4 METHODOLOGY FOR APPLICATION OF MASTER CURVE TEST DATA

The following methodology discusses the application of irradiated (or unirradiated) direct fracture toughness test data for the evaluation of RPV integrity considering embrittlement. This methodology involves the evaluation of test data used to determine the fracture toughness transition temperature (T_0), Section 4.2, adjusting the data to reflect the RPV material best-estimate properties and irradiation conditions, Section 4.3, and the inclusion of margins to account for test, material, and irradiation uncertainties, Section 4.4. This methodology utilizes irradiated data, as discussed in Section 4.1, however unirradiated T_0 data can be used if irradiated data is not available.

For PTS evaluations, Equation 1 will be used (an exemption to 10 CFR 50.61 is required to use this methodology, see Section 3.1):

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

Where *adjustment* and *margin* are defined in Sections 4.3 and 4.4, respectively.

Either Equation 2 or Equation 3 can be used for 10 CFR 50, Appendix G P-T curve development (See Section 3.2).

Using the 2017 ASME Section XI, Appendix G (ksi√in and °F):

$$K_{Ic} = 33.2 + 20.734 \exp[0.02\ (T - \{T_0 + 35 + \textit{adjustment} + \textit{margin}\})] \qquad \text{[Equation 2]}$$

Using Code Case N-830 as modified by the NRC condition [25 and 26] (ksi√in and °F):

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

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.

For 10 CFR 50, Appendix G P-T curve development, the methodology in this topical report provides an alternative to specific sections of WCAP-14040-A, Revision 4 and BAW-10046, Revisions 2 and 4, as discussed in subsection 3.2.1, and does not affect the other sections in these NRC approved topical reports.

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 data. ~~Alternatively, t~~The T_0 *(or* RT_{T0}*) + adjustment + margin* values 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 ΔT_{30} predictions. Then the absolute values of the differences between the 6 predicted ΔT_{30} and the predicted ΔT_{30} based on the RPV material $(predicted\ RPV\ \Delta T_{30})$ are summed and divided by the predicted ΔT_{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 weight factor, w_i ($w_i \geq 0$) as shown in Equation 4a. The weight factor is multiplied by each T_0 *(or* RT_{T0}*) + adjustment + margin* value, summed and divided by the sum of the weight 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 T0 provides the measured effect of embrittlement without the need for the full prediction uncertainty. If only unirradiated T0 is available, the approach discussed herein can also be used.~~

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

[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 weight 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.

4.1 GENERATION AND VALIDATION OF IRRADIATED DATA

Ideally, the material to be evaluated would be obtained from a surveillance capsule irradiated in the RPV being evaluated. A review of plant-specific information determined that only a small portion of the U.S. PWR plants have all of their P-T curve limiting and near-limiting materials included in their surveillance programs, since inclusion of all near-limiting materials is not a requirement for surveillance program design. In addition, the RPV limiting material can change depending on Charpy shift measurements, credibility determination and embrittlement projection methods. Therefore, it is advantageous to have direct fracture toughness test data for all RPV materials that might become limiting. Most plants have their P-T curve limiting and near-limiting materials in unirradiated archive storage. Therefore, it is advantageous to be able to irradiate specimens at a high flux to produce relevant fluence data in a reasonable time period. As discussed in Appendix B.2, Material Test Reactor (MTR) irradiations typically produce representative or conservatively biased results. For the purposes of this methodology, “high flux” is defined as having a flux greater than that of any surveillance capsule in commercial PWRs. ASTM E900-15 [4], identifies the maximum flux for a PWR irradiation included in the database which formed the basis of the embrittlement trend correlation (ETC) as 5×10^{12} E > 1 MeV, $n/cm^2/s$.

As discussed in [40], the effect of flux on embrittlement shift is dependent on the Cu level and fluence. High flux irradiation is discussed further in Appendix B. Depending on where in the Cu-related hardening regime the material is during irradiation, the effect can vary. There are three general categories of materials for vessel embrittlement: low Cu, medium Cu, and Cu saturated. The low Cu level and the level at which Cu saturation occurs is included in the ASTM E900-15 ETC Cu term. Therefore, validation materials are grouped into these three categories:

- Low Cu: Cu weight percent (wt. %) ≤ 0.053
- Medium Cu: Cu wt. % between 0.053 and 0.28
- High Cu: Cu wt. % ≥ 0.28

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 irradiated in the same MTR irradiation campaign with the same heat~~ 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. Materials in the same group would be expected to behave similarly with respect to any flux effect, especially at high fluence (≥ 60-year RPV core region fluence) when Cu precipitation has already occurred. The validation material results are used in the overall methodology to ensure conservatism of the test results as discussed in subsection 4.3.4.2.

4.2 SPECIMEN TEST DATA

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 data with a 95% confidence level can be determined for forgings, plates, and welds based on common manufacture, material class, or flux types. The method described in Section 9.12 of NUREG-1475, Revision 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 plus the Equation 5 margin 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:

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

Specimens must be removed from approximately the ¼ or ¾ thickness location in a plate or forging, and weld specimens can be removed from any depth location except near the surfaces. Refer to ASTM E185-82 [38] for additional details on specimen location with reference to the source material. Plate and forging specimens are to be oriented in the transverse (weak) direction, while weld specimens are to be oriented with crack growth parallel to the weld seam as shown in Figure 1 of ASTM E185-82 [38].

