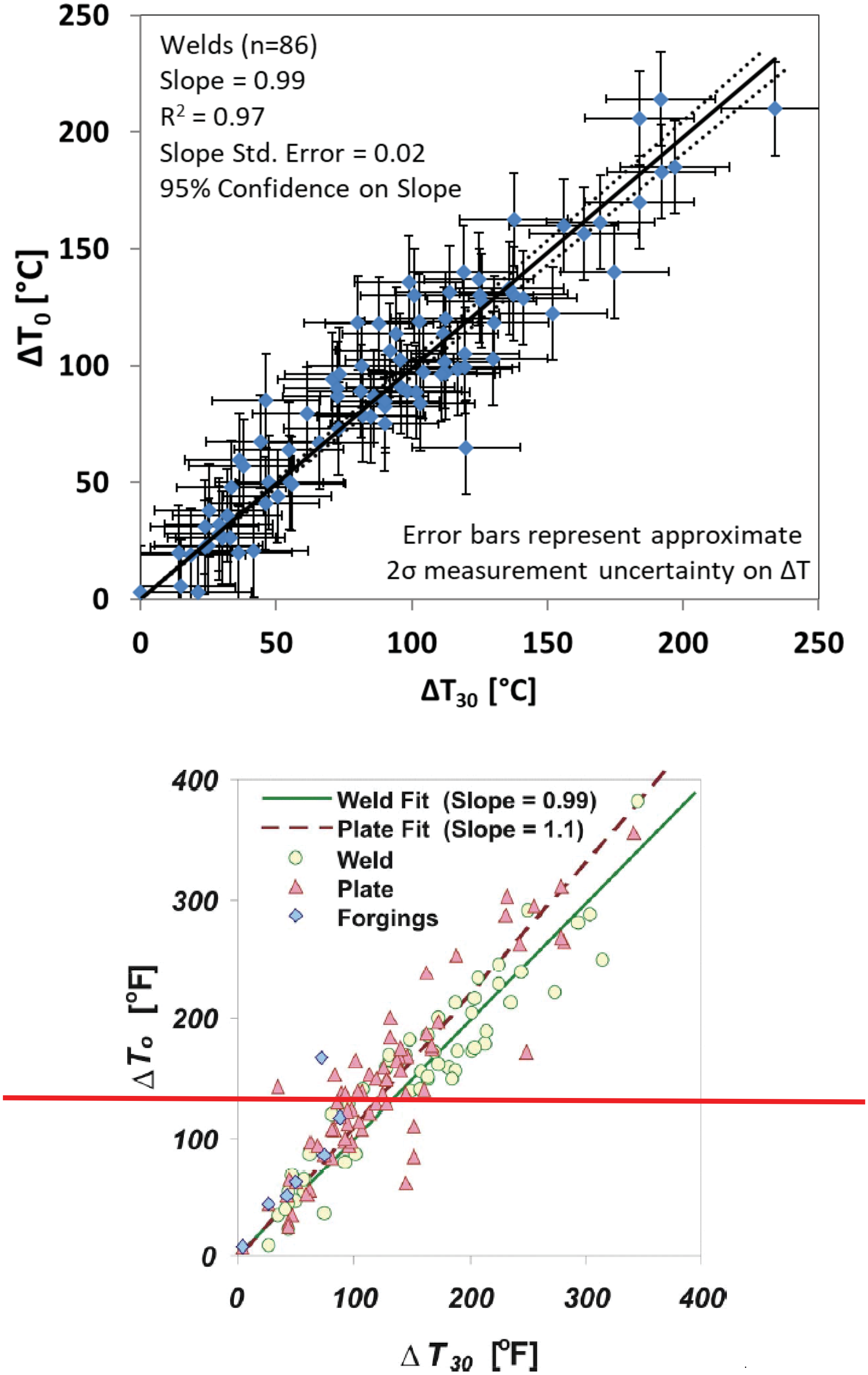


Figure 6: Relationship of Embrittlement Shift between ΔT_{30} and ΔT_0 for Welds ~~(Reproduction of Figure 32 of [43])~~

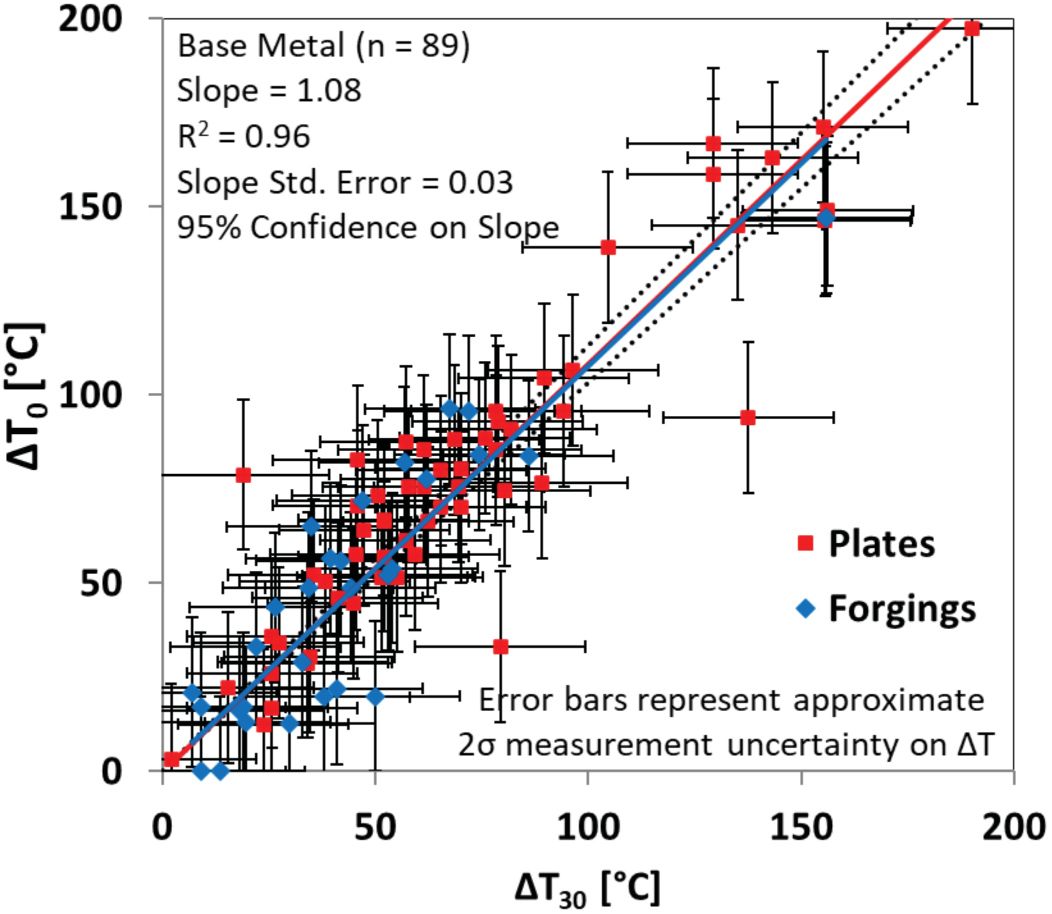
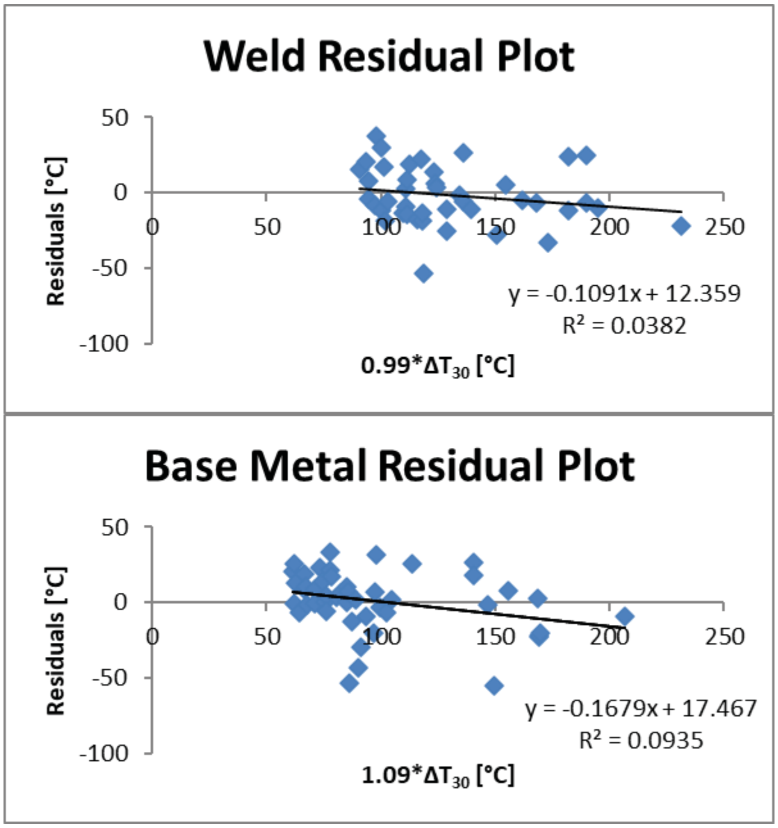


Figure 7: Relationship of Embrittlement Shift between ΔT_{30} and ΔT_0 for Base Metals

