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:

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

> When MTR data is used, ~~E~~each Cu grouping ~~material irradiated in a high flux test reactor~~ must have at least one validation material heat ~~in the corresponding Cu grouping~~ which is also being or has been irradiated in a PWR (within ±50% of the MTR validation material fluence) to provide a quantitative evaluation of any flux effects.

**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:

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.

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

Section 4.2:

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 $T_0$ values with a 95% confidence level can be determined for forgings, plates, and welds based on a common manufacture, class, or flux types. The method described 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 from the mean $T_0$ (S), and the 95/95 one-sided tolerance limit factor ($k_1$).

The generic 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 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 10, Equation 5 below will be used in lieu of the Equation 10 margin term in Section 4.4:

$$\text{Margin} = \sqrt{(k_1 S)^2 + (2\sigma_{ETCRPV})^2 + (2\sigma_{tempRPV})^2 + (2\sigma_{fluenceRPV})^2} \quad \text{[Equation 5]}$$

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 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:

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:

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 $T_0$ corresponding to the least tough datapoint being on the $K_{Jc\text{-}lower95\%}$ curve plus $\sigma_{E1921}$ ($\sigma$ 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

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

the lower toughness material within the data set such that the datapoint may not be representative of the $K_{Jc\text{-}lower95\%}$ curve.

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

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.

<u>Response:</u>

The Staff's interpretation is correct.

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.

<u>Response:</u>

With 20 or more tests, the data set size is large enough to provide reasonable assurance that the $K_{Jc\text{-}lower95\%}$ curve positioned on the lowest toughness point would bound at least 95% of the data from a larger population. With a homogeneous data set of 20, approximately one result would be expected to fall below the $K_{Jc\text{-}lower95\%}$ curve. With an inhomogeneous data set of 20, a subset of the tests that are less tough would have a larger portion falling below the $K_{Jc\text{-}lower95\%}$ curve with the use of $T_0$. If there were more test data with a similar nonhomogeneous distribution, some of the data would be from the lower toughness material with a portion of it falling below the $K_{Jc\text{-}lower95\%}$ curve. However, as a whole data set, only a small percentage would be expected to fall below this curve, thus achieving the ~95% confidence level. In addition, the margin term is 2 times the square root of the sum of the squares of the uncertainty terms defined in Section 4.4 of the TR. This ensures a conservative bound of the measured data (and the majority of other potential measurements) since the $T_0$ determined using the least tough datapoint uses only 1 times $\sigma_{E1921}$.

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.

<u>Response:</u>

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 $\sigma_{Tm}$ = 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. A $K_{Jc\text{-}lower95\%}$ curve positioned on the lowest toughness point from any contiguous subset of 20 or more tests from this highly inhomogeneous data set of 111 tests would be sufficiently conservative. Other large data sets assessed in Reference [1] found to be inhomogeneous produced reasonable bimodal or multimodal results. Section 4.2 and ASTM E1921-20 Appendix X5.2 provide a bounding curve as an alternative to the potentially unrealistically conservative ASTM E1921-20 paragraphs X5.3.2 or X5.3.3 methods as shown by the Midland Beltline Irradiated Weld example shown in TR Figure C-2 and Reference [1].

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

The following will be deleted 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 $\sigma_{E1921}$ (σ per ASTM E1921-20 paragraph 10.9).~~

**RAI 05 – Section 4.3 of the TR – Data Adjustments**

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

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 $\Delta T_{30}$ of the irradiated tested material” term within the parentheses in Equation 4 in Section 4.3 of the TR is not called “**measured** $\Delta T_{30}$ of the irradiated tested material” instead (emphasis added) because $\Delta T_{30}$ values from tested materials should have measured $\Delta T_{30}$ values by definition, not predicted $\Delta T_{30}$ values.

c. With respect to the Part b question above, if the intent of Equation 4 is to calculate the $\Delta T_{30}$ value of the irradiated test material predicted by E900-15, the NRC staff is not clear why the measured $\Delta T_{30}$ 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** $\Delta T_{30}$ above…” (emphasis added).

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

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.

Response:

The TR will be revised to eliminate the assertion that any systemic errors in the ETC model (model uncertainty) would be considered negligible. The below changes will be made. These include the term name $\sigma_{additional}$ being changed to $\sigma_{adjustment}$ for clarity throughout the revised TR and the $\sigma_{additional}$ formula (Eq. 10) being updated.

The following will be deleted 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.~~

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

~~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 sentence in Section 4.4.2 will be deleted:

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

The Equation 11 (formerly Equation 10) in Section 4.4.2 will be updated to that shown below:

$$\sigma_{\cancel{additional}adjustment} = \left|\sigma_{ETCRPV} - \cancel{\sigma}SD_{ETCRPV\,adj\cancel{specimen}}\right| * \ (1.0 \text{ for welds or } 1.1 \text{ for base metals})$$

[Equation 11]

b. Clarify why the "predicted $\Delta T_{30}$ of the irradiated tested material" term within the parentheses in Equation 4 in Section 4.3 of the TR is called "predicted $\Delta T_{30}$ of the irradiated tested material" instead of "**measured** $\Delta T_{30}$ of the irradiated tested material."

Response:

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** $\Delta T_{30}$ 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 $\Delta T_{30}$ value of the irradiated test material is not used in Equation 4.

Response:

If there were a bias in the measured $\Delta T_{30}$ value relative to the ETC prediction, an adjustment using the measured $\Delta T_{30}$ value would include this bias. Since $\Delta T_0$ and $\Delta T_{30}$ are correlated, the measured $T_0$ that is being adjusted includes the bias, therefore including measured $T_0$ and measured $\Delta T_{30}$ 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** $\Delta T_{30}$ above…"

Response:

The cited sentence should begin with "The predicted $\Delta T_{30}$ 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 $\Delta T_{30}$. 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:

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. $T_{cold}$ 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:

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~~ are to 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 ($predicted\ RPV_{1TM}\ \Delta T_{30}$), 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 $\Delta T_{30}$ predictions. Then the absolute value of the differences between the 6 $\Delta T_{30}$ and the $\Delta T_{30}$ based on the RPV material ($predicted\ RPV\ \Delta T_{30}$) are summed and divided by the $\Delta T_{30}$ for the RPV material. This provides a metric for the closeness of the test material to the RPV which is used for the weighting factor. This closeness metric is divided by the ASTM E900-15 prediction of the RPV and subtracted from 1 to form 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 $T_0$ provides the measured effect of embrittlement without the need for the full prediction uncertainty. If only unirradiated $T_0$ is available, the approach discussed herein can also be used.~~

$$w_i = \max\left(0, 1 - \sum^{Cu,Ni,Mn,P,fluence,temp} \frac{|predicted\ RPV\ \Delta T_{30} - predicted_{1TM}\ \Delta T_{30}|}{predicted\ RPV\ \Delta T_{30}}\right)$$

[Equation 4a]

$$Weighted\ average\ (T_0 + adjustment + margin) = \frac{\sum_1^n (T_{0,i} + adjustment_i + margin_i)\, w_i}{\sum_1^n w_i}$$

[Equation 4b]

Where:

$w_i$ = the weighting factor of each measured *$T_0$ (or $RT_{T0}$) + adjustment + margin* value
n = 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:

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:

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 $\Delta T_{30}$ 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:

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 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:

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 nearly 0.

**RAI 08 – Section 4.0 of TR – 10 CFR 50.55a Condition on Use of Irradiated $T_0$**

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:

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 $T_0$ 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:

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

> *adjustment* = (predicted $\Delta T_{30}$ of the RPV material at the fluence of interest – predicted $\Delta T_{30}$ of the ~~irradiated~~ tested material) * ~~average shift difference between $\Delta T_0$ and $\Delta T_{30}$~~(1.0 for welds or 1.1 for base metals)

If only unirradiated $T_0$ data is available, the "predicted $\Delta T_{30}$ of the tested material" will = 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.

The margin term is calculated as described in Section 4.4 of the TR with $\sigma_{test}$ calculated as defined in Section 4.4.1. The $\sigma_{tempspecimen}$ and $\sigma_{fluencespecimen}$ would be equal to 0 for an unirradiated $T_0$ in Equation 10 (formerly Equation 9). In Equation 11 (formerly Equation 10), the $\sigma_{additional}$ (changed to $\sigma_{adjustment}$ in the TR revision) would be equal to the full $\sigma_{ETCRPV}$ (since $\sigma_{ETCspecimen}$ = 0) which is the ASTM E900-15 $SD_{ETC}$. Therefore, an unirradiated $T_0$ would have the full ASTM E900-15 $\Delta T_{30}$ prediction adjustment to the RPV condition and the associated $SD_{ETC}$ is included in the margin term.

**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:

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 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 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:

Appendix A provides a significant database comparing the $T_0$ developed 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 expectations 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:

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 "Adjusted$T_{0highfluxVM}$" 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 "Adjusted$T_{0highfluxVM}$" 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 "Adjusted$T_{0highfluxVM}$ – $T_{0PWRVM}$" or the absolute value of "Adjusted$T_{0highfluxVM}$ – $T_{0PWRVM}$" instead of "$T_{0PWRVM}$ – Adjusted$T_{0highfluxVM}$".

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 $\Delta T_0$ data or if $T_{30}$ and $\Delta T_{30}$ (along with the $\Delta T_0$/ $\Delta T_{30}$ correction ratio) data can be used in this assessment.

Response:

Revised Equation 8 (formerly Equation 7) in Section 4.3.4.2 only uses $T_0$ and the adjusted $T_0$. Equation 8 (formerly Equation 7) will be revised as follows:

$$Adjusted\ T_{0high\ flux\ VM} \geq T_{0PWR\ VM} \cancel{- 2 \cdot \sqrt{\sigma_{T0hig\ \ fluxVM}{}^2 + \sigma_{T0PWR}{}^2}} \qquad \text{[Equation 8~~7~~]}$$

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

Equation 8 (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 according to Equation 9 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:

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 differing weight on n depending on toughness, which is not addressed in the basic Z calculation described in NUREG-1475, Rev. 1. Therefore, it is not a like-for-like comparison. The revision to Equation 8 (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:

Only $T_{0highfluxVM}$ is adjusted to the PWR VM conditions. This is only a comparison of the validation material between the MTR irradiation and the PWR irradiation to ensure sufficient conservatism. Therefore, an adjustment is only made to one measurement to the condition of the other material condition for the comparison in Equation 8 (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:

For multiple validation data sets within the same MTR irradiation and Cu material grouping, all are relevant and should be considered as described in the TR. The purpose of the validation is to ensure the mean behavior of the represented Cu grouping is representative of the PWR irradiation. There is normal scatter in the measured data and the data collectively should be considered to ensure representativeness. $T_{0IN}$ is also used in the comparison to ensure the limiting toughness for each dataset is used for the comparison, since $T_{0IN}$ will be used in any evaluation. In the revised example shown in Appendix C.1 for two of the 3 PWR capsules, the MTR capsule is nonconservative compared to the PWR capsules. The BR2 data compared to the Capsule A-35 data (Table C-2) is 2.1% nonconservative; the BR2 data compared to the Kewaunee Capsule T data (Table C-3) is 11% nonconservative; the BR2 data compared to the Kewaunee Capsule S data (Table C-3) is -8.7% which is conservative. When all three are considered together in an average manner, the adjustment increase is 1.5%.

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 Section 4.3.4.2 3rd paragraph TR text will be revised as follows:

> If multiple data sets are available from the same MTR irradiation or the same PWR irradiation, the Equation 8 inequality should be determined for each data set with the same heat. Then each of the inequalities should be added together (i.e., the left sides of the inequalities should be summed, and the right sides of the inequalities should be summed) to determine if the inequality is satisfied with consideration of all the data.

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:

For data sets which have a validation material irradiated in a 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 9 (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 described 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:

The next to the last paragraph of Section 4.3.4.2 will be revised as follows to be more specific regarding how multiple data sets are treated in Equation 9 (formerly Equation 8):

> When multiple data sets are available for validation from the same MTR irradiation, the Equation 9 variables contained in brackets will ~~should~~ be the average of the values determined with each heat data set if the Equation 8 inequality is not met. Likewise, if the Equation 8 inequality is not met and multiple data sets are available from separate independent MTR irradiations, then the MTR irradiation which resulted in the most representative result will be used.