The test data must meet the requirements of ASTM E1921-20. If test data was produced in accordance with another version of ASTM E1921 or another test standard (e.g. ASTM E399), the data must be reviewed and the calculations must be revised to ensure compliance with ASTM E1921-20. Extra specimens are recommended to be tested to ensure that a valid T_0 is obtained. The data set will be screened for inhomogeneity as discussed in paragraph 10.6 of ASTM E1921-20. Data sets that fail the screening criterion will be evaluated in accordance with Appendix X5 "Treatment of Potentially Inhomogeneous Data Sets," of ASTM E1921-20 with T_0 set equal to T_{0IN} (T_{0IN} is a biased T_0 accounting for data screened as inhomogeneous as defined in Appendix X5.2) for all subsequent calculations and validations in this methodology. 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.~~ For large data sets (20 or more) which are screened as inhomogeneous, regardless of the ASTM E1921-20 treatment method used or the analysis result, the T_0 that is used does not have to be more conservative than the T_0 corresponding to the least tough datapoint being on the $K_{Jc\text{-}lower95\%}$ curve plus σ_{E1921} (σ per ASTM E1921-20 paragraph 10.9).~~

Test data from specimens of any ASTM E1921 standard geometry including the mini-C(T) size (0.16 inch thick). Significant experience has shown that the mini-C(T) specimen size produces results that are indistinguishable from larger C(T) specimens (see Appendix A). 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 added to the test temperature of each 3PB specimen when calculating T_0~~included~~.~~ 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.~~

4.3 DATA ADJUSTMENTS

Irradiated specimens will rarely reflect the exact same irradiation conditions and chemistry as the represented RPV material. Therefore, adjustments are necessary to compensate for differences between test samples and the actual RPV materials. The ETC contained in ASTM consensus Standard Guide E900-15 [4] is the most recent internationally accepted consensus standard for predicting RPV embrittlement. ASTM E900-15 is used to account for this difference, as discussed below. This ETC is the latest and most robust international consensus embrittlement shift prediction model available. In addition, the NRC presented a technical basis for a potential alternative to RG 1.99, Revision 2 where use of ASTM E900-15 is recommended [42]. It is based on a Charpy 30 ft-lb transition temperature shift (ΔT_{30}) database comprised of 1,878 power reactor surveillance program shift measurements [4]. Average ΔT_{30} is not exactly the same as ΔT_0, but there is a clear relationship between the two values (see Figure 6 and Figure 7) and differences can be accounted for using the adjustment of 1.0 for welds or 1.1 for base metals as shown in Equation ~~4~~6.

adjustment = (predicted ΔT_{30} of the RPV material at the fluence of interest – predicted ΔT_{30} of the ~~irradiated~~ tested material) * ~~average shift difference between ΔT_0 and ΔT_{30}~~(1.0 for welds or 1.1 for base metals) [Equation ~~4~~6]

The predicted ΔT_{30} above is calculated in accordance with ASTM E900-15 using the inputs discussed in the following sections. None of the adjustments can be made using data outside the calibration range of the shift prediction model, which in the case of the ASTM E900-15 ETC is described in [4]. It is noted that flux may be outside the calibration range in the case of an MTR; however, flux is not used to determine data adjustments and whether the data is representative is validated as discussed in Section 4.1. The calibration range for the ASTM E900-15 ETC is reproduced in Table 1. The "(1.0 for welds or 1.1 for base metals)~~average shift difference between ΔT_0 and ΔT_{30}~~" in Equation ~~4~~6 is addressed in subsection 4.3.5.

Table 1: Independent Variables in the ASTM E900-15 Embrittlement Shift Model and the Range of the Calibration Data [4]

Variable	Description	Range
Cu	Copper content (wt %)	0.0–0.4
Mn	Manganese content (wt %)	0.55–2.0
Ni	Nickel content (wt %)	0.0–1.7
P	Phosphorous content (wt %)	0.0–0.03
Φ	Neutron fluence, E > 1 MeV (n/cm^2)	1×10^{17}–2×10^{20}
T	Irradiation temperature (°F)	491–572

~~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.~~

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

~~Where,~~

~~TTS = E900-15 predicted shift in 30 ft-lb transition temperature (°C)~~

~~C and D are provided in Table 2:~~

~~**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.~~ The ASTM E900-15 ΔT_{30} is calculated with the inputs discussed in the following subsections for the irradiated test samples and the RPV material for the operating time of interest. The difference in ΔT_{30} values is used to adjust the T_0 determined from the test data as shown in Equation ~~4~~6.

4.3.1 Chemistry (Cu, Mn, Ni and P)

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

For welds, there generally is a chemistry difference between the test material source (usually the surveillance weld) and the RPV weld best-estimate. The test specimen material source chemistry and heat best-estimate chemistry for the RPV should be used when determining the adjustment calculation.

4.3.2 Temperature

The time-weighted average temperature for the RPV thickness location that corresponds to the fluence projection should be used for the RPV, and the test sample irradiation time-weighted average temperature should be used in the adjustment calculation. For P-T limit calculations the temperature at the ¼ or ¾T crack tip can be used in the ETC calculation. Alternatively, if a simplified conservative approach is used, the value of average cold leg temperature (T_{cold}) can be used in the ETC, which will over-estimate the effect of embrittlement on ΔT_{30}. Gamma heating of the RPV in the beltline region increases the RPV wall temperature toward the insulated outside RPV surface. ~~in depth away from the wetted clad~~ During normal operation, the wetted surface remains at ~~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}.

4.3.3 Fluence

The best-estimate fluence (E > 1 MeV) at both the RPV thickness location of interest and the test specimens must be determined to make the necessary adjustments. The RPV and test material fluence shall be determined using an NRC-approved[5] methodology of fluence evaluation consistent with the plant licensing basis, or another NRC-approved[5] methodology for fluence evaluation. RPV wall neutron attenuation to the postulated flaw tip location can be determined one of three ways using an NRC-approved[5] fluence calculation methodology:

1. Consistent with RG 1.99, Revision 2 [21],

$$\boldsymbol{fluence_x = fluence_{surface} \bullet e^{-0.24x}}$$ [Equation ~~6~~7]

Where,

fluence$_{surface}$ = neutron fluence (10^{19} n/cm^2, E > 1 MeV) at inner wetted surface of RPV

x = the depth into the RPV wall measured from the RPV inner wetted surface (inches).

2. 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~~7, or

[5] If this methodology is implemented outside of the U.S., the regulatory authority that regulates the plant site would be substituted for "NRC".

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

4.3.4 Flux

Adjustments related to the irradiation fluence rate (flux) are discussed for the typical PWR flux and for the high flux of an MTR in the following sections. Flux is the fluence divided by effective full power years (EFPY).

4.3.4.1 Power Reactor Flux

Specimens irradiated in a power reactor at a flux not considered "high" (i.e., a flux less than 5×10^{12} E > 1 MeV, n/cm^2/s) generally are considered to have a flux that is representative of the RPV. The ASTM E900-15 ETC has no flux term, since the flux did not have a statistically significant effect within the power reactor irradiation flux range.