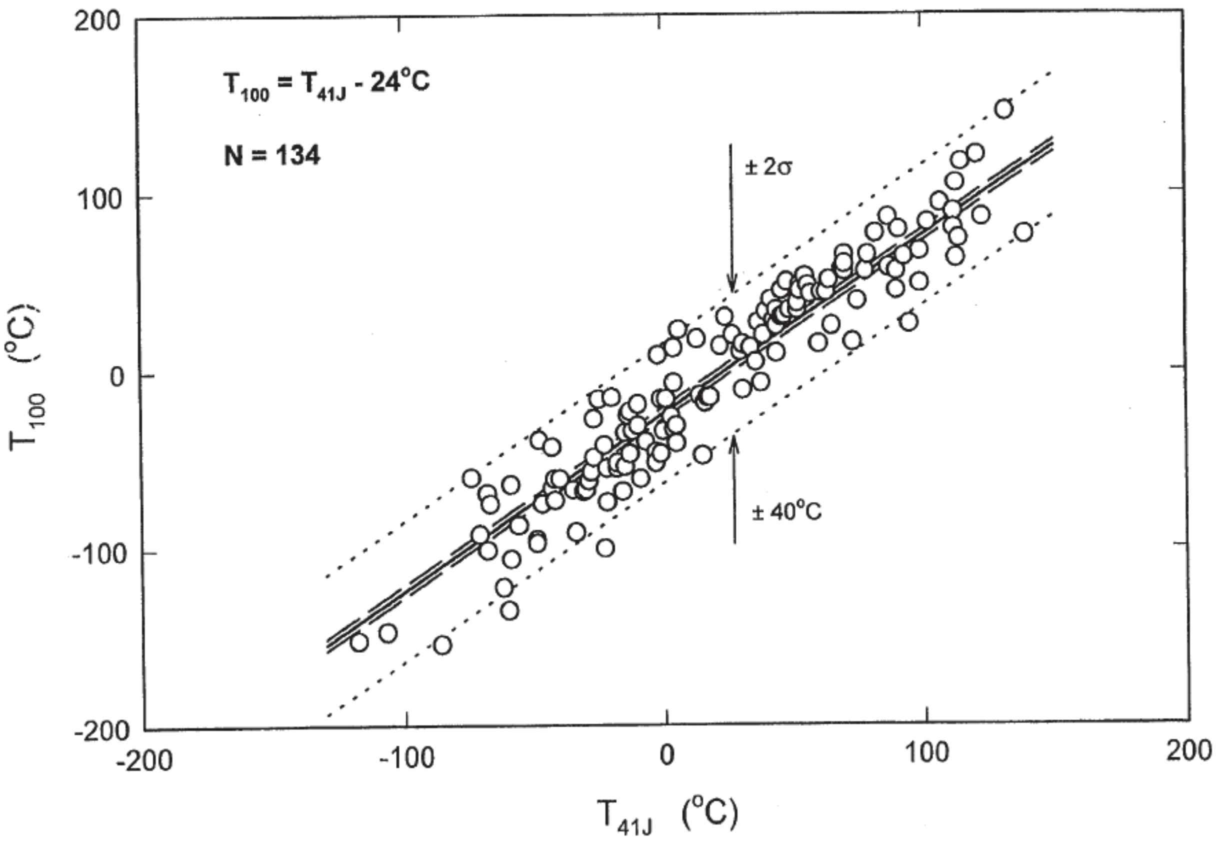
b. Address differences between the data in Figure 6, which use unirradiated data as the reference state and the intended use of this correlation in the TR, which principally uses irradiated data as the reference state.

Response to RAI 13.b:

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 $\Delta T_0/\Delta T_{30}$ slope is the same with the reference state for both 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. Both the ASTM E23 Charpy impact specimens tested in the ductile-brittle transition temperature (DBTT) region (and fit with tanh to determine the reference temperature at 30 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 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 available data with the same material having both ΔT_0 and ΔT_{30} at multiple fluence levels is very limited and likely would not produce statistically significant results due to the small sample size. A recent collection of weld and plate data 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 revised Figure 6 and new Figure 7 [7] in the TR. 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). A best-fit line is shown below for the error in the linear fits (residual) of ΔT_0 and ΔT_{30} starting from a mid-shift (fluence) to a higher fluence. The best-fit line shows a statistically insignificant error trend as shown by the low R^2 and low slope.



The figure below is contained in NUREG/CR-6609 [8] and 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 $R^2 = 0.90$. The reported 1σ residual uncertainty is 20°C and does not appear to change with T_{41J}. This absolute residual is similar to the residuals determined for the shift comparison shown in Table 2 of 17°C for welds and base metal. Therefore, 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 above in Figures 6 and 7.



NUREG/CR-6609 [8] Figure 12

Therefore, using the overall linear slope with no added uncertainty to adjust the irradiated data is appropriate.

[7] M. Kirk, N. Miura, T. Shinko and M. Yamamoto, "Obtaining Low-Cost Estimates of the Master Curve Index Temperature T_0 from Existing Information," ASME PVP2022-83905, 2022.
[8] NUREG/CR-6609, "Comparison of Irradiation-Induced Shifts of K_{Jc} and Charpy Impact Toughness for Reactor Pressure Vessel Steels," U.S. Nuclear Regulatory Commission, November 2000. (ADAMS Accession No. ML003774072)

c. Demonstrate the continued applicability of this correlation given the differences in the initial material reference state.

Response to RAI 13.c:

Please see the response to RAI 13 b. above.

d. Demonstrate the appropriateness of applying the rationale from NUREG-1807 Section 4.2.3.4.2.

Response to RAI 13.d:

Section 5.3 of MRP-462 [9] provides a more detailed analysis of larger data populations than what is presented in NUREG-1807. For welds, the mean is 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 13a and the revision to Section 4.3.5 of the TR.

Please see the response to RAI 13a above and the revision to Section 4.3.5 of the TR.

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% confidence interval (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.

[9] "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.

RAI 14 – Section 4.4.3 of the TR – Determination of σtempspecimen and σtempRPV

NRC Comment

Section 4.4.3 of the TR provides the following equation for the term $\sigma_{tempRPV}$:
$\sigma_{tempRPV}$ = The effect of the uncertainty of the RPV irradiation temperature on embrittlement using the ETC ***** (ΔT_0 / ΔT_{30} Slope) at the RPV best estimate condition. Additionally, Section 4.4.3 states that "…the uncertainty of the average (standard error) irradiation temperature is less than or equal to 2°F after averaging at least four cycles of data. 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…" The NRC staff is not clear on how 2°F was derived based on the information above.

NRC Request

Describe how the 2°F is derived.

Response to RAI 14:

There are multiple calibrated resistance temperature detectors (RTDs) in the reactor coolant loops. Evidence supports total PWR instrument reactor coolant loop temperature standard deviation is ± 2.4°F random with a total bias of ± 1.2°F as taken from thermal design procedure uncertainty calculations. Since the reactor coolant temperature is measured often and averaged over many cycles, the standard error (standard error = standard deviation/$\sqrt{N}$) is small. Considering this, the uncertainty of the average (standard error) irradiation temperature is less than 2°F after averaging at least 4 cycles of data. There may be some unique situations (i.e., short irradiation time), however, the 2°F uncertainty in the time weighted average irradiation temperature can be used conservatively for surveillance capsule and RPV wall irradiations.

RAI 15 – Sections 4.4.3 and 4.4.4 of the TR - Determination of σtempspecimen, σtempRPV, σfluencespecimen, and σfluenceRPV

NRC Comment

The last paragraphs of Sections 4.4.3 and 4.4.4 of the TR states that the uncertainty values related to temperature (Section 4.4.3) or fluence (Section 4.4.4) are the effect on the ETC prediction as a result of the temperature or fluence uncertainty. The NRC staff needs confirmation on the understanding of the referenced paragraphs.

NRC Request

Confirm that one would calculate the change in ETC for a given temperature uncertainty or fluence uncertainty applied in the conservative direction, then multiply by ΔT_0 / Δ T_{30} slope to calculate the corresponding uncertainty value. Provide an example.

Response to RAI 15:

The Staff's understanding is correct. The effect of the input uncertainty on the ETC output is as stated in the definition of the terms in Sections 4.4.3 and 4.4.4 of the TR. There are examples provided in Appendix C, Table C-5 and Table C-13, with the ETC input uncertainties presented in the text preceding these tables.

RAI 16 – Section 4.5 – Uncertainty due to Material Variability

NRC Comment

The second paragraph of Section 4.5 of the TR states that "…Data sets that fail the [homogeneity] screening criterion, regardless of the reason, are evaluated in accordance with Appendix X5 of ASTM E1921-20…," but does not state that these data would be submitted to the NRC for review and approval. The NRC staff is not clear whether data sets evaluated in accordance with Appendix X5 of ASTM E1921-20 will be sent for NRC review and approval.

NRC Request

Clarify whether or not a data set fails the homogeneity screening criterion, whether the data set will be evaluated according to ASTM E1921-20 without NRC review and approval. If yes, discuss how the evaluation of the data set in accordance with Appendix X5 of ASTM E1921-20 for inhomogeneous data sets will be documented.