The above validation process ensures that MTR-irradiated RPV steel is representative of, or conservative, relative to irradiation in the RPV of interest. For example, if validation heat A and B from the same Cu grouping showed the adjusted MTR $T_0$ (summation of the left side of Equation 8) to be lower than the respective PWR irradiated $T_0$ according to Equation 8 (formerly Equation 7), then a $T_0$ increase via Equation 9 is required for all heats from the same Cu grouping. The increase (term within the Equation 9 brackets) is the average increase for both heat A and B calculated individually and is applied to all the heats in the Cu group being validated. The average is used to provide a reasonable increase considering all data thus, since Equation 8 must be satisfied, ensuring conservative results.

g. Clarify the baseline or reference condition for the "$\Delta T_{\text{high flux VM}}$" and "$\Delta T_{\text{high flux}}$" 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 $\Delta T_0$ (or $\Delta T_{30}$) 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:

Please see response to RAI 12 below which revises Equation 8 (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 $\Delta T_{\textit{high flux VM}}$:

$\Delta T_{\textit{high flux VM}}$ = 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 $\Delta T_{\textit{high flux VM}}$ should be:

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

Response:

The PWROG agrees with the Staff comment. Section 4.3.4.2 of the TR will be revised as follows, which contains other clarifications:

Improved Equation 9 (formerly Equation 8):

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

$\Delta T_{30\ \textit{high flux VM}}$ = predicted $\Delta T_{30}$ ~~shift~~ of the ~~PWR~~ high flux validation material using the ASTM E900-15 ETC

$\Delta T_{30\ RPV\ \cancel{\textit{high flux}}}$ = predicted $\Delta T_{30}$ of the RPV material at the fluence of interest ~~shift of the high flux material~~ using the ASTM E900-15 ETC

$T_{0\ \textit{high flux}}$ = 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 $\Delta T_{30}$ and $\Delta T_0$**

NRC Comment

The NRC staff noted that the discussion of the correlation between $\Delta T_{30}$ and $\Delta T_0$ (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 $\Delta T_0$, the NRC staff noted that the spread in observed $\Delta T_{30}$ values can easily be greater than 100°F. Thus, there are other factors contributing to this scatter in the $\Delta T_{30}$ and $\Delta T_0$ relationship than just measurement uncertainty associated with individual value. Also, the correlation between $\Delta T_{30}$ and $\Delta T_0$ 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 $\Delta T_{30}$ and $\Delta T_0$ 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:

The uncertainty (standard deviation) of a $T_0$ measurement tested in accordance with ASTM E1921 can be as high as ~13°F when testing the minimum number (6 or 7) of specimens. The uncertainty of a typical $T_{30}$ measurement can be as high as ~6°F to 18°F [4, 5, 6]. Each $\Delta T_{30}$ and $\Delta T_0$ 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 added Figure 7 in the TR. 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:

$$\sqrt{T_{0init}^2 + T_{0ir}^2 + T_{30init}^2 + T_{30irr}^2} \approx \sqrt{13^2 + 13^2 + 6^2 + 18^2} = 27\text{°F}$$


[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 $\Delta T_{30}$ and $\Delta T_0$. Since the ETC model used is based on $\Delta T_{30}$, this difference ~~should be~~ is taken into account. There is no industry accepted ETC model based on $\Delta T_0$. Figure 6 and Figure 7 show a number of shift measurements comparing ~~the two shifts [43]~~$\Delta T_0$ and $\Delta T_{30}$ 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 $\Delta T_0$ to $\Delta T_{30}$ ~~shift difference~~ for welds is 0.99 and ~~1.1~~ 1.09 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 Equation 6 and Equation 11. The addition of the 0.01 conservatism is more conservative than adding the slope standard error of ~0.03 into the margin term of Equation 10 where it would be combined with all the other uncertainties diminishing 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 18°C (32°F). Each $\Delta T_0$ and $\Delta T_{30}$ measurement is comprised of an uncertainty of both the unirradiated and irradiated measurements with the typical combined measurement standard deviation using the square root of the sum of the squares (SRSS) shown as error bars in Figure 6 and Figure 7 of 10°C (18°F) for both $\Delta T_0$ to $\Delta T_{30}$. If the independent shift measurement uncertainties are combined using the SRSS, 62% of the weld and 68% of the base metal measurement uncertainty error bars overlap the best-fit slope. Considering this measurement uncertainty, the scatter of the data observed in Figure 6 and Figure 7 is consistent with the expected 68%. Since the $T_0$ measurement uncertainty is included in the Equation 10 margin term, the measurement uncertainty shown in Figure 6 and Figure 7 should not be 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 adding no uncertainty when converting from $\Delta T_{30}$ to $\Delta T_0$ (or vice versa) where the author concludes that when measured $\Delta T_0$ 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 $\Delta T_{30}$ and $\Delta T_0$ 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* | 66 | 14 | 1.09 | 0.03 | 19 | 0.96 | 1.1 |
| *Forging* | 29 | 14, 43, 44, 45, 46 | 1.08 | 0.06 | 16 | 0.93 | 1.1 |
| *Plate & Forging Combined* | 95 | 14, 43, 44, 45, 46 | 1.09 | 0.03 | 18 | 0.95 | 1.1 |