4.3.4.2 MTR Flux

For high flux irradiations, a set of validation specimens must be irradiated and tested to validate that the high flux irradiated specimens are representative of or conservative compared to PWR flux specimens, as discussed in Section 4.1. T_0 data obtained from a PWR flux irradiation must be available in order to provide a comparison for the same material heat to the high flux validation specimens.

After adjusting for differences in exposure using the ASTM E900-15 ETC, the high flux and PWR irradiated T_0 values determined in Section 4.2 must be compared to validate that the high flux irradiation produced representative or conservative results. The adjustment method described in Section 4.3 is used for the comparison. If the following inequality (Equation ~~7~~8) is met, the T_0 values in the corresponding material grouping ("low Cu", "medium Cu", or "high Cu" per Section 4.1) for the high flux irradiation are considered representative of, or conservative, compared to the RPV irradiation and can be used without Equation 9 for RPV integrity evaluations using Equations 1-3:

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

Where,

Adjusted $T_{0high\ flux\ VM}$ = The T_0 (per Section 4.2) of the high flux validation material plus adjustment per Equation ~~4~~8 where the PWR irradiated validation material variables are substituted for RPV material variables to adjust for differences in fluence, chemistry, temperature, etc.

$T_{0PWR\ VM}$ = ~~T~~the T_0 (per Section 4.2) of the validation material irradiated with a PWR flux

~~$\sigma_{test\ high\ flux\ VM}$ = The uncertainty of the T_0 test measurement determined with the high flux validation material specimens according to subsection 4.4.1~~

~~$\sigma_{test\ PWR\ VM}$ = The uncertainty of the T_0 test measurement determined with the PWR flux validation material specimens according to subsection 4.4.1~~

If the above inequality is not met, then the T_0 values of materials in the corresponding material grouping ("low Cu", "medium Cu", or "high Cu" per Section 4.1) will be increased to ensure the results are representative of the PWR RPV using Equation 8. In this case, the difference in T_0 results is assumed to be a result of differences in embrittlement shift due to irradiation in the MTR. Therefore, the increase in T_0 for the materials in the corresponding material grouping are a proportion of the predicted embrittlement shift as shown in Equation ~~8~~9. If multiple data sets are available from the same MTR irradiation or the same PWR irradiation, the Equation ~~7~~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.

$$Adjusted\ T_{0high\ flux} = \left\{\frac{\left(T_{0PWR\ VM} - Adjusted\ T_{0high\ flux\ VM}\right)}{\Delta T_{30highflux\cancel{PWR}VM}}\right\} \cdot \Delta T_{30RPV\cancel{high\ flux}} + T_{0high\ flux} \quad \text{[Equation } \cancel{8}9\text{]}$$

Where (when not defined previously),

Adjusted $T_{0high\ flux}$ = The T_0 adjusted for MTR flux effects to be used in Equations 1, 2, or 3 for RPV integrity evaluation. Note that the "adjustment" term in Equations 1–3 must still be utilized to make adjustments relative to the RPV material. The adjustment in Equation ~~8~~9 only considers adjustment from the MTR irradiation to the PWR irradiation.

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

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

$T_{0\ high\ flux}$ = The T_0 (T_0 per Section 4.2) determined using the high flux material from the same Cu group as the validation material

When multiple data sets are available for validation from the same MTR irradiation, the Equation ~~8~~9 variables contained in brackets ~~should~~ will 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.

4.3.5 Correlation between ΔT_{30} and ΔT_0

In some cases, there is a measured difference between the embrittlement shift in ΔT_{30} and ΔT_0. Since the ETC model used is based on ΔT_{30}, this difference ~~should be~~is taken into account. There is no industry accepted ETC model based on ΔT_0. Figure 6 and Figure 7 show~~s~~ a number of shift measurements comparing ΔT_0 and ΔT_{30} ~~the two shifts~~for welds and base metals, respectively ~~[43]~~. The linear fit parameters and statistics for the welds, plates and forgings are shown in

Table 2. The statistics show that the plate and forging fits are indistinguishable and are therefore combined as base metal. On average, the ~~ratio~~ slope of ΔT_0 to ΔT_{30} ~~shift difference~~ for welds is 0.99 and 1.09~~1~~ 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 ΔT_0 and ΔT_{30} measurement is comprised of an uncertainty of both the unirradiated and irradiated measurements with the typical combined measurement standard deviation using 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 ΔT_0 to ΔT_{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 value of 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 ΔT_{30} to ΔT_0 (or vice versa) where the author concludes that when measured ΔT_0 values are determined from a large number of specimens, there is less scatter; therefore, the scatter is largely an artifact of the measurement uncertainty.

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

Product Form	Number	Data Sources	Slope	Standard Error on Slope	Standard Deviation on Fit Residuals (°C)	R^2	Equation 6 Adjustment
Weld	86	14, 31, 44, 46	0.99	0.02	17	0.97	1.0
Plate	66	14	1.09	0.03	19	0.96	1.1
Forging	29	14, 44, 45, 46, 47	1.08	0.06	16	0.93	1.1
Plate & Forging Combined	95	14, 44, 45, 46, 47	1.09	0.03	18	0.95	1.1