Response to RAI 16:

The TR methodology addresses homogenous data sets, and also if the data set does not satisfy the homogeneity screening criterion, i.e., that the data will be evaluated in accordance with Appendix X5 of ASTM E1921-20. After the NRC issues the Safety Evaluation (SE) for the TR, that approves the methodology, the methodology will be applied consistent with the NRC SE, which includes addressing non-homogenous data sets. Therefore, NRC review of the application of the specifics of the methodology regarding non-homogenous data is not required.

Section 4.2 of the TR will be revised as follows:

Alternatively, the procedures of X5.3.2 or X5.3.3 may be used for large inhomogeneous data sets (N ≥ 20) exhibiting bimodal or multimodal behavior, respectively.

RAI 17 – Section 4.3 of the TR – Data Adjustments

NRC Comment

Section 4.3 of the TR states that "if the calculated adjustment exceeds the prediction model uncertainty (SD_{ETC}) shown in Equation 5 of the TR, then additional margin is added as described in Section 4.4." The NRC staff noted that while the uncertainty should clearly be a function of the amount of adjustment, there is no basis provided for why it should be zero until the adjustment exceeds the standard deviation of the ETC model. The implication of this approach is that the larger the standard deviation of the ETC model, the larger the adjustment has to be before margin is added. This logic appears counterintuitive.

NRC Request

Provide the basis for why there is no ETC model uncertainty until the adjustment exceeds the standard deviation of the ETC model, and why a gradual increase of the standard deviation that, in the limit of a large enough adjustment, would be equal to the E900-15 SD_{ETC}, is not more appropriate.

Response to RAI 17:

The ability to set the adjustment uncertainty term to 0 will be removed from the TR. Please see the response to RAI 5.a. above and RAI 20.a. below. This clarifies that when the condition of the irradiated test specimens is essentially the same, the RPV condition of interest (all the inputs used in the ETC for the specimens and the RPV are the same), there is no adjustment made and therefore there is no uncertainty in the adjustment, however a 9°C minimum will be used for $\sigma_{adjustment}$ to account for material variability. The Margin Term includes uncertainties associated with the T_0 measurement, fluence calculations and irradiation temperature(s).

RAI 18 – Section 4.3.3 of the TR – Fluence

NRC Comment

Section 4.3.3 of the TR states: "The ratio of dpa at the postulated flaw depth to dpa at the inner surface may be substituted for the exponential attenuation factor in Equation 6." 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). Therefore, it's not clear how the dpa ratio alone provides that information.

NRC Request

Clarify how the approach cited above can be used to determine the fluence at the depth of the postulated flaw tip using Equation 6 of the TR.

Response to RAI 18:

The exponential attenuation factor in Equation 7 (formerly Equation 6) is “$e^{-0.24x}$”. Substituting (flaw depth dpa)/(inner surface dpa) would reduce the surface fluence to the flaw depth fluence. For example: $\text{fluence}_{1/4T} = \text{fluence}_{\text{surface}} * \text{dpa}_{1/4T} / \text{dpa}_{\text{surface}}$. This is consistent with the guidance provided in Section 1.1 of Regulatory Guide 1.99, Revision 2. Equation 8 has been added for clarity.

$$\boldsymbol{fluence_x = fluence_{surface} \bullet \frac{dpa\ at\ x}{dpa\ at\ inner\ surface}} \qquad \text{[Equation 8]}$$

RAI 19 – Section 4.4.1 of the TR – Determination of σtest

NRC Comment

In Section 4.4.1 of the TR, the PWROG discussed the determination of the uncertainty due to specimen testing, σ_{test}. The NRC staff also noted that there are several examples in Appendix C of the TR where the T_0 uncertainty of smaller data sets is less than the uncertainty of larger data sets. It is not clear why the uncertainty is less when material inhomogeneity has been detected. The NRC staff noted that the ASTM E1921 T_0 uncertainty is based on the "r" value and for T_{0IN}, the "r" value is typically less than 50% of the total data set. When T_{0max} is calculated, r = 1. The NRC staff also noted that a datapoint based on a single toughness measurement does not necessarily mean there is no uncertainty in the associated T_{0max} value. Also, the NRC staff is not clear about the basis for the uncertainty being a function of the difference between T_{0max} and T_{0IN}, which seems to imply that T_{0max} be calculated for any number of specimens (N) of less than 20, when it is only a specified ASTM E1921 calculation if N is less than 10. Finally, staff is also not clear why the uncertainty measure prescribed for homogeneous data sets in E1921 Section 10.9 is appropriate for inhomogeneous materials.

NRC Request (a, b, c, d, e)

Provide the basis for the determination of σ_{test} in Section 4.4.1 of the TR as summarized in Table 3 of the TR, addressing the following issues:

a. Basis for small, or zero, T_0 uncertainty when the data set is small.

Response to RAI 19.a:

The use of σ_{test} for inhomogeneous materials will be removed from the TR, with σ_{E1921} being consistent with the ASTM E1921-20 definition.

b. Basis for small, or zero, T_0 uncertainty when material inhomogeneity has been detected.

Response to RAI 19.b:

The use of σ_{test} for inhomogeneous materials will be removed from the TR, with σ_{E1921} being consistent with the ASTM E1921-20 definition.

c. Basis for the uncertainty being a function of the difference between T_{0max} and T_{0IN} in Table 3.

Response to RAI 19.c:

The use of σ_{test} for inhomogeneous materials will be removed from the TR, with σ_{E1921} being consistent with the ASTM E1921-20 definition.

d. Clarification and justification for both the calculation and use of T_{0max} for $10 < N < 20$.

Response to RAI 19.d:

The use of σ_{test} for inhomogeneous materials will be removed from the TR, with σ_{E1921} being consistent with the ASTM E1921-20 definition.

e. Basis for assigning $\sigma_{test} = \sigma_{E1921}$ for inhomogeneous data sets, instead of the σ values prescribed in ASTM E1921 Appendix X5 or other possibly appropriate measures.

Response to RAI 19.e:

The use of σ_{test} for inhomogeneous materials will be removed from the TR, with σ_{E1921} being consistent with the ASTM E1921-20 definition.

Section 4.4.1 of the TR will be revised as follows:

> ~~If N ≥ 20, then $\sigma_{test} = \sigma_{E1921}$ per paragraph 10.9 of ASTM E1921 regardless of the homogeneity screening outcome.~~ σ_{E1921} is calculated in accordance with paragraph 10.9 of ASTM E1921 (with standard calibration practices, σ_{exp} = 4°C). Alternatively, if the procedures of X5.3.2 or X5.3.3 are used for large inhomogeneous data sets (N ≥ 20), then the associated σ will be substituted for σ_{E1921}, as the number of samples will ensure that there is a sufficient population of low toughness data included in the result.

RAI 20 – Section 4.4.2 of the TR – Determination of σadditional

NRC Comment (a, b, c, d)

a. In Section 4.4.2 of the TR, the PWROG discussed the determination of the uncertainty term, $\sigma_{additional}$. Similar to the development and use of Equation 5 (and RAI-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 application and not solely a function of the standard deviation of the ETC. A bigger shift between the RPV and specimen should have more uncertainty. Equation 10 of the TR does not account for the amount of shift at all. The NRC staff also noted that the additional margin should exactly equal the ETC standard deviation if one of the conditions is the unirradiated state. Equation 10 of the TR does not approach that standard deviation in the limit.

b. Section 4.4.2 of the TR states: “Furthermore, any chemistry variation is considered indirectly through the homogeneity screening, which identifies atypical toughness variation.” The NRC staff noted that the TR documents need to correct for chemistry differences between test data and the application of interest. Therefore, it is not clear if the chemistry variation discussed in this section refers to these bulk chemistry differences or local differences in the test material or the application of interest that vary from the bulk chemistry.

c. 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 is not clear why the TR does not evaluate both σ_{ETCRPV} and $\sigma_{ETCspecimen}$ and choose the greatest uncertainty value in this situation.

d. Section 4.4.2 of the TR states that the term $\sigma_{additional}$ double counts several of the uncertainties that are explicitly included in the margin term (Equation 9) of the TR but is not clear about what other terms in Equation 9 of the TR the $\sigma_{additional}$ term double counts for and why or how it double counts. Clarification and explanation of what margin terms the $\sigma_{additional}$ term double counts for will help the NRC staff determine if the uncertainties are reasonably accounted.

<u>NRC Request (a, b, c, d)</u>

a. Justify Equation 10 of the TR associated with $\sigma_{additional}$ and specifically why, if adjustments do not exceed the standard deviation of the ETC, that $\sigma_{additional}$ should be set to zero.

<u>Response to RAI 20.a:</u>

The allowance to set the adjustment uncertainty term to 0 will be removed from the TR.

As the *adjustment* gets larger due to the difference in TTS between the RPV and the specimens, so does $\sigma_{additional}$ (revised to be $\sigma_{adjustment}$ in the TR, as discussed in the response to RAI 5.a, above 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 9°C minimum has been added to account for material variability and other uncertainties with small adjustments. A draft 2024 ASME PVP Conference paper, "An Examination of Margins Needed to Ensure Conservative Application of T_0 to RPV Fracture Toughness," is included as an Attachment, which provides this basis.