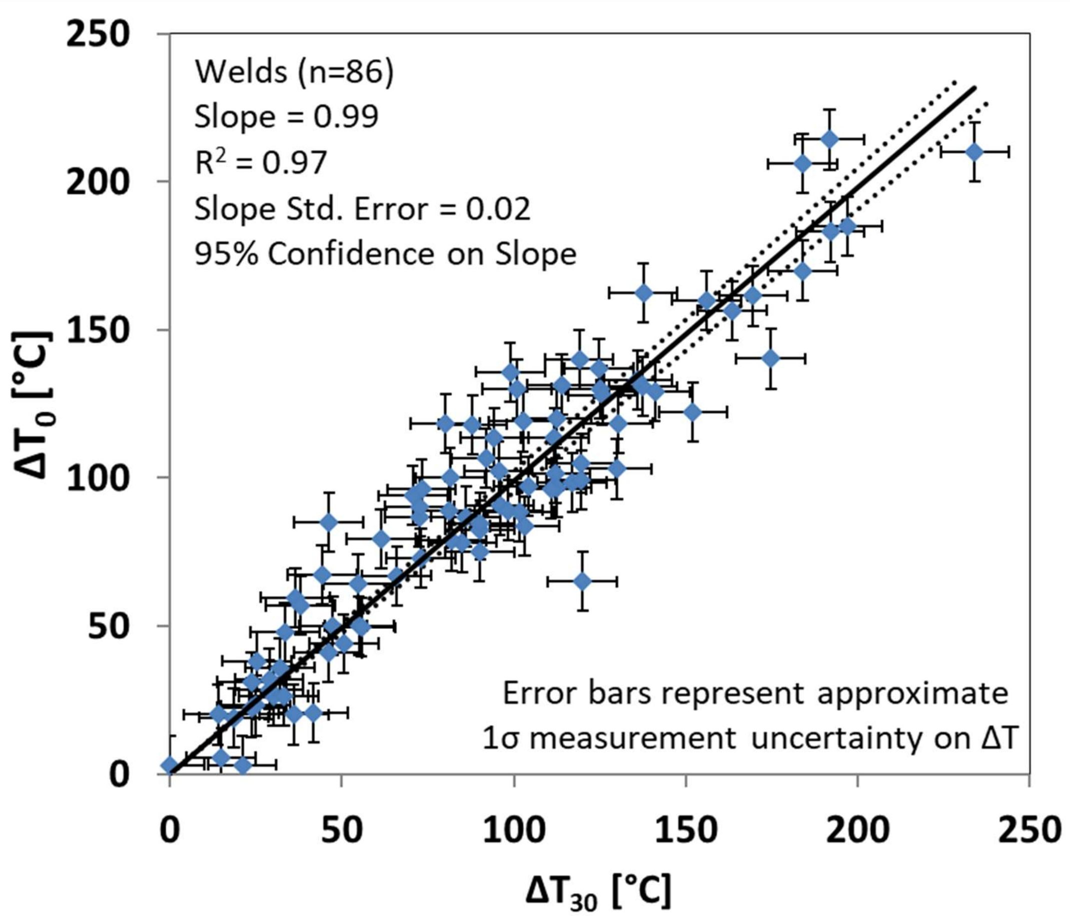



**Figure 1: Relationship of Embrittlement Shift between $\Delta T_{30}$ and $\Delta T_0$ for Welds ~~(Reproduction of Figure 32 of [43])~~**

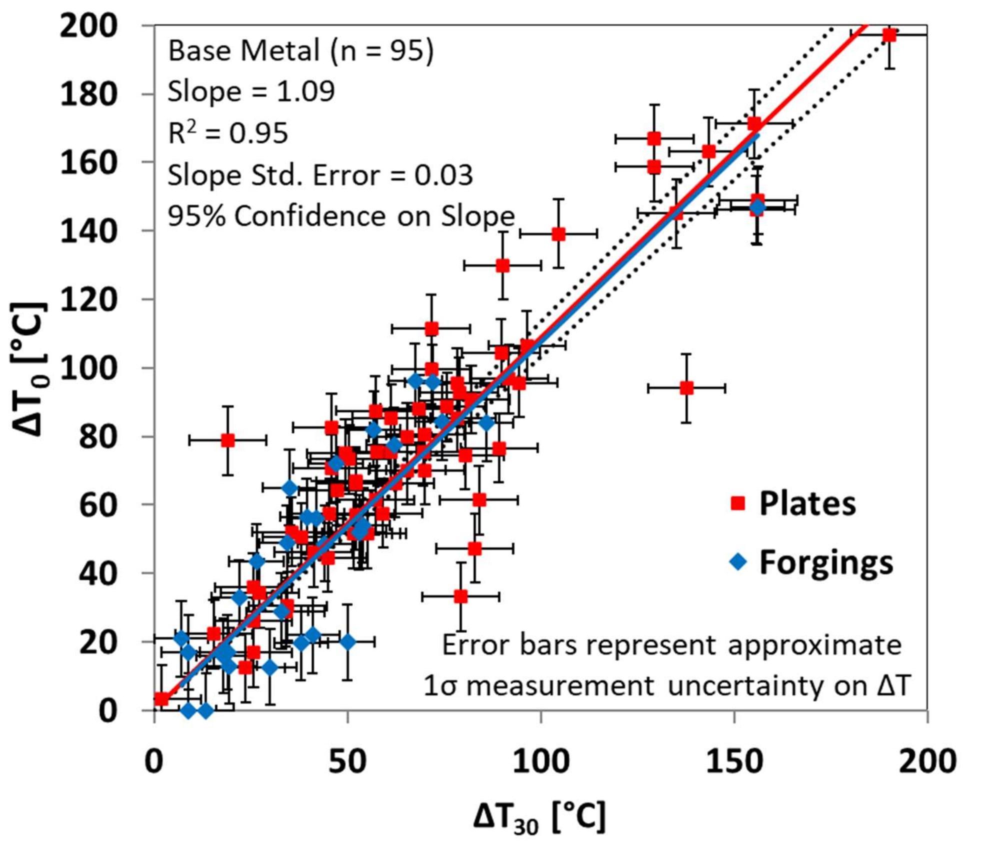
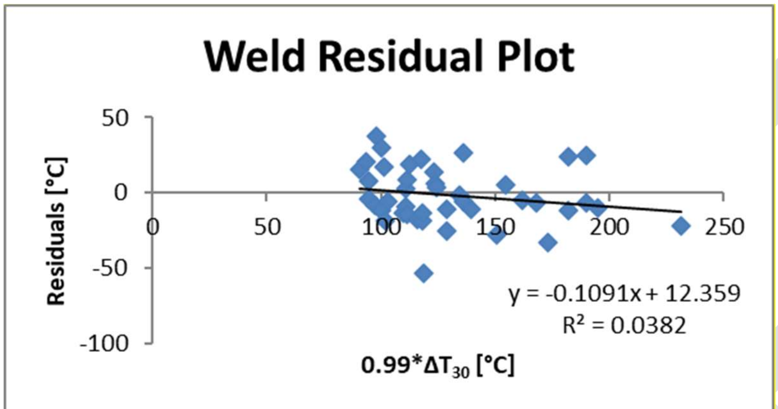