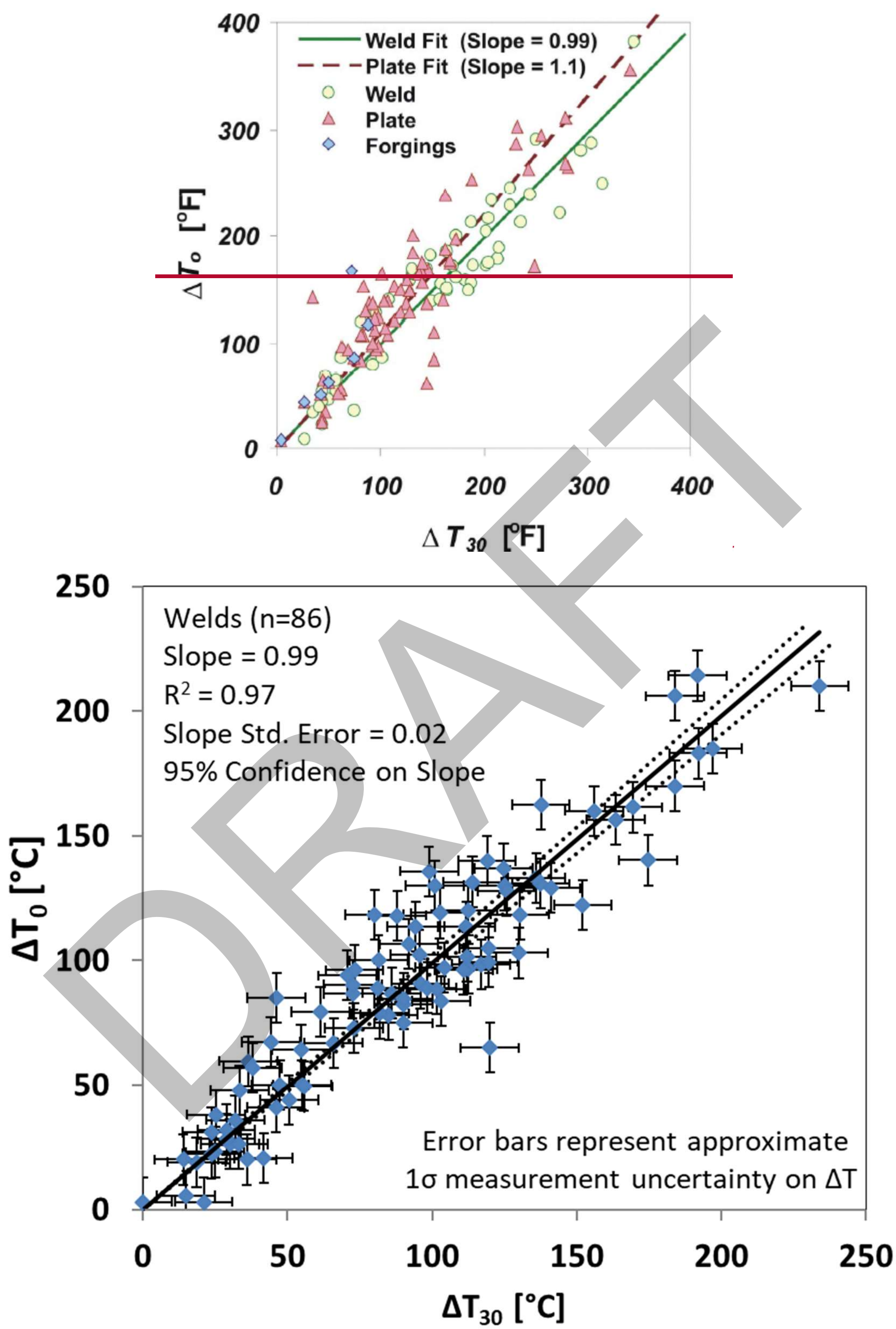

Figure 6: Relationship of Embrittlement Shift between ΔT_{30} and ΔT_0 for Welds~~(Reproduction of Figure 32 of [43])~~

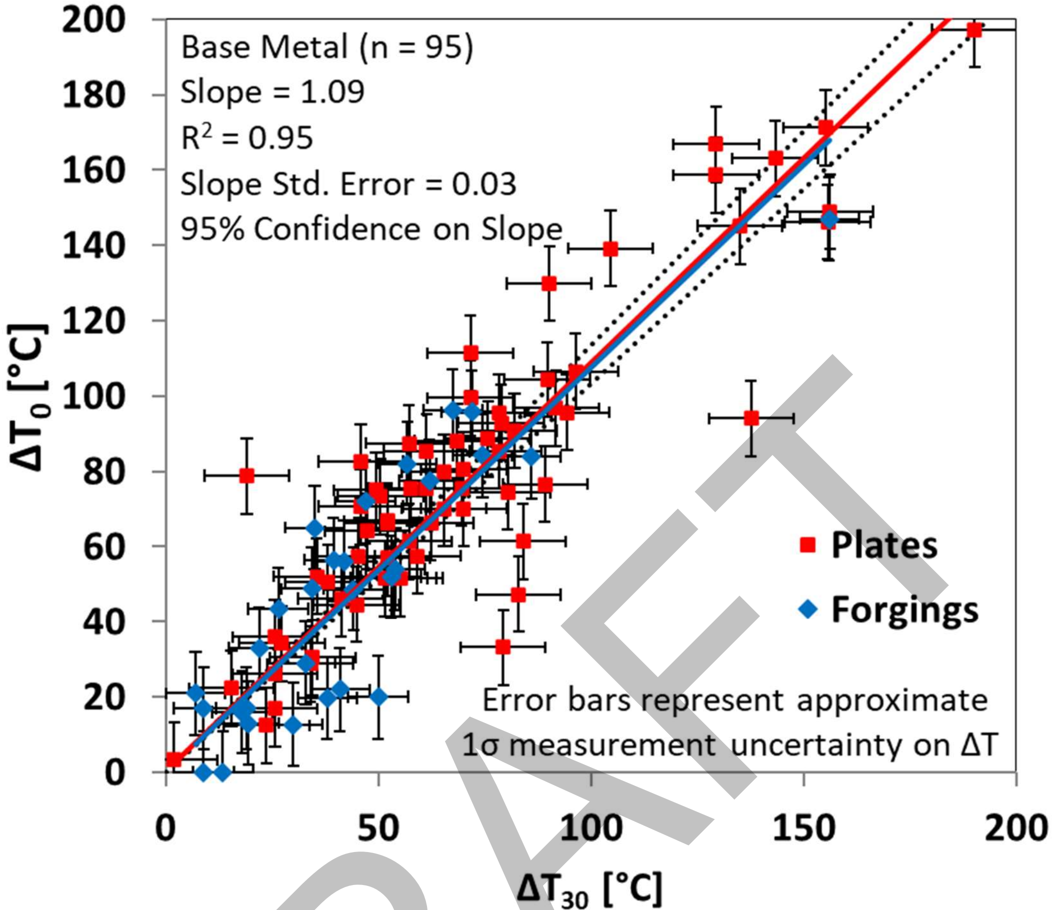

Figure 7: Relationship of Embrittlement Shift between ΔT_{30} and ΔT_0 for Base Metals

4.4 MARGIN TERM

To account for uncertainties in the test measurement of T_0, the adjustment uncertainty (if required), irradiation temperature uncertainty of the test specimens and RPV, and fluence uncertainty of the test specimens and RPV, a margin term is added. Since these uncertainties are independent, they are combined using the ~~the square root of the sum of the squares (~~SRSS~~)~~ using Equation 10~~9~~.

$$\mathrm{Margin} = 2 \cdot \sqrt{\sigma_{test}^2 + \sigma_{\cancel{additional}adjustment}^2 + \sigma_{tempspecimen}^2 + \sigma_{tempRPV}^2 + \sigma_{fluencespecimen}^2 + \sigma_{fluenceRPV}^2} \quad \text{[Equation 10}\cancel{9}\text{]}$$

The Equation 10~~9~~ uncertainty terms are defined in subsection 4.4.1 through subsection 4.4.4.