Equation 11 (formerly Equation 9) (TR Section 4.4) will be revised as follows:

$$Margin = 2 \bullet 1.8\frac{°\mathrm{F}}{°\mathrm{C}} \bullet \sqrt{\sigma^2_{\cancel{test}E1921} + \sigma^2_{\cancel{additional}adjustment} + \sigma^2_{tempspecimen} + \sigma^2_{tempRPV} + \sigma^2_{fluencespecimen} + \sigma^2_{fluenceRPV}}$$

[Equation 11]

Section 4.4.2 of the TR including Equation 12 (formerly Equation 10) will be revised as follows:

$\sigma_{adjustment}$ is required to account for the uncertainty of adjusting the measured T_0 to the RPV condition of interest as determined by Equation 12. $\sigma_{adjustment}$ 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.
~~If adjustments exceed the standard deviation of the ETC as described in Section 4.3,.. If adjustments do not exceed the standard deviation of the ETC, $\sigma_{additional}$ is set equal to zero.~~

$$\sigma_{adjustment} = \boldsymbol{max}\left[\boldsymbol{9°C}, \{\boldsymbol{C} \bullet ([If\ BM, 1.1] \bullet \Delta T_{30RPV})^{\boldsymbol{D}}\} \bullet \frac{|adjustment\,|}{(If\ BM, 1.1) \bullet \Delta T_{30\ RPV}}\right] \quad \text{[Equation 12]}$$

Where,

C and D are provided in Table 3

Table 3: Coefficients for ASTM E900-15 Embrittlement Shift Model Uncertainty [4]

Product Form	**C**	**D**
Forgings	6.972	0.199
Plates	6.593	0.163
Welds	7.681	0.181

b. Clarify the statement in Part b of the issue above because the NRC staff noted that the methodology described in the TR appears to adjust for known chemistry differences.

Response to RAI 20.b:

The TR methodology adjusts for 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. There is still variation in chemistry about the best estimate and if this chemistry variation were to significantly affect the 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 TD 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 in the TR, as well as in Reference [1] (See the response to RAI 4.c).

For clarity, Section 4.4.2 of the TR will be revised as follows:

> Furthermore, any local chemistry variation is considered indirectly through the homogeneity screening, which identifies atypical toughness variation.

c. Demonstrate that Equation 10 is appropriate for calculating $\sigma_{additional}$ for a specific heat of material. Clarify why σ_{ETCPRV} and $\sigma_{ETCspecimen}$ are not evaluated, and then $\sigma_{additional}$ set to the maximum uncertainty value.

Response to RAI 20.c:

The response to RAI 20.a above includes a revision to Section 4.4.2 of the TR. The revised TR methodology now has a minimum $\sigma_{\text{adjustment}}$ of 9°C and for larger adjustments, the $\sigma_{\text{adjustment}}$ is defined in the new Equation 12. A draft 2024 ASME PVP Conference paper, “An Examination of Margins Needed to Ensure Conservative Application of T_0 to RPV Fracture Toughness,” is being provided as an Attachment for this basis using a large amount of data demonstrating the conservativeness of the approach.

d. Clarify which margin terms in Equation 9 of the TR the $\sigma_{\text{additional}}$ term double counts for and explain why or how the term double counts the other margin terms.

Response to RAI 20.d:

Section 4.4.2 of the TR has been revised as follows:

> The minimum value of 9°C also addresses other unidentified uncertainties such as material variability. The ASTM E900-15 standard deviation (SD) ~~SD_{ETC}~~ is based on the SD of the measured data relative to the ETC ΔT_{30} ~~TTS~~ prediction which represents the uncertainty in making a single prediction, which includes ~~measurement and input~~ 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.
>
> …
>
> ~~Therefore, for the same heat, σ_{ETCRPV} and $\sigma_{\text{ETCspecimens}}$ are not independent and do not need to be combined using the SRSS. Instead, these uncertainties are combined as a simple difference in Equation 10, implying the uncertainties are fully dependent. Although σ_{ETCRPV} and $\sigma_{\text{ETCspecimens}}$ are neither fully dependent nor fully independent, the approximation of being fully dependent is appropriate, since some uncertainties are being double counted in this methodology.~~ When using Equation 12 ~~10~~ with unirradiated test specimens, ~~$\sigma_{\text{ETCspecimens}}$ = 0°F and, therefore,~~ $\sigma_{\text{adjustment}}$~~$_{\text{additional}}$~~ becomes the ASTM E900-15 SD.

RAI 21– Section 4.5 – Uncertainty due to Material Variability

NRC Comment (a, b)

a. In Section 4.5 of the TR, the PWROG discussed the uncertainty due to material variability, (i.e., uncertainty due to variability within the same material heat). The PWROG stated that “no explicit uncertainties are required to consider material variability aside from those associated with the homogeneity screening.” The NRC staff noted that, in principle, 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 amount 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 does not provide sufficient information to demonstrate that material variability does not need to be considered in the TR methodology.

b. In Section 4.5 of the TR, the PWROG stated: “measurement of irradiated fracture toughness near the condition of interest removes uncertainty associated with embrittlement prediction...” Similar to the issue associated with RAI-7, the TR does not appear to clearly articulate the criteria and/or limitations that assure that the condition in the measurement of irradiated fracture toughness is sufficiently “near the condition of interest.”

NRC Request (a, b)

a. Provide further justification that demonstrates that material variability does not need to be considered in the TR methodology and that the uncertainty that the limiting condition has been appropriately evaluated and is not a function of both the amount of representative material tested and the degree to which it can be demonstrated that the representative material appropriately represents, or bounds, the limiting material.

Response to RAI 21.a:

All product forms have material variability to different degrees. The E1921-20 method has been demonstrated to represent the product tested from a small set of sampled material. For example, Reference [1] (See the response to RAI 4.c) evaluated worst case small sample subsets 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% of the data from any test temperature was bounded for the least conservative subset assessed, as demonstrated in Table 4 of Reference [1]. If all subsets were considered from the ten large data sets shown in [1], the data bounded is considerably more than 95%. Conservative results were obtained in all cases. See the response to RAI 19.b. above. In addition, ASME Code 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. For further details see Section 2 of PWROG-15109-NP-A [10] on flaw size detection capabilities in RPVs.

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 sufficient to cause cleavage initiation in the 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. Cleavage fracture typically initiates at grain triple points, carbides or other microscopic stress concentrators. If there is a sufficient density of sufficiently sized triggers, 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. 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 precrack tip. Therefore, for a macroscopically homogeneous material, the consistency of the small 4 mm test specimen results with larger size test specimens, as shown in TR Appendix A, demonstrates that sufficient microscopic initiators are being sampled by the crack front.

For macroscopically inhomogeneous materials, the ASTM E1921 inhomogeneous screening procedure identifies these materials in many cases, and T_{0IN} conservatively addresses the identified lower toughness material.

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 during tempering. The ASME Section III, Division 1, NB-2300 qualification specimens and T_0 test specimens are removed at the 1/4 thickness from the surface. Therefore, the T_0 developed in accordance with the TR methodology are from the 1/4 thickness. The average improvement in surface toughness for RPV forgings is 36.5°F [10] relative to the 1/4T location. Therefore, the peak fluence will inherently occur in material which has better fracture toughness than the tested specimens. This conclusion also considers the potential impact of carbon macro-segregation discussed by Saillet [11], which can cause lower toughness at the surface in large forgings.

Secondly, 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.

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 majority of U.S. PWRs with RPVs fabricated from plates were fabricated by CE. The plates were procured by CE primarily from two suppliers for U.S. PWRs: Lukens and Marrel Freres. Each supplier would typically produce a heat for which the chemical content would be analyzed while still molten to provide a heat (ladle) analysis which met the purchase specification. The heat would be poured to produce an ingot, and a “check analysis” performed to ascertain that the cast steel met the purchase specification. The ingot was assigned a heat (melt) number and then typically cut into 2 or 3 sections; e.g., ingot heat number C5192 became C5192-1 and C5192-2, producing 2 pieces of the same heat for beltline shell plates. Each piece was rolled into a plate. The rolling would typically be in two directions to attain the desired dimensions. The majority of the rolling would be parallel to the length of the plates and this would be marked as the direction of major rolling. The supplier would then remove a portion of the plate for heat treatment and mechanical testing. The results from the mechanical testing and chemistry testing (both “heat” and “check”) would be entered on the supplier’s (plate mill) certification material test report (CMTR) and submitted to the fabricator for approval.

Upon acceptance by CE, the plate would be shipped from the supplier. The fabricator would perform non-destructive testing, repairs (as necessary), and then hot form it into a shell plate of the desired radius. Each shell plate was procured with excess material used for ASME Code testing and the surveillance program. The code test piece was given a simulated post weld heat treatment. Mechanical test specimens were machined and tested for compliance with contract and specification requirements. The results were included in the CMTR along with the mill chemistry. CE would perform chemical analysis of most of the individual plates following the forming and heat treatment steps. This chemistry was then generally reported as the chemistry for each plate.

The reported chemistries (looking at all elements reported) were verified to be different for each plate removed from the same ingot studied herein, meaning independent measurements were taken from different locations. Independent chemistry measurements taken from different plates removed from the same ingot (i.e., C5192-1 and C5192-2) were then compared when performed by the same mill or fabricator to develop an appropriate representation of the variability in typical RPV plates. There were also instances where the chemistry was measured by Westinghouse on surveillance program plates and irradiated Charpy specimens tested from the surveillance program at the Westinghouse hot cell. When available, this data was also included as an independent measurement adding to the measurements of material variability. There are over 50 ingots from which multiple plates were formed (Lukens) and 9 heats with multiple measurements from top and bottom (Marrel Freres) contained in the PWR fleet beltline used to derive the difference in measurements to quantify variability in plate C. The results are shown in the table below.