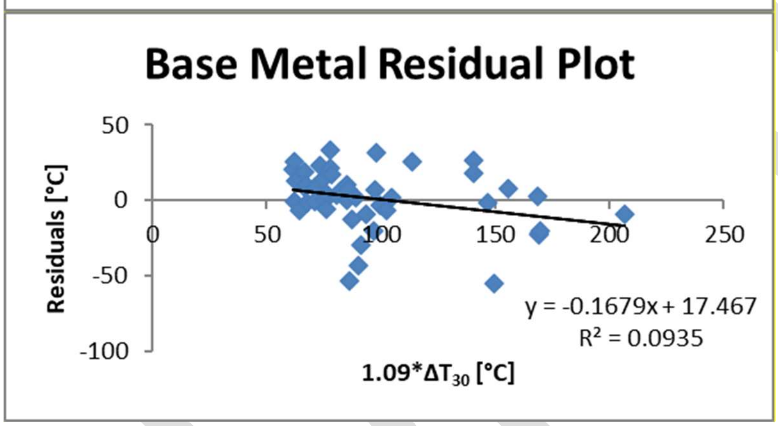

Figure 2: Relationship of Embrittlement Shift between $\Delta T_{30}$ and $\Delta T_0$ for Base Metals

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:

The TR allows for adjustment of both unirradiated and irradiated $T_0$ measurements. Unirradiated measurements use the same reference state and so therefore there is no difference. For the adjustment of irradiated $T_0$ values, in most cases the adjustments are small and any deviation in 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 being unirradiated vs. irradiated, as discussed below. There is no change in 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 measures are different, but the change (shift) due to neutron irradiation is caused by the same mechanisms (initiation of the cleavage event), so the underlying physics are 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 $\Delta T_0$ and $\Delta T_{30}$ 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 similar slope as shown in revised Figure 6 and added Figure 7 [7] in the TR. The preponderance of data shows a linear relationship between $\Delta T_0$ and $\Delta T_{30}$ with no significant deviation in trend at higher shifts (which tends to represent high fluence). A best-fit line is presented below for the error in the linear fits (residual) of $\Delta T_0$ and $\Delta T_{30}$ 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.




Therefore, using the overall linear slope to adjust 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.

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

Response:

Please see response to RAI 13 b. above.

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

Response:

Section 5.3 of MRP-462 [8] 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 revised response RAI 13a and revised Section 4.3.5 of the TR.

Please see the revised response RAI 13a and revised 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 $\Delta T_{30}$ to $\Delta T_0$ 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 $\Delta T_0$ / $\Delta T_{30}$ slope for the welds is 0.95 to 1.03 and for base metal is 1.04 to 1.16.

[8] “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 $\sigma_{tempspecimen}$ and $\sigma_{tempRPV}$**

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 ***** ($\Delta T_0$ / $\Delta T_{30}$ 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:

There are multiple calibrated resistance temperature detectors in the plant coolant loop which are used for plant control. The total PWR instrument 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 temperature is measured often and averaged over many cycles, the standard error (standard error = standard deviation/√N) is small. Considering this, the uncertainty of the average (standard error) irradiation temperature is no greater 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 $\sigma_{tempspecimen}$, $\sigma_{tempRPV}$, $\sigma_{fluencespecimen}$, and $\sigma_{fluenceRPV}$**

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 $\Delta T_0$ / $\Delta$ $T_{30}$ slope to calculate the corresponding uncertainty value. Provide an example.

Response:

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 the 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:

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 as modified by the TR. 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:

The ability to set the adjustment uncertainty term to 0 will be deleted 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. The Margin Term still 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:

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: $fluence_{1/4T} = fluence_{surface} * dpa_{1/4T} / dpa_{surface}$. This is exactly the same as the guidance provided in Section 1.1 of Regulatory Guide 1.99, Revision 2.

**RAI 19 – Section 4.4.1 of the TR – Determination of $\sigma_{test}$**

NRC Comment

In Section 4.4.1 of the TR, the PWROG discussed the determination of the uncertainty due to specimen testing, $\sigma_{test}$. 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 $\sigma_{test}$ 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:

Reduction of $\sigma_{test}$ relative to $\sigma_{E1921}$ is only applicable to data sets that are screened as inhomogeneous. Please see response to RAI 19.b. below.

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

Response:

For data sets screened as inhomogeneous, the $T_{0max}$ and $T_{0IN}$ values are biased conservatively using the least tough data from the data set, therefore $\sigma_{test}$ can be reduced while still conservatively bounding the data set. This approach was demonstrated in Reference [1] (See RAI 4) for ten large data sets.

The method described in Section 4.4.1 of the TR was applied to many subsets (most of them with N < 20), which would be representative of the typical number of specimens tested, as demonstrated for ten large RPV weld and base metal measured data sets in Reference [1]. Some data sets were homogeneous and some were not. Using the least conservative subsets with the TR methodology, the modified margin term of Section 4.4.1 mitigates some of the over conservatism that would occur if the full $2\sigma_{E1921}$ margin adjustment were added to $T_{0IN}$ or $T_{0max}$. The Section 4.4.1 $\sigma_{test}$ still provided adequately conservative results (average of ~95% of the data bounded for the least conservative subset), as shown in Table 4 of Reference [1]. If all subsets were considered from the ten large data sets, the data bounded would be considerably more than 95%. Adequately conservative results were obtained in all cases, even when the subset $T_0$ was significantly lower than the full data set $T_0$. Reference [1] shows the robustness of the Section 4.4.1 methodology even when the test specimens happen to be from the lowest toughness portion of a large data population.

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

Response:

The basis is demonstrated in the ASTM *Journal of Testing and Evaluation* [1]. Please also see the response to RAI 19.b above.

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

Response:

The calculation and use of $T_{0max}$ for 10 < N < 20 was successfully applied to many subsets with 10 < N <20 and bounds > 95% of the data on average from the larger represented data sets [1]. Therefore, the calculation and use of $T_{0max}$ for 10 < N < 20 is conservative and applicable to the methodology in this TR.