4.4.1 Determination of σ_{test}

σ_{test} is calculated according to Table 3 where σ_{E1921} is calculated in accordance with paragraph 10.9 of ASTM E1921 (with standard calibration practices, σ_{exp} = 4°C) with fewer than 20 specimens (N). However, in some cases, σ_{test} can be set to zero. For data sets that fail the homogeneity screening procedure and have T_0 set using the least tough datapoint ($T_{0IN} = T_{0max}$) or have $T_{0IN} > T_{0max}$ (N < 20), no margin is needed since the highest T_{0i} sets T_0 and the 95% lower bound curve based on T_{0max} is sufficiently conservative without adding test uncertainty. Evidence is presented for this conclusion in Appendix C. Table 3 summarizes the applicable value of σ_{test} to be used in Equation 10~~9~~ and ensures that the T_0 value plus two times σ_{test} is not greater than T_{0max} (when T_0 is established using the least tough datapoint) if the homogeneity screening procedure is not met. ~~If N ≥ 20, then σ_{test} = σ_{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 σ_{test}, as the number of samples will ensure that there is a sufficient population of low toughness data included in the result.

Table 3: σ_{test} Modification as a Function of ASTM E1921-20 Paragraph 10.6.3 Homogeneity Screening Procedure Result (N < 20)

Result	σ_{test}
Pass	$\sigma_{test} = \sigma_{E1921}$ per paragraph 10.9 of ASTM E1921
Fail; if $T_{0IN} \geq T_{0max}$ following paragraph X5.2	$\sigma_{test} = 0$
Fail; if $T_{0IN} < T_{0max} \leq (T_{0IN} + 2\sigma_{E1921})$ following paragraph X5.2	$\sigma_{test} = (T_{0max} - T_{0IN})/2$
Fail; if $T_{0IN} + 2\sigma_{E1921} < T_{0max}$ following paragraph X5.2	$\sigma_{test} = \sigma_{E1921}$ per paragraph 10.9 of ASTM E1921

4.4.2 Determination of $\sigma_{\cancel{additional}adjustment}$

If adjustments exceed the standard deviation of the ETC as described in Section 4.3, $\sigma_{\cancel{additional}adjustment}$ is required as determined by Equation 11~~0~~. ~~If adjustments do not exceed the standard deviation of the ETC, $\sigma_{additional}$ is set equal to zero.~~

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

[Equation 11~~0~~]

Where:

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

σ_{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 ΔT_{30} predictions. The absolute value of the differences between this 6 predicted ΔT_{30} and the predicted ΔT_{30} based on the RPV material ($predicted\ RPV\ \Delta T_{30}$) are summed producing $adjTTS_{sum}$ in Equation 12

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

[Equation 1~~1~~2]

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

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

[Equation 1~~2~~3]

~~$\sigma_{ETCspecimens}$ = the standard deviation of the ETC prediction for the tested specimens as determined by Equation 5~~11

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

$$SD_{ETC} = C \bullet (Predicted\ RPV\ \Delta T_{30})^{D}$$ [Equation 14~~5~~]

Where,

Predicted RPV ΔT_{30} = the ASTM E900-15 predicted shift in the 30 ft-lb transition temperature (°C)

C and D are provided in Table 4~~Table 2~~:

Table 4: 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

The intent of $\sigma_{\cancel{additional}adjustment}$ is to include the uncertainty of the adjustment due to the underlying uncertainty of the ETC trend. SD_{ETC} is based on the standard deviation of the measured data relative to the ETC ΔT_{30}~~TTS~~ prediction which represents the uncertainty in making a single prediction, which includes measurement and input uncertainties. The Equation 10~~9~~ margin term independently accounts for uncertainties in measurement, temperature, and fluence. Furthermore, any local chemistry variation is considered indirectly through the homogeneity screening, which identifies atypical toughness variation. Therefore, use of $\sigma_{\cancel{additional}adjustment}$ double counts several of the uncertainties that are explicitly included in the margin term. The uncertainty of the ASTM E900-15 prediction within a specific heat (after the heat ~~bias~~ difference has been compensated for) is less than SD_{ETC}. Therefore, for the same heat, σ_{ETCRPV} and $SD_{ETCRPVadj}$~~$\sigma_{ETCspecimens}$~~ are not independent and do not need to be combined using the SRSS. Instead, these uncertainties are combined as a simple difference in Equation 1~~0~~1, implying the uncertainties are fully dependent. Although σ_{ETCRPV} and $SD_{ETCRPVadj}$~~$\sigma_{ETCspecimens}$~~ are neither fully dependent nor fully independent, the approximation of being fully dependent is appropriate, since some uncertainties are being double counted in this methodology. Using Equation 1~~0~~1 with unirradiated test specimens, $SD_{ETCRPVadj}$~~$\sigma_{ETCspecimens}$~~ = 0°F and, therefore, $\sigma_{\cancel{additional}adjustment} = \sigma_{ETCRPV} = SD_{ETC}$. This approach is very similar to the approach in BAW-2308 [31], where unirradiated data is used with the full σ_{ETC} and is combined with σ_{To} and $\sigma_{MonteCarlo}$ (a measure of material variability).