Carbon Measurements from Plates

Number of plate measurements	209
Standard deviation relative to heat average (wt%)	**0.0121**
Standard deviation of all data (wt%)	0.023
Average (wt%)	0.22
Minimum (wt%)	0.154
Maximum (wt%)	0.290

Forgings were supplied by several vendors. Each supplier would typically melt selected scrap steel, refine it, and make alloying additions to produce a heat. They would provide a heat (ladle) and check analysis on the chemical content of the melt and cast ingot, respectively, to establish conformance with the specification. The ingot was then assigned a heat number, if more than one forging was to be made from the ingot, it was cut into sections and each section was assigned a serial number. The sections were forged into the product. Portions of each forging were removed for testing after heat treatment. The results were entered into the CMTR for CE approval prior to shipment. CE would typically not perform any additional chemical analysis.

Forging CMTRs were reviewed for multiple chemistry measurements to provide a quantitative assessment of chemistry variability. Many CMTRs of the RPV nozzle forgings had chemistry product check measurements from the qualification samples which were taken 180° apart at the 1/4T location in addition to the ladle measurement (inlet or outlet nozzle data was used for approximately 50% of the forging data in this assessment). Relatively few RPV shell forgings contain more than one check analysis; however, when available the data was included.

Differences from the heat average were taken for each forging to assess the typical variation. There were a few instances where several measurements were made on individual RPV forgings. There are also instances where the chemistry was measured on irradiated Charpy specimens tested from the surveillance program at the Westinghouse hot cell.

Fifty relevant forging heats with multiple chemistry measurements were found in the literature, CMTRs, and WCAPs contained in the PWR fleet beltline used to derive the information shown in the table below.

Carbon Measurements from Forgings

Number of forgings measurements	173
Standard deviation relative to heat average (wt%)	**0.0074**
Standard deviation of all data (wt%)	0.0182
Average (wt%)	0.200
Minimum (wt%)	0.167
Maximum (wt%)	0.240

The C standard deviation of the difference from the average measurements is 0.0121% for plates and 0.0074% for forgings. 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% [12 and 13] 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 13a 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).

A draft 2024 ASME PVP Conference paper, “An Examination of Margins Needed to Ensure Conservative Application of T_0 to RPV Fracture Toughness,” is included as an Attachment for this basis which considers a large amount of measured fracture toughness and T_0 data demonstrating the conservativeness of the approach. This paper analyzes many datasets where 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 2nd (or more) measurement 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 2nd (or more) measured datasets assessing the margin needed to ensure an evaluation of the RPV would be bounding. The draft paper demonstrates that greater than 95% of the measured T_0 values and fracture toughness values are bounded by the TR methodology. This is consistent with the level of safety in ASME B&PV Code Section III NB-2300, ASME B&PV Code Section XI, Appendix G and ASME Section XI Code Case N-830 which are all endorsed by the NRC.

[10] “PWR Pressure Vessel Nozzle Appendix G Evaluation,” PWROG-15109-NP-A, January 2020. https://www.nrc.gov/docs/ML2002/ML20024E573.pdf
[11] Saillet, S., Rupa, N. and Benhamou, C., “Impact of Large Forging Macrosegregations of the Reactor Pressure Vessel Surveillance Program,” presented at the International Symposium Fontevraud 6, Paper No. A067-T01, France, September 2006.
[12] Materials Reliability Program: Evaluation of Risk from Carbon Macrosegregation in Reactor Pressure Vessel and Other Large Nuclear Forgings, Revision 1 (MRP-417, Rev. 1). EPRI, Palo Alto, CA: 2018. 3002012328.
[13] Coppard, R., Coulon, P., Koyama, Y. and Endo, M., “Impact of Carbon Macro Segregation on The Mechanical Properties of Low Alloy Steel Forgings,” ASME PVP PVP2019-94059]

b. Describe the criteria and/or limitations with the TR methodology that assure that the condition in the measurement of irradiated fracture toughness is sufficiently “near the condition of interest.”

Response to RAI 21.b:

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 theoretically could be 0 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 (formerly Equation 10) in the TR. In addition, the chemistry adjustments are limited, since the adjustment between the tested specimens and the RPV best estimate is limited to the chemistry variation within the heat. Also, as discussed in response to RAI 20.b above, the inhomogeneity screen identifies atypical toughness variation, and the TR contains a methodology to conservatively treat the data.

The last sentence in Section 4.5 of the TR will be revised as follows since the $\sigma_{adjustment}$ term is reduced when the adjustment is small:

> Measurement of direct fracture toughness reduces the uncertainty associated with the correlation of RT_{NDT} to fracture toughness and measurement of irradiated fracture toughness ~~near the condition of interest removes~~ reduces the uncertainty associated with embrittlement prediction.

RAI 22 – Figures B-1 and B-2 of the TR – Flux Effect on Welds and Forgings

NRC Comment (a, b)

a. In Figures B-1 and B-2 of the TR, the PWROG showed plots of the effect of flux on RPV welds and forgings. The NRC staff noted that the correlation between ΔT_{41J} and ΔT_0 in Figures B-1 and B-2 does not appear to be as close to the nearly 1-to-1 general correlation illustrated in Figure 6 of the TR. The data in these figures seems to imply that the ΔT_0 shift is higher than the ΔT_{41J} shift and that this disparity increases with fluence.

b. The NRC staff also noted that Figures B-1 and B-2 contain limited high-flux data, especially at high fluences (i.e., above 1E+20 n/cm^2).

NRC Request (a, b)

a. Explain the apparent differences between the ΔT_{41J} to ΔT_0 correlation implied in Figures B-1 and B-2 of the TR and the ΔT_{30} to ΔT_0 correlation in Figure 6 of the TR.

Response to RAI 22.a:

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 the revised Figure 6 and new Figure 7 of the TR. Section 5.3 in MRP-462 [9] (See responses to RAIs 13.a through 13.d) and revised TR Section 4.3.5 contain a more detailed analysis of the correlation of ΔT_{30} to ΔT_0 with larger data populations than what is shown in the TR Appendix B, Figures B-1 and B-2. The responses to RAI 13.a through 13.d above provide a more detailed discussion of the correlation of ΔT_{30} to ΔT_0.

b. Explain 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. As part of this response, address 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. This RAI is related to RAI-11, but the focus here is specifically on the treatment of high-fluence data given its relative paucity.

Response to RAI 22.b:

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 Cu grouping identified in the TR, the comparison to the validation material exposed in an MTR to 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% 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* $T_{0high\ flux\ VM}$ term in Equation 9 (formerly Equation 7) in the TR.

The last paragraph in Section 4.1 of the TR will be revised as discussed in the response to RAI 01 above.

RAI 23 – ASME Code Cases and Other Regulations

NRC Comment

There are other regulations and ASME Code Cases that could potentially utilize the methods described in the TR. For example, 10 CFR 50.61a requires calculation of RT_{Max} values for the end of the licensed operating period that incorporate an embrittlement trend curve prediction. Also, the TR references use of this method in conjunction with ASME Code Case N-830. The NRC staff noted that ASME Code Case N-830 is referenced in the TR and that it is in the list of currently approved code cases with conditions in Regulatory Guide 1.147, Revision 20. The NRC staff also noted that the ASME Code has recently approved Code Case N-830-1, which is Revision 1 of Code Case N-830. The NRC staff is not clear on how the methodology described in the TR interfaces with either 10 CFR 50.61a or Code Case N-830-1.

NRC Request

Clarify whether or how the methodology described in the TR interfaces with Code Case N-830-1. Specifically, explain if the methodology in the TR will be allowed within the framework of Code Case N-830-1. For example, explain if an end-of-life T_0 value using the TR methodology could be determined and applied within Code Case N-830-1 to determine other fracture properties. Additionally, clarify if it is intended that the TR methodology be utilized within 10 CFR 50.61a evaluations and, if so, describe how it would be applied within 10 CFR 50.61a and if, for example, the TR methodology would replace the equations specified in 10 CFR 50.61a to calculate RT_{Max} values, while retaining the 10 CFR 50.61a acceptance criteria.

Response to RAI 23:

The following will be added to Section 4 of the TR:

The use of this methodology has not been evaluated for applicability to Code Case N-830-1. This methodology cannot be used as an alternative for calculating RT_{Max} for 10 CFR 50.61a.

RAI 24 – Section 4.0 of the TR – Master Curve Approach Process

NRC Comment

The NRC staff noted that, given the complexity of the methodology of applying the master curve approach described in Section 4 of the TR, the process by which the final calculated irradiated T_0 value (with adjustment and margin as specified in the TR) is determined starting from a data set or multiple data sets 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 provide some discussion on how the TR methodology is applied, they do not provide a clear guide on the process steps.