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:

The use of $\sigma_{test} \leq \sigma_{E1921}$ is applied to inhomogeneous data sets with N < 20. For larger inhomogeneous data sets (N ≥ 20) $\sigma_{test} = \sigma_{E1921}$. There should be sufficient material sampled from the low toughness portion to provide a $T_{0IN}$ representative of the low toughness data, but there will likely not be sufficient low toughness data to get an accurate measure of uncertainty. $\sigma_{E1921}$ is based on the behavior of ferritic steel generally and applicable to the low toughness material; therefore, it is appropriate for the potentially small sample size of low toughness material.

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.~~ 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 $\sigma_{test}$, 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 $\sigma_{additional}$**

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

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 $\sigma_{ETCRPV}$ and $\sigma_{ETCspecimen}$ are the same, then $\sigma_{additional}$ is zero. The NRC staff is not clear why the TR does not evaluate both $\sigma_{ETCRPV}$ 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:</u>

The allowance to set the adjustment uncertainty term to 0 will be deleted from the TR. Please see the response to RAI 5.a. above. $SD_{ETC}$ is a function of the predicted shift (TTS also *Predicted RPV* $\Delta T_{30}$) per Equation 14 (formerly Equation 5) taken from E900-15:

$$\boldsymbol{SD_{ETC} = C \bullet TTS^{D}}$$

As the difference between $\sigma_{ETCRPV}$ and $\sigma_{ETCSpecimens}$ 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, and used in the discussion below). With an unirradiated $T_0$, $\sigma_{ETCSpecimen}$ is 0, since TTS = 0, thus making $\sigma_{adjustment} = \sigma_{ETCRPV}$ which is the full value of $SD_{ETC}$ consistent with the basis of E900-15.

Equations 10 (formerly Equation 9) (TR Section 4.4) and 11 (formerly Equation 10) (TR Section 4.4.2) will be revised as follows:

$$Margin = 2\sqrt{\sigma^2_{test} + \sigma^2_{\cancel{additional}adjustment} + \sigma^2_{tempspecimen} + \sigma^2_{tempRPV} + \sigma^2_{fluencespecimen} + \sigma^2_{fluenceRPV}}$$

[Equation 10]

…

$$\sigma_{\cancel{additional}adjustment} = \left|\sigma_{ETCRPV} - SD_{ETCRPVadj}\right| * \text{ (1.0 for welds or 1.1 for base metals)}$$

[Equation 11]

Where:

$\sigma_{\cancel{additional}adjustment}$ = the additional margin to be included to account for the adjustment uncertainty

$\sigma_{ETCRPV}$ = the standard deviation of the ETC prediction ($SD_{ETC}$) for the RPV material of interest as determined by Equation ~~5~~13

In a similar manner as described in Section 4.0, each of the ASTM E900-15 inputs are individually changed to be equal to that of the test material while all other inputs are kept at the RPV condition ($predicted\ RPV_{1TM}\ \Delta T_{30}$). There are 6 independent inputs (Cu, Ni, Mn, P, fluence, and temperature), therefore there are 6 $\Delta T_{30}$ predictions. The absolute value of the differences between this 6 predicted $\Delta T_{30}$ and the predicted $\Delta T_{30}$ based on the RPV material ($predicted\ RPV\ \Delta T_{30}$) are summed producing *adjTTS*$_{sum}$ in Equation 12.

$$adjTTS_{sum} = \left(\sum^{Cu,Ni,Mn,P,fluence,temp} \left|predicted\ RPV\ \Delta T_{30} - predicted\ RPV_{1T}\ \Delta T_{30}\right|\right)$$

[Equation 12]

Then $SD_{ETCRPVadj}$ is calculated for the predicted RPV $\Delta T_{30}$ - $adjTTS_{sum}$ in Equation 13:

$$\boldsymbol{SD_{ETCRPVadj} = C \bullet (max(0, predicted\ RPV\ \Delta T_{30} - adjTTSsum))^{D}}$$

[Equation 13]

$SD_{ETC}$ = the uncertainty (standard deviation) determined by the applicable ETC. The equation for the E900-15 $SD_{ETC}$ is shown in Equation 14.

$$\boldsymbol{SD_{ETC} = C \bullet (Predicted\ RPV\ \Delta T30)^{D}}$$

[Equation 14]

Where,

*Predicted RPV* $\Delta T_{30}$ = the E900-15 predicted shift in the 30 ft-lb transition temperature (°C)

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:

The TR 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., Cu variation in an irradiated weld, if not saturated, could affect the toughness distribution), the inhomogeneity screen in Section 4.2 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 RAI 4).

To clarify, 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 $\sigma_{ETCPRV}$ and $\sigma_{ETCspecimen}$ are not evaluated, and then $\sigma_{additional}$ set to the maximum uncertainty value.

Response:

The response to RAI 20.a includes a revision to Section 4.4.2 of the TR. The revised TR methodology will consider the effect of all differing inputs to the ASTM E900-15 $\Delta T_{30}$ independently and the absolute values will be summed to capture the uncertainty of all adjustments. Therefore, there cannot be any offsetting adjustments which would reduce the adjustment uncertainty.

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

Response:

The $\sigma_{adjustment}$ term in Equation 10 (formerly Equation 9) should be proportional to the amount of adjustment and should only consider the portion of $SD_{ETC}$ which is associated with the uncertainty of the ETC slope. Equation 11 (formerly Equation 10) in the TR is proportional to the amount of the adjustment and is a portion of $SD_{ETC}$. The other parts of $SD_{ETC}$ are addressed explicitly in Equation 10 (formerly Equation 9) of the TR as described in the response to RAI 20.c. above.

**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:

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 RAI 4) evaluated worst case small sample subsets from large specimen populations removed from RPV forgings, plates and welds, in which large portions of those products were tested. 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, the 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 [9] 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 to 0.045 mm. For a mini-CT specimen with a 4mm thickness (crack front length), approximately 100 grains or more are sampled. With ~10 specimens tested according to 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 4mm test specimen results with larger test specimens, as shown in TR Appendix A, demonstrates that sufficient microscope initiators are being sampled by the crack front.

For macroscopically inhomogeneous materials, the ASTM E1921 inhomogeneous screening procedure identifies these materials 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 qualification specimens and $T_0$ test specimens are removed at the 1/4 thickness from the surface. Therefore, the $T_0$ developed according to this TR are from the 1/4 thickness. The average improvement in surface toughness for RPV forgings is 36.5°F [9] 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 described by Saillet [10], 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.