4.4.3 Determination of $\sigma_{tempspecimen}$ and $\sigma_{tempRPV}$

$\sigma_{tempspecimen}$ = The effect of uncertainty of the specimen irradiation temperature on T_0 embrittlement using the ETC * (1.0 for welds or 1.1 for base metals)~~(ΔT_0 / ΔT_{30} Slope)~~ at the specimen best estimate condition

$\sigma_{tempRPV}$ = The effect of the uncertainty of the RPV irradiation temperature on embrittlement using the ETC * (1.0 for welds or 1.1 for base metals) ~~(ΔT_0 / ΔT_{30} Slope)~~ at the RPV best estimate condition

The total PWR instrument loop temperature is measured often and averaged over many cycles; therefore, the standard error of the time weighted average (standard error = standard deviation/√N) is small. Therefore, 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. For MTR irradiations, the temperature uncertainty should be provided by the irradiation facility. If the specimens were irradiated in a surveillance capsule contained in the assessed RPV, the temperature of both are largely controlled by the coolant in the downcomer region. Therefore, the capsule irradiation temperature uncertainty is addressed in the RPV irradiation temperature uncertainty term and $\sigma_{tempspecimen}$ can be set to zero.

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

4.4.4 Determination of $\sigma_{fluencespecimen}$ and $\sigma_{fluenceRPV}$

$\sigma_{fluencespecimen}$ = The effect of uncertainty of the specimen fluence on embrittlement using the ETC * (1.0 for welds or 1.1 for base metals)~~(ΔT_0 / ΔT_{30} Slope)~~ at the specimen best estimate condition

$\sigma_{fluenceRPV}$ = The effect of uncertainty of the RPV fluence on embrittlement using the ETC * (1.0 for welds or 1.1 for base metals)~~(ΔT_0 / ΔT_{30} Slope)~~ at the RPV best estimate condition

The fluence uncertainty may not be completely captured in the variation of the test specimen fluence and, thus, toughness. Therefore, the fluence uncertainty is based on the NRC-approved[5] methodology used to calculate fluence. The RPV fluence uncertainty may be one standard deviation of the methodology uncertainty. Dosimetry activity measurements can be used to reduce the uncertainty in the calculated fluence values; therefore, use of a least-squares evaluation considering in-capsule dosimetry measurements is acceptable for determining the specimen fluence uncertainty. If ex-vessel dosimetry measurements are available, use of a least-squares evaluation considering the dosimetry measurements is acceptable for determining the RPV fluence uncertainty.

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

4.5 UNCERTAINTY DUE TO MATERIAL VARIABILITY

The existing approach for accounting for the material variability in RPV integrity embrittlement [1 and 21] relies on the uncertainty of the prediction model which is based on many embrittlement shift measurements of many materials. Thus, empirical ETCs inherently contain uncertainty related to material variation and chemistry uncertainties in the prediction standard deviation. However, when measuring the fracture toughness reference temperature (T_0) in the irradiated condition, an embrittlement prediction is not used (except to make adjustments). The variation in the chemistry in the product which affects embrittlement shift and any initial fracture toughness variation must be considered to ensure an appropriate level of conservatism.

The homogeneity screening procedure prescribed in paragraph 10.6 of ASTM E1921-20 is designed to detect if the data set may be representative of a macroscopically inhomogeneous material. Inhomogeneity in toughness could be the result of at least two effects: initial properties or variation in embrittlement effects. Data sets that fail the screening criterion, regardless of the reason, are evaluated in accordance with Appendix X5 of ASTM E1921-20.

It is possible that variability in the entire product may go undetected in the tested material as a result of macroscopic variation (i.e., macro segregation) which may not be contained in the tested material. However, this scenario could also be present using current methods in which qualification samples are removed from only a small portion of the component. ASME Code safety factors such as a 1/4T flaw size, a safety factor of two on pressure stress, and the use of material properties from the 1/4T location ensure that sufficient conservatism is included [48]. Likewise, 10 CFR 50.61 contains inherent conservatism [49]. S. Saillet, et al., demonstrated that an RPV ring forging containing macro segregation had toughness at the inside surface no lower than the 1/4T toughness of the acceptance ring even when considering the reduced toughness in the macro segregated region [50]. The methodology in this topical report does not change the safety factors in the ASME B&PV Code, 10 CFR 50 Appendix G, nor 10 CFR 50.61. Thus, no explicit uncertainties are required to consider material variability aside from those associated with the homogeneity screening. 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.

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 ΔT_{30} in accordance with ASTM E900-15 using the test material source best estimates
        - Calculate the RPV predicted ΔT_{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 σ_{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 ΔT_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 ΔT_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.

5 OVERALL SUMMARY

This topical report presents a methodology that justifies the use of ductile-brittle transition temperature direct fracture toughness data to evaluate reactor pressure vessel (RPV) integrity as an alternative to the requirements of pressurized thermal shock (PTS) (10 CFR 50.61) and pressure-temperature (P-T) limit curves (10 CFR 50, Appendix G). Specifically, this topical report discusses a methodology to:

- Determine the ductile-brittle transition reference temperature (T_0)
- Adjust the data for differences between the tested material and the RPV component of interest
- Account for test result uncertainty and material variability in the respective RPV component
- Apply the data using the ASME Section XI Code

Transitioning from the current unirradiated reference temperature for nil ductility transition (RT_{NDT}), and the predicted embrittlement shift approach for RPV integrity evaluations to a direct fracture toughness (master curve) approach will provide a benefit in RPV evaluation for license renewal and subsequent license renewal by reducing uncertainties. The available irradiated master curve data show in many cases, that substantial conservatism exists due to uncertainties in the current approach. Thus, application of irradiated master curve data, as an alternative to the current 10 CFR 50.61 and 10 CFR 50, Appendix G RPV evaluations, is expected to show margin in these analyses. Establishing a robust fracture toughness basis will ensure public health and safety by reducing uncertainty and enabling a statistical understanding of the actual irradiated RPV fracture toughness.

The approach taken in this topical report uses NRC approved methodologies in ASME Section XI, Appendix G, subsection G-2110 (RT_{T0}) and the NRC endorsed Code Case N-830, however, exemptions to 10 CFR 50.61 or 10 CFR 50, Appendix G are still required to implement them. The methodology uses the industry consensus ASTM E1921-20 Standard Test Method and the ASTM E900-15 Standard Guide for predicting embrittlement and ensures uncertainties are properly addressed and appropriately bounding. This topical report provides a methodology to use irradiated (or unirradiated) ASTM E1921-20 T_0 as an alternative to specific sections of NRC-approved topical reports WCAP-14040-A, Revision 4, BAW-10046A, Revision 2 and BAW-10046, Revision 4 which are identified in Section 3.2.1.

Appendix C provides examples showing the application of this methodology.