NRC Request

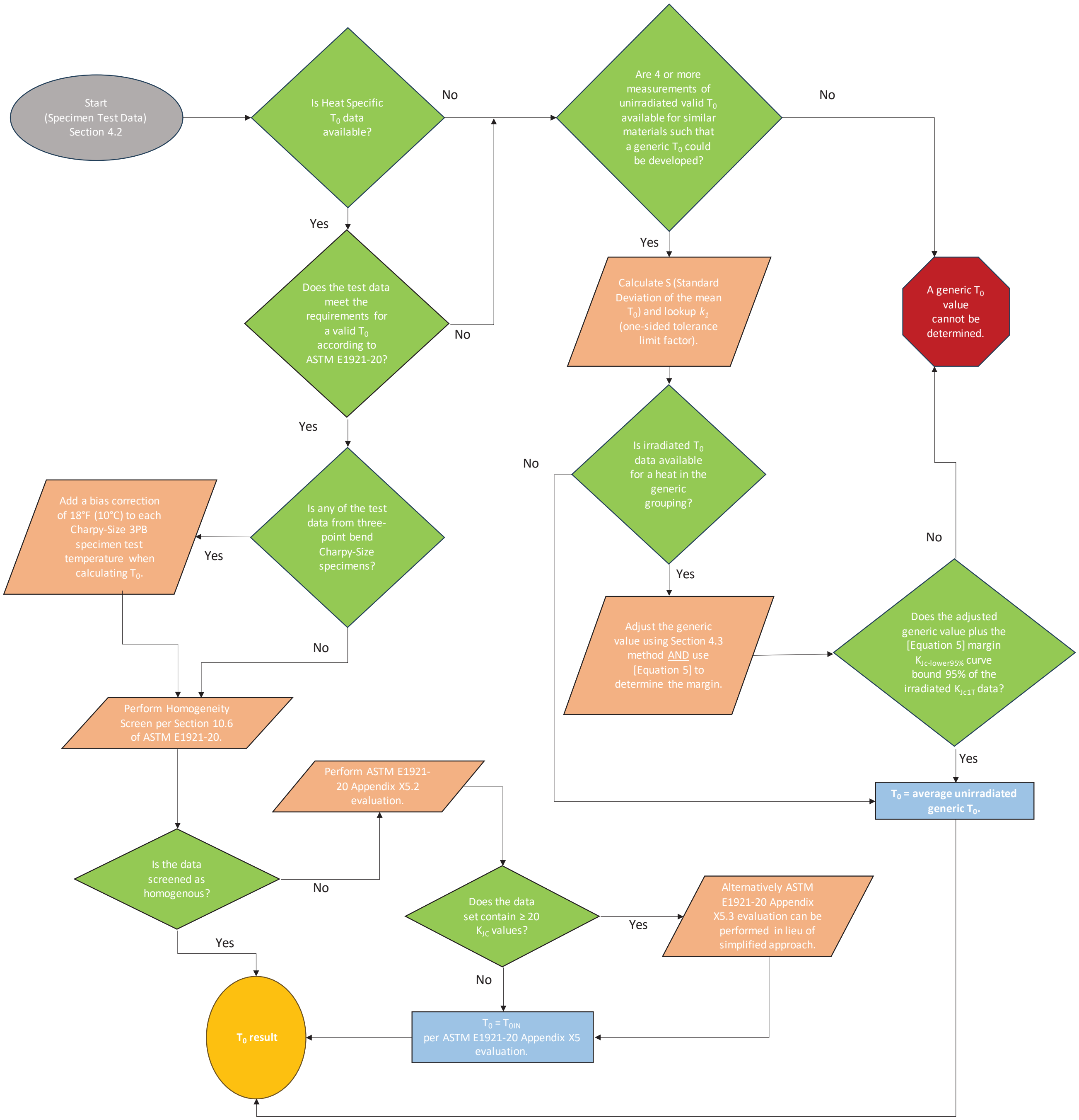
Provide a detailed description of the process by which the final calculated irradiated T_0 value (with adjustment and margin as specified in the TR) is determined starting from a data set or multiple data sets of T_0 values (irradiated and/or unirradiated).

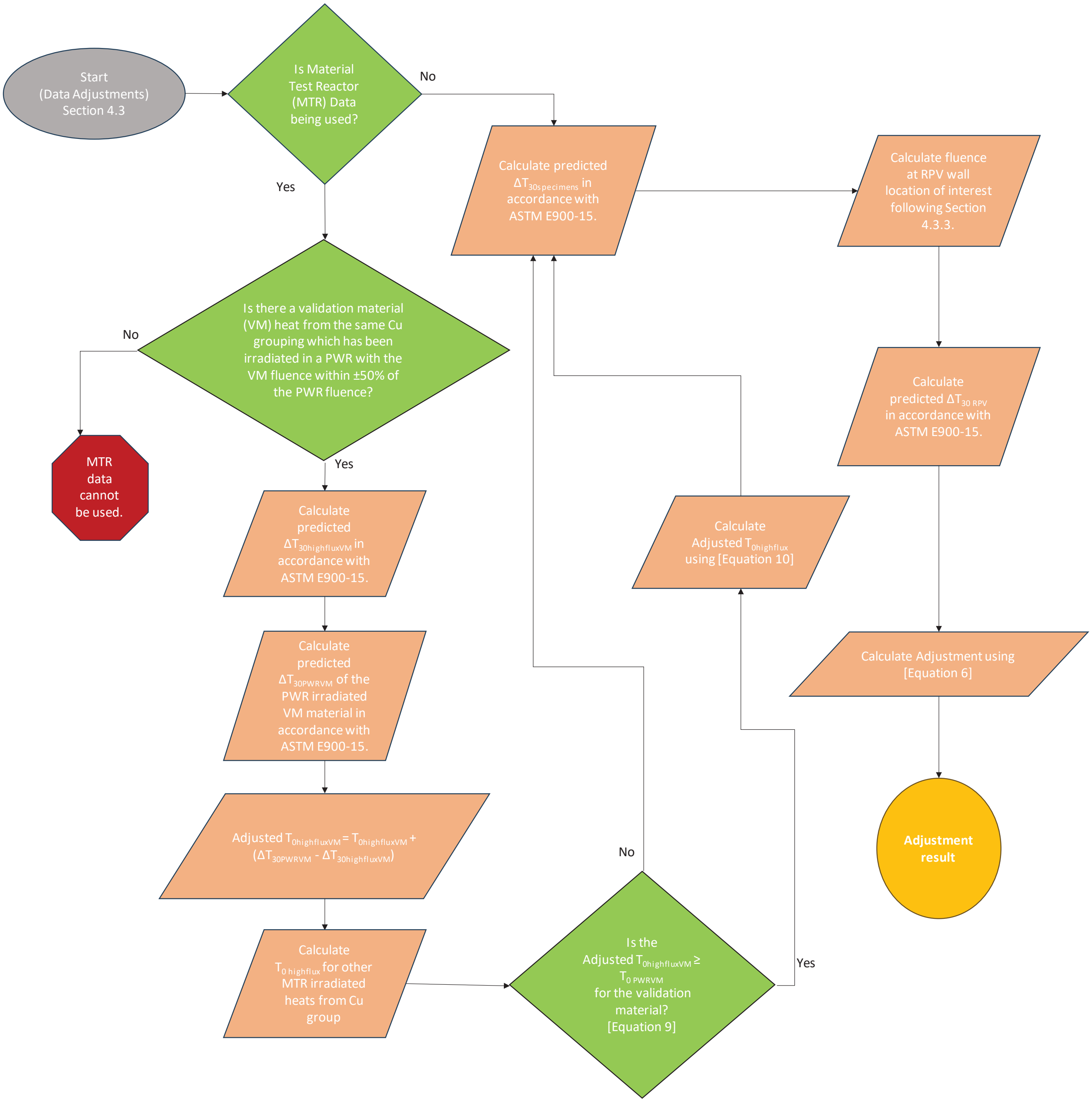
Response to RAI 24:

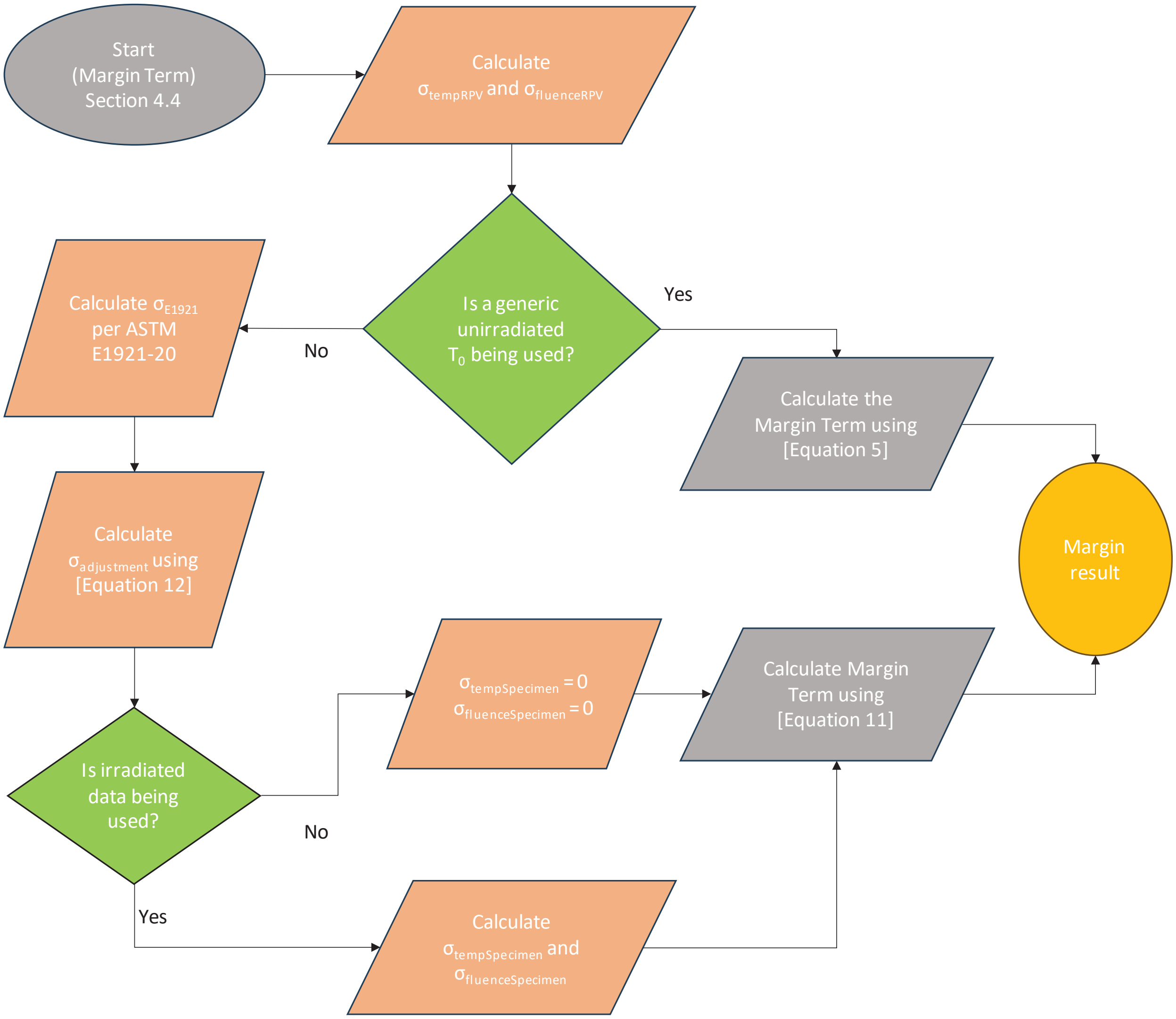
The following process will be added as new Section 4.6 in the TR.

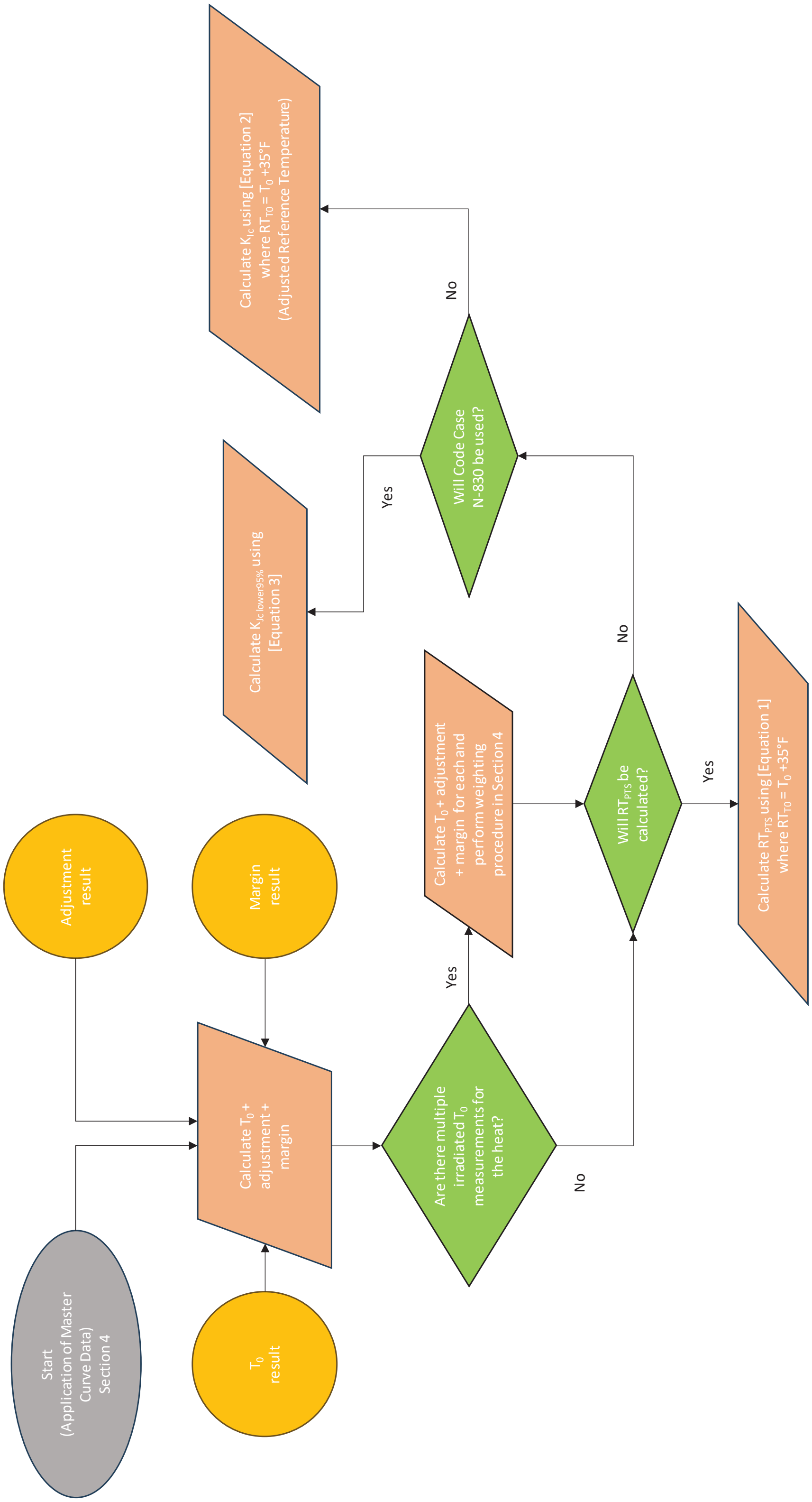
4.6 APPLICATION PROCESS

The following process flow chart can be used for guidance in determining the inputs to Equations 1 through 3. For details, see the referenced Equations and Sections.


Start (Specimen Test Data) Section 4.2
Is Heat Specific T_0 data available?
No
Yes
Does the test data meet the requirements for a valid T_0 according to ASTM E1921-20?
No
Yes
Is any of the test data from three-point bend Charpy-Size specimens?
Yes
Add a bias correction of 18°F (10°C) to each Charpy-Size 3PB specimen test temperature when calculating T_0.
No
Perform Homogeneity Screen per Section 10.6 of ASTM E1921-20.
Is the data screened as homogenous?
No
Yes
Perform ASTM E1921-20 Appendix X5.2 evaluation.
Does the data set contain ≥ 20 K_{Jc} values?
Yes
No
Alternatively ASTM E1921-20 Appendix X5.3 evaluation can be performed in lieu of simplified approach.
$T_0 = T_{0IN}$ per ASTM E1921-20 Appendix X5 evaluation.
T_0 result
Are 4 or more measurements of unirradiated valid T_0 available for similar materials such that a generic T_0 could be developed?
No
Yes
A generic T_0 value cannot be determined.
Calculate S (Standard Deviation of the mean T_0) and lookup k_1 (one-sided tolerance limit factor).
Is irradiated T_0 data available for a heat in the generic grouping?
No
Yes
Adjust the generic value using Section 4.3 method AND use [Equation 5] to determine the margin.
Does the adjusted generic value plus the [Equation 5] margin $K_{Jc\text{-}lower95\%}$ curve bound 95% of the irradiated K_{Jc1T} data?
No
Yes
T_0 = average unirradiated generic T_0.


Start (Data Adjustments) Section 4.3
Is Material Test Reactor (MTR) Data being used?
No
Yes
Is there a validation material (VM) heat from the same Cu grouping which has been irradiated in a PWR with the VM fluence within ±50% of the PWR fluence?
No
MTR data cannot be used.
Yes
Calculate predicted $\Delta T_{30highfluxVM}$ in accordance with ASTM E900-15.
Calculate predicted $\Delta T_{30PWRVM}$ of the PWR irradiated VM material in accordance with ASTM E900-15.
Adjusted $T_{0highfluxVM} = T_{0highfluxVM} + (\Delta T_{30PWRVM} - \Delta T_{30highfluxVM})$
Calculate $T_{0\ highflux}$ for other MTR irradiated heats from Cu group
Is the Adjusted $T_{0highfluxVM} \geq T_{0\ PWRVM}$ for the validation material? [Equation 9]
No
Yes
Calculate Adjusted $T_{0highflux}$ using [Equation 10]
Calculate predicted $\Delta T_{30specimens}$ in accordance with ASTM E900-15.
Calculate fluence at RPV wall location of interest following Section 4.3.3.
Calculate predicted $\Delta T_{30\ RPV}$ in accordance with ASTM E900-15.
Calculate Adjustment using [Equation 6]
Adjustment result