[9] "PWR Pressure Vessel Nozzle Appendix G Evaluation," PWROG-15109-NP-A, January 2020. https://www.nrc.gov/docs/ML2002/ML20024E573.pdf

[10] 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.

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:

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 would be 0 if there were no adjustment, and the full $SD_{ETC}$ term if the tested material were unirradiated in accordance with Equation 11 (formerly Equation 10) in the TR. In addition, since the adjustment is limited to any chemistry difference within the heat that is tested, the chemistry adjustments are limited. Also, as described in RAI response 20.b, the inhomogeneity screen identifies atypical toughness variation with the TR providing a method 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 $\Delta T_{41J}$ and $\Delta T_0$ 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 $\Delta T_0$ shift is higher than the $\Delta T_{41J}$ 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 $\Delta T_{41J}$ to $\Delta T_0$ correlation implied in Figures B-1 and B-2 of the TR and the $\Delta T_{30}$ to $\Delta T_0$ correlation in Figure 6 of the TR.

Response:

The $\Delta T_{41J}$ and $\Delta T_0$ 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 added Figure 7 of the TR. Section 5.3 in MRP-462 [8] (See RAI 13.a through 13.d) and the revised TR Section 4.3.5 contains a more detailed analysis of correlation of $\Delta T_{30}$ to $\Delta T_0$ with larger data populations than what is shown in Figures B-1 and B-2. The responses to RAI 13.a through 13.d above provides a more detailed discussion of the correlation of $\Delta T_{30}$ to $\Delta T_0$.

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:

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 PWR reactor irradiated validation material used for comparison to the MTR irradiated material must be irradiated and should have a similar fluence, although the TR does not quantify the maximum allowed adjustment of the *Adjusted* $T_{0high\ flux\ VM}$ term in Equation 8 (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 1:

> When MTR data is used, ~~E~~each Cu grouping ~~material irradiated in a high flux test reactor~~ must have at least one validation material heat ~~in the corresponding Cu grouping~~ which is also being or has been irradiated in a PWR (within ±50% of the MTR validation material fluence) to provide a quantitative evaluation of any flux effects.

**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:

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

> Where *adjustment* and *margin* are defined in Sections 4.3 and 4.4, respectively. The TR does not address Code Case N-830-1 because the objective of the methodology in the TR is to prevent non-ductile failure of the RPV. The use of Code Case N-830 in the methodology in the TR will prevent non-ductile failure of the RPV, and therefore, the use of Code Case N-830-1 is not required to prevent non-ductile failure of the RPV. The TR methodology is not an alternative for calculating $RT_{Max}$ in 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:

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

**4.6 APPLICATION PROCESS**

The following general process steps are used to determine the inputs to Equations 1 through 3. For details, see the referenced Sections discussed below.

- Section 4.2 Specimen Test Data
  - Add 10°C (18°F) to the Charpy size three-point bend specimen test temperatures
  - Evaluate the test data in accordance with E1921-20
  - Screen the test data for inhomogeneity in accordance with E1921-20 paragraph 10.6
    - If the test data is inhomogeneous, set $T_0 = T_{0IN}$. For datasets with N > 20 see Section 4.2 for details
  - An unirradiated generic mean $T_0$ or $RT_{T0}$ can be developed and used, when no heat specific $T_0$ is available.
    - If irradiated fracture toughness data is available from the generic group, adjust the generic $T_0$ to the irradiated data condition add the Equation 5 margin and ensure 95% of the data is bounded

- Section 4.3 Data Adjustments
  - Calculate the adjustment from the test data condition to the RPV projected condition of interest using Equation 6
    - Calculate the test data predicted $\Delta T_{30}$ in accordance with ASTM E900-15 using the test material source best estimates
    - Calculate the RPV predicted $\Delta T_{30}$ in accordance with ASTM E900-15 using the RPV material heat best estimates
    - Calculate the adjustment using Equation 6
  - If MTR data is used
    - Compare the validation material $T_0$ irradiated in the MTR that is adjusted to the PWR irradiated validation material $T_0$ using Equation 8
    - If Equation 8 is not satisfied, calculate the MTR adjustment for materials in the Cu group using Equation 9

- Section 4.4 Margin Term
  - Calculate the margin term using Equation 10
    - If a generic unirradiated $T_0$ or $RT_{T0}$ is used substitute Equation 5 for Equation 10
    - Calculate $\sigma_{test}$ using Table 3
    - For unirradiated data $\sigma_{ETCspecimen}$, $\sigma_{tempspecimen}$ and $\sigma_{fluencespecimen}$ are = 0
    - Calculate the data $\sigma_{adjustment}$ to include the adjustment uncertainty using Equations 11 through 15
    - Calculate the difference in the ETC $\Delta T_0$ prediction * (1.0 for welds or 1.1 for base metals) for the best estimate condition and the best estimate condition -σ or +σ to determine the effect of the input uncertainty on $\Delta T_0$ for $\sigma_{tempspecimen}$, $\sigma_{fluencespecimen}$, $\sigma_{tempRPV}$ and $\sigma_{fluenceRPV}$.

- Section 4 Application of Master Curve Test Data

- Determine the $RT_{PTS}$ (Equation 1) and/or the adjusted reference temperature values to be used with ASME Section XI, Appendix G in Equations 2 or 3 by adding:
  - $T_0$ from Section 4.2
  - The adjustment determined in Section 4.3
    - Include the MTR adjustment, if applicable
  - The margin term determined in Section 4.4
  - For $RT_{PTS}$ use $RT_{T0}$ by adding 35°F to $T_0$
- For data sets from multiple irradiated sources, average them with the weighting factor using Equations 4a and 4b in Section 4.

**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 $\sigma_{test}$ values do not appear to be a function of "r" as required in ASTM E1921. Some description on how the $\sigma_{test}$ 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 $\Delta T_{30}$ 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:

Different data sets have different amounts of certainty 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 RAI 4) demonstrates $T_0 + 2\sigma_{test}$ bounds more than 95% of the data from large data sets as discussed in the responses to RAIs 4, 19 and 21.

b. Provide a description of how each $\sigma_{test}$ 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:

$\sigma_{E1921}$ is a function of r as shown in Table 2 of the revised TR (Table 3 of the original TR), which uses E1921-20 paragraph 10.9. $\sigma_{test}$ modifies $\sigma_{E1921}$ using the $T_{0IN}$ and $T_{0max}$ values according to Table 2 of the TR for N < 20.