28. Commonwealth Edison Company (Zion Nuclear Power Station, Unit Nos. 1 and 2) [Docket Nos. 50-295 and 50-304] Exemption Notice, Federal Register, Vol. 59, No. 40, March 1, 1994.

29. "Kewaunee Nuclear Power Plant – Exemption from the Requirements of 10 CFR Part 50, Appendix G, Appendix H, and Section 50.61 (TAC No. MA8585)," U.S. Nuclear Regulatory Commission, May 2001. (ADAMS Accession No. ML011210180)

30. "Safety Evaluation by the Office of Nuclear Reactor Regulation Regarding Amendment of the Kewaunee Nuclear Power Plant License to Include the Use of a Master Curve-Based Methodology for Reactor Pressure Vessel Integrity Assessment," U.S. Nuclear Regulatory Commission, May 2001. (ADAMS Accession No. ML011210180)

31. "Initial RT_{NDT} of Linde 80 Weld Materials," BAW-2308, Revision 1-A, B&W Owners Group, August 2005.

32. "Initial RT_{NDT} of Linde 80 Weld Materials," BAW-2308, Revision 2-A, PWR Owners Group, March 2008.

33. Code of Federal Regulations, 10 CFR Part 50.61a, "Alternate Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock Events," U.S. Nuclear Regulatory Commission, 75 FR 72653, November 26, 2010.

34. "Palisades Nuclear Plant - Issuance of Amendment Re: License Amendment Request to Implement 10 CFR 50.61a, 'Alternate Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock Events,' (CAC NO. MF4528)," U.S. Nuclear Regulatory Commission, November 2015. (ADAMS Accession No. ML15209A791)

35. Westinghouse Report WCAP-14040-A, Revision 4, "Methodology Used to Develop Cold Overpressure Mitigating System Setpoints and RCS Heatup and Cooldown Limit Curves," May 2004. (ADAMS Accession No. ML050120209)

36. "Methods of Compliance with Fracture Toughness and Operational Requirements of 10 CFR 50, Appendix G," Framatome, BAW-10046A, Revision 2, June 1986 and BAW-10046, Revision 4, November 1999.

37. Code of Federal Regulations, 10 CFR 50, Appendix H, "Reactor Vessel Material Surveillance Program Requirements," U.S. Nuclear Regulatory Commission, 85 FR 62207, October 2, 2020.

38. ASTM E185-82, "Standard Practice for Conducting Surveillance Tests for Light-Water Cooled Nuclear Power Reactor Vessels," ASTM International, 1982.

39. ASTM E23-18, "Standard Test Methods for Notched Bar Impact Testing of Metallic Materials," ASTM International, 2018.

40. "Review of Dose Rate Effects on RPV Embrittlement," Joint EPRI-CRIEPI RPV Embrittlement Studies (1999-2004), EPRI, Palo Alto, CA: 2002, 1003529 and CRIEPI, Tokyo, Japan: T980204.

~~41. .~~

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

68. Yamamoto, M., “Trial Study of the Master Curve Fracture Toughness Evaluation by Mini-C(T) Specimens for Low Upper Shelf Weld Metal Linde-80,” Proceedings of the ASME 2018 Pressure Vessels & Piping Conference, PVP2018-84906, 2018.

69. Chaouadi, R., et al., “On the Importance of MTR–Accelerated Data in Support of RPV Surveillance for Long Term Operation,” Workshop on RPV Embrittlement and Surveillance Programmes, 14 October 2015, Prague, Czech Republic.

70. Fabbri, S., Chocron, M. and Versaci, R., “Regulatory Aspects of Aging Management in Argentina,” Material Degradation and Related Managerial Issues at Nuclear Power Plants, Proceedings of a Technical Meeting Organized by the IAEA, 2006.

71. Van Walle, E., et al., “The Role of The BR2 Material Test Reactor to Determine the Material Properties of the Flaked RPV Shells in Support of the Structural Integrity Assessment,” European Nuclear Conference ENC-2016, Paper ENC2016-A0124, 2016.

72. Todeschini, P., et al., “Revision of the Irradiation Embrittlement Correlation Used for the EDF RPV Fleet,” presented at the International Symposium Fontevraud 7, Paper A084-T01, Avignon, France, September 2010.

73. Kirk, M. and Erickson, M., “Code Case: Accounting for Embrittlement,” Presentation to ASME SC-XI WGOPC & WGFE, Record # 19-1113, Minneapolis, MN, August 2019.

74. NUREG/CR-7153, “Expanded Materials Degradation Assessment (EMDA),” Volume 3, “Aging of Reactor Pressure Vessels,” U.S. Nuclear Regulatory Commission, October 2014. (ADAMS Accession No. ML14279A349)

75. Westinghouse Report WCAP-9875, Revision 0, “Analysis of the Maine Yankee Reactor Vessel Second Accelerated Surveillance Capsule,” March 1981.

76. Westinghouse Report WCAP-14279, Revision 1, “Evaluation of Capsules from the Kewaunee and Capsule A-35 from the Maine Yankee Nuclear Plant Reactor Vessel Radiation Surveillance Programs,” September 1998.

77. Westinghouse Report WCAP-16641-NP, Revision 0, “Analysis of Capsule T from the Dominion Energy Kewaunee Power Station Reactor Vessel Radiation Surveillance Program,” October 2006.

78. Westinghouse Report WCAP-16609-NP, Revision 0, “Master Curve Assessment of Kewaunee Power Station Reactor Pressure Vessel Weld Metal,” October 2006. (ADAMS Accession No. ML063250418)

79. PWROG Report ANP-2650, “Updated Results for Request for Additional Information Regarding Reactor Pressure Vessel Integrity,” July 2007. (ADAMS Accession No. ML072250093)

80. Sokolov, M., “Use of Mini-CT Specimens for Fracture Toughness Characterization of Low Upper-Shelf Linde 80 Weld Before and After Irradiation,” Proceedings of the ASME 2018 Pressure Vessels and Piping Conference, PVP2018-84804, July 2018.

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

APPENDIX C
EXAMPLE APPLICATIONS

Master curve test data is available on some irradiated materials which is used to demonstrate the application of this methodology for two shut-down RPVs. This Appendix details a few examples of how the methodology described in the body of report is applied using preexisting data sets. The examples demonstrate the homogeneity screening procedure and high flux validation material process.

The first example shown in Section C.1 uses data from weld Heat # 1P3571 that is applicable to the Kewaunee RPV beltline circumferential weld. As discussed in subsection 2.3.2, irradiated T_0 data was used in a method accepted by the NRC. The same data used in [30] along with additional irradiated T_0 measurements are assessed using the methodology described in this report and compared to the previous Kewaunee NRC-accepted method results from [30].

The second example shown in Section C.2 uses data from Linde 80 weld wire Heat # 72105 which was used in constructing the Midland Unit 1 RPV and irradiated in both Michigan's Ford MTR and in PWRs. The results are applied to the Crystal River Unit 3 RPV.

~~Note that due to timing, the examples herein were completed using the 2019 version of ASTM E1921. The only difference between ASTM E1921-19 and ASTM E1921-20 for the purposes of these examples are related to rounding differences of coefficients in certain ASTM E1921 equations. These rounding differences do not result in any significant differences to the values reported herein, thus reference to ASTM E1921-20 is maintained in this appendix for consistency with the body of the report.~~

C.1 KEWAUNEE WELD 1P3571

This example is for the Kewaunee circumferential RPV weld Heat # 1P3571. Three sets of specimens tested for T_0 were irradiated in a PWR and one set was irradiated in an MTR. The use of the master curve method for this material was approved by the NRC [30]. There are some commonalities between the methodology presented herein and that accepted by the NRC for Kewaunee; therefore, this example provides a relevant comparison. Since the original analysis was approved by the NRC, additional testing was performed and the previous analyses were updated using the NRC approved methodology, the required input information is provided primarily in WCAP-9875 [75], WCAP-14279 [76], WCAP-16641-NP [77] and WCAP-16609-NP [78] for the PWR irradiations.

To test the feasibility of the approach herein and to provide MTR comparison data, mini-C(T) specimens were machined from unirradiated archive Maine Yankee RPV surveillance Heat # 1P3571 in 2018, shipped to SCK-CEN in Belgium, irradiated in the BR2 MTR, returned to Westinghouse Churchill in Pittsburgh, PA and tested for T_0. ASTM E1921-20 calculations of T_0~~,~~ and homogeneity screening, T_{0IN}, ~~and specimen geometry bias~~ are shown in Table C-1 for Weld 1P3571 specimens irradiated in Kewaunee Capsule T, Kewaunee Capsule S, Maine Yankee Capsule A-35, and in the BR2 MTR. All four data sets have enough data for a valid T_0. Data from Capsules T, A-35, and BR2 fail the ASTM E1921-20 paragraph 10.6.3 Homogeneity Screening Procedure, while data from Capsule S passes it. The 12 tests from Capsule T fall under ASTM E1921-20 paragraph X5.2.2 and $T_{0IN} = T_{0scrn}$. Since the number of tests for Capsule A-35 and BR2 are 9 or less, ASTM E1921-20, paragraph X5.2.1 applies. In both cases, $T_{0max} - T_{0scrn}$ is less than 8ºC (14.4ºF), therefore $T_{0IN} = T_{0scrn}$. In all three inhomogeneous cases, $T_{0IN} > T_{0max}$, the margin is set to 0. For the homogeneous Capsule S data set, σ_{test} is the ASTM E1921-20 margin adjustment (σ_{E1921}). All the PWR irradiated test specimens were Charpy 3PB, therefore ~~an~~ 18ºF was ~~bias is~~ added to each test temperature to~~in~~ calculate~~ing~~ T_0. The BR2 irradiated specimens were C(T)s~~, therefore no bias is added~~.

Table C-1: Calculation of T_0 per ASTM E1921-20 for Weld 1P3571

	Capsule T	**Capsule S**	**Capsule A-35**	**BR2-MTR**
Toughness Data Source	WCAP-16641-NP Table C-1	WCAP-16609-NP Table A-2	WCAP-16609-NP Table A-3	Westinghouse
Number of Tests	12	12	8	9
T_0 (°F)	179.1~~160.6~~	**163.8~~145.5~~**	243.8~~225.3~~	146.5~~1~~
Valid per ASTM E1921-20, paragraph 10.5	Yes	Yes	Yes	No*
T_{0scrn} per ASTM E1921-20, paragraph 10.6 (°F)	230.5~~11.3~~	169.7~~50.8~~	2~~5~~76.4~~7.7~~	192.6~~1.8~~
Screening criterion ASTM E1921-20, paragraph 10.6.3 (°F)	14.1~~0~~	13.5	17.6	16.2
Homogeneous	No	Yes	No	No
T_{0IN} Calculation ASTM E1921-20, Appendix X5	X5.2.2	Not applicable	X5.2.1	X5.2.1
T_{0IN} (°F)	**230.5~~11.3~~**	Not applicable	**276.4~~57.7~~**	**192.6~~1.8~~**
T_{0max} (°F) paragraph X5.2.1	220~~2~~.0	Not applicable	273.6~~55.6~~	176.0
σ_{test} per subsection 4.4.1 (°F)	0.0	11.8	0.0	0.0
T_{0IN} or T_0 ~~+ Bias~~ (°F)	230.5~~29.3~~	163.8~~5~~	276.4~~5.7~~	192.6~~1.8~~

*Seven of the nine tests used in calculating T_0 exceeded the allowable ASTM E1921-20 final precrack K (20 MPa√m) by up to 15%. Because the final precrack K exceeded the limit by a relatively small magnitude and the measured K_{Jc} values are substantially higher than the actual precrack K, the T_0 result is considered to be representative of a valid result for this example.

To represent a typical case where only one capsule with fracture toughness data is available, the irradiated samples the BR2 MTR irradiation are validated against the A-35 Maine Yankee irradiation as though only the Capsule A-35 data is available in Table C-2. The 1P3571 specimens from the BR2 MTR irradiation had a reported average temperature of 288° ± 5°C (550° ± 9°F). The ETC predicted shift is calculated for Capsule A-35 irradiation using the Maine Yankee reactor vessel surveillance program (RVSP) chemistry. Comparing the BR2 MTR irradiation to the A-35 irradiation results, the adjusted T_{0IN} (Table C-2) for BR2 is slightly lower than the A-35 result resulting in~~making~~ ~~. Since σ_