Start
(Margin Term)
Section 4.4
Calculate
$\sigma_{tempRPV}$ and $\sigma_{fluenceRPV}$
Is a generic unirradiated T_0 being used?
Yes
No
Calculate σ_{E1921} per ASTM E1921-20
Calculate the Margin Term using [Equation 5]
Margin result
Calculate $\sigma_{adjustment}$ using [Equation 12]
$\sigma_{tempSpecimen} = 0$
$\sigma_{fluenceSpecimen} = 0$
Calculate Margin Term using [Equation 11]
Is irradiated data being used?
No
Yes
Calculate $\sigma_{tempSpecimen}$ and $\sigma_{fluenceSpecimen}$


Start (Application of Master Curve Data) Section 4
T_0 result
Adjustment result
Margin result
Calculate T_0 + adjustment + margin
Are there multiple irradiated T_0 measurements for the heat?
Yes
No
Calculate T_0 + adjustment + margin for each and perform weighting procedure in Section 4
Will RT_{PTS} be calculated?
Yes
No
Calculate RT_{PTS} using [Equation 1] where $RT_{T0} = T_0$ +35°F
Will Code Case N-830 be used?
Yes
No
Calculate $K_{Ic\ lower95\%}$ using [Equation 3]
Calculate K_{Ic} using [Equation 2] where $RT_{T0} = T_0$ +35°F (Adjusted Reference Temperature)

RAI-25 – Example applications of the TR methodology in Appendix C of the TR

NRC Comment (a, b, c)

a. The NRC staff noted in the example shown in Table C-13 of the TR that the variation in margin using data from representative materials, different test specimen type, etc., is notable. Because of the notable variation in margin values, it is not clear whether there should be a minimum margin value to ensure conservatism in the TR methodology.

b. The NRC staff noted in Table C-9 that the σ_{test} values do not appear to be a function of "r" as required in ASTM E1921. Some description on how the σ_{test} values were assigned for these individual data sets, referencing appropriate sections in the TR as needed, should be provided.

c. Example C.2.2, in Table C-12 provides the ΔT_{30} value for the limiting material (i.e., CR-3 US to LS Circ. weld) but the final predicted (or measured) T_0 and/or RT_{T0} values for the limiting material should also be included in Table C-14 to demonstrate the appropriateness of the individual predictions.

NRC Request (a, b, c)

a. Provide other available data or studies to verify the conservatism in the margin using the methodology proposed in the TR.

Response to RAI 25.a:

Different data sets 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. Reference [1] (See response to RAI 4) demonstrates that $T_0 + 2\sigma_{E1921}$ bounds greater than 95% of the data from large data sets as discussed in the responses to RAI 21 above. In addition, a draft 2024 ASME PVP Conference paper, "An Examination of Margins Needed to Ensure Conservative Application of T_0 to RPV Fracture Toughness," is included as an Attachment to provide additional basis.

b. Provide a description of how each σ_{test} value in Table C-9 was determined for each individual data set. The section(s) in the TR providing the basis for each selection should be referenced, as appropriate.

Response to RAI 25.b:

σ_{E1921} is a function of r (the number of uncensored data per ASTM E1921-20) as shown in Table 2 in the revised TR (Table 3 in the original TR), which uses ASTM E1921-20 paragraph 10.9.

Table C-9 shows the revised TR Table C-9 to show how the various values 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 10.a above, 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 Attached markup of the TR.

Table C-9 Calculation of T_0 per ASTM E1921-20 for the Midland Unit 1 Beltline Weld Ford MTR Irradiation

Midland Unit 1 Beltline Weld	**#**	**N, r**	**Homo-geneous**	**T_0 (ºF)**	**σ_{E1921} (ºF)**	**T_{0scrn} or T_{0IN} (ºF)**	**T_0 Basis per 4.2**
All data	111	86, 63	No	60.9	8.3	**103.1**	T_{0IN}
Lab A mini-C(T)	13	13, 8	Yes	**94.9**	14.7	94.9	T_0
Lab B mini-C(T)	13	9, 5	-	Invalid	-	-	-
Lab C mini-C(T)	12	12, 8	No	58.5	14.0	**83.8**	T_{0IN}
Lab D mini-C(T)	13	13, 10	No	94.7	13.5	**127.6**[1]	T_{0IN}
>50ºC 1TC(T) [65]	27	13, 10	No	80.8	12.5	**96.1**	T_{0IN}
35ºC & 20ºC [65] 1TC(T) & 1/2TC(T)	12	12, 12	Yes	**87.9**	11.8	95.0	T_0
22ºC 1TC(T) & 3PB[2] Charpy [65]	13	10, 8	No	95.7	13.5	**122.5**	T_{0IN}
0ºC 3PB[2] Charpy [65]	8	8, 8	Yes	**123.9**	14.7	132.4	T_0

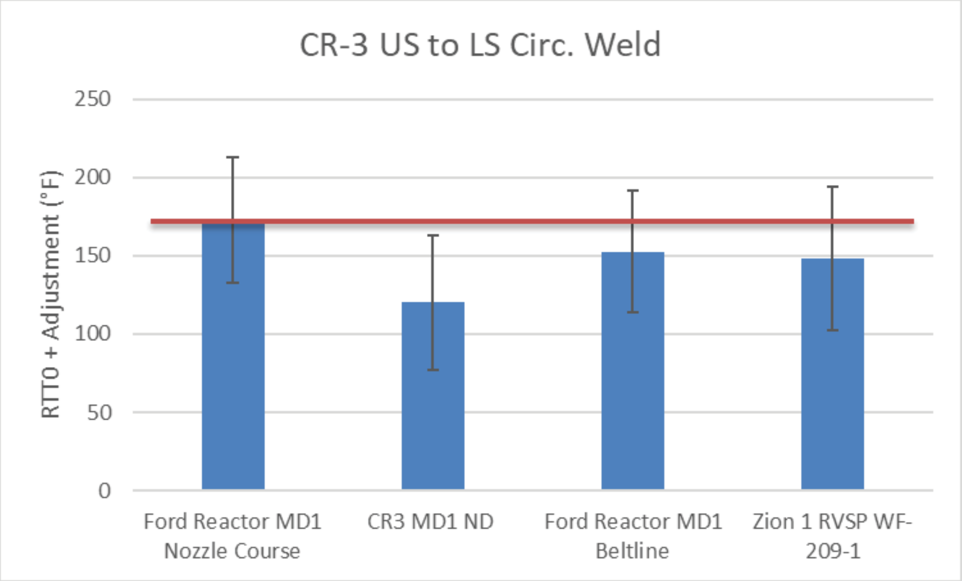
Notes:

1. Must allow use of data greater than T_{0IN} ± 50°C; see ASTM E1921-20
2. 18°F was added to the test temperature of each 3PB specimen when calculating T_0.

c. Provide the final predicted or measured T_0/RT_{T0} values, as appropriate, for the limiting material (i.e., CR-3 US to LS Circ. weld) in Table C-14 and then describe the accuracy and appropriateness of using either individual or average T_0/RT_{T0} values for the four individual data sets in Table C-14 for assessing the limiting material using the TR methodology.

Response to RAI 25.c:

The RT_{PTS} value of 253.8°F will be added to Table C-14 for the “CR3 US to LS Circ. Weld” from the license renewal application [14] for comparison to the bounding average RT_{T0} value. The RT_{PTS} value is comprised of the initial RT_{NDT} + ΔRT_{NDT} + Margin [-26 + 223.8 + 56.0 = 253.8°F]. The ΔRT_{NDT} uses the prediction method in 10CFR50.61, which is based on 177 ΔT_{30} measurements. ΔT_{30} is determined using ASTM E900-15, which was developed using over 1800 ΔT_{30} measurements and has been demonstrated to be more accurate than the 10 CFR 50.61 embrittlement prediction [15]. ASTM E900-15 determines an embrittlement of 186.7°F (TR Table C-12). Therefore, one of the significant differences is the very conservative prediction in 10CFR50.61 for this Linde 80 weld heat. Measurement of the transition temperature in the irradiated condition reduces the inaccuracy and uncertainty versus predicting embrittlement from the unirradiated condition. The margin term includes an initial RT_{NDT} uncertainty and the ΔT_{30} prediction uncertainty. In the CR3 example, T_0 was measured in the irradiated condition and adjusted to the RPV condition. The uncertainty with a relatively small adjustment is much smaller than predicting embrittlement from the unirradiated condition and is reflected in the smaller margin term. Both methods have similar measurement uncertainties included in the margin term. The CR3 initial RT_{NDT} was reset using direct fracture toughness. The TR methodology specifically accounts for the fluence and temperature uncertainties in the margin term, whereas the 10CFR50.61 methodology is dependent on these uncertainties being included in the ETC uncertainty (28ºF for welds), which is based on the 177 ΔT_{30} data scatter. The TR methodology also uses the ASTM E1921-20 method to check for inhomogeneous data behavior in the test data and the TR conservatively bounds the lower toughness data. The following figure plots the data from TR Table C-14 and compares each adjusted RTT_0 and the margin shown in TR Appendix C Table C-14 as indicated with the uncertainty bars. The red line represents the PWR irradiated weighted average RTT_0 + Adjustment + Margin (176.2ºF). The four adjusted measurements are in reasonable agreement when considering the margin.



[14] Crystal River Unit 3 License Renewal Application, December 2008. https://www.nrc.gov/reactors/operating/licensing/renewal/applications/crystal/crystal-lra.pdf

[15] NRC Public Meeting Presentation, “RG 1.99 Revision Evaluation Effort,” May 19, 2020, ML20139A030.