The table below includes 3 columns which are not in Table C-9 showing how the various values are calculated: “N, r”, “$T_0$ Basis” and “$\sigma_{test}$ Basis”. The values have been determined using the proposed change to the TR methodology discussed in the response to RAI 10.a above, where the Charpy bias is added to the test temperature.

**Table C-9 Supplemental Information: 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) | $\sigma_{E1921}$ (ºF) | $T_{0scrn}$ or $T_{0IN}$ (ºF) | $T_{0max}$ (ºF) | $T_0$ Basis | $\sigma_{test}$ (ºF) | $\sigma_{test}$ Basis | $T_0$ or $T_{0IN}$ + $2\sigma_{test}$ (ºF) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| All data | 111 | 86, 63 | No | 60.9 | 8.3 | **103.1** | - | $T_{0IN}$ per 4.2 | **8.3** | $\sigma_{test} = \sigma_{E1921}$ per 4.4.1 | 119.7 |
| Lab A mini-C(T) | 13 | 13, 8 | Yes | **94.9** | 14.7 | 94.9 | - | $T_0$ per 4.2 | **14.7** | $\sigma_{test} = \sigma_{E1921}$ per Table 2 | 124.3 |
| Lab B mini-C(T) | 13 | 9, 5 | - | Invalid | - | - | - | - | - | - | - |
| Lab C mini-C(T) | 12 | 12, 8 | No | 58.5 | 14.0 | **83.8** | 108.3 | $T_{0IN}$ per 4.2 | **12.4** | ($T_{0max}$ - $T_{0IN}$)/2 per Table 2 | 108.3 |
| Lab D mini-C(T) | 13 | 13, 10 | No | 94.7 | 13.5 | **127.6*** | 133.1 | $T_{0IN}$ per 4.2 | **2.8** | ($T_{0max}$ - $T_{0IN}$)/2 per Table 2 | 133.1 |
| >50ºC 1TC(T) [65] | 27 | 13, 10 | No | 80.8 | 12.5 | **96.1** | 112.7 | $T_{0IN}$ per 4.2 | **8.3** | ($T_{0max}$ - $T_{0IN}$)/2 per Table 2 | 112.7 |
| 35ºC & 20ºC [65] 1TC(T) & 1/2TC(T) | 12 | 12, 12 | Yes | **87.9** | 11.8 | 95.0 | - | $T_0$ per 4.2 | **11.8** | $\sigma_{test} = \sigma_{E1921}$ per Table 2 | 111.5 |
| 22ºC 1TC(T) & 3PB Charpy [65] | 13 | 10, 8 | No | 95.7 | 13.5 | **122.5** | 125.1 | $T_{0IN}$ per 4.2 | **1.3** | ($T_{0max}$ - $T_{0IN}$)/2 per Table 2 | 125.1 |
| 0ºC 3PB Charpy [65] | 8 | 8, 8 | Yes | **123.9** | 14.7 | 132.4 | - | $T_0$ per 4.2 | **14.7** | $\sigma_{test} = \sigma_{E1921}$ per Table 2 | 153.3 |

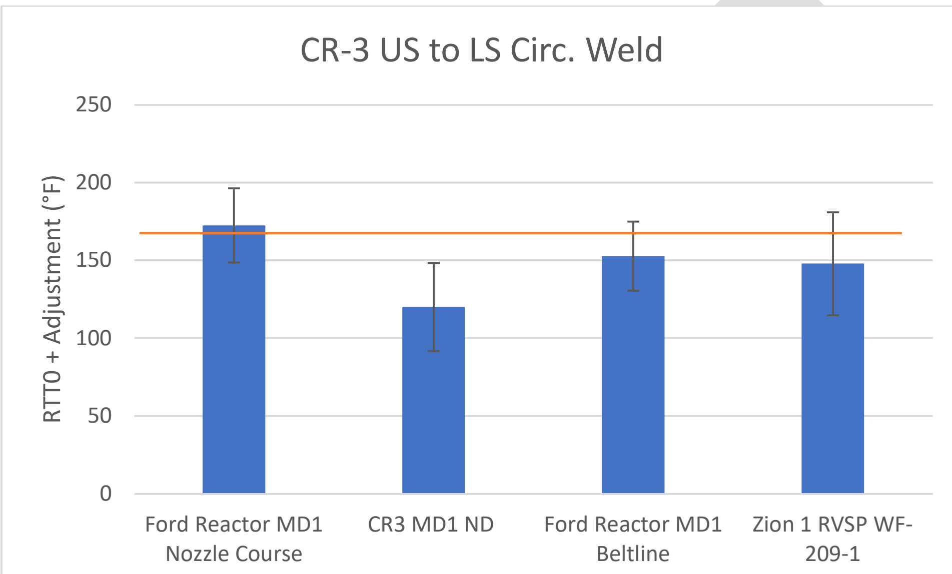
* Must allow use of data greater than $T_{0IN}$ ± 50°C; see ASTM E1921-20

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:

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 [12] for comparison to the bounding average $RT_{T0}$ value. The $RT_{PTS}$ value is comprised of the initial $RT_{NDT}$ + $\Delta RT_{NDT}$ + Margin [-26 + 223.8 + 56.0 = 253.8°F]. The $\Delta RT_{NDT}$ uses the prediction method in 10CFR50.61, which is based on 177 $\Delta T_{30}$ measurements. $\Delta T_{30}$ is predicted using ASTM E900-15, which was developed using over 1800 $\Delta T_{30}$ measurements and has been demonstrated to be more accurate [ML20139A030]. ASTM E900-15 predicts 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 $\Delta T_{30}$ 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 include the measurement uncertainty in the margin term which are not significantly different. 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 depends on these uncertainties being captured in the ETC uncertainty (28ºF for welds), which is based on the 177 $\Delta T_{30}$ 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 as indicated with the uncertainty bars. The red line represents the PWR irradiated weighted average $RTT_0$ + Adjustment + Margin (162.4ºF). The four adjusted measurements are in reasonable agreement when considering the margin.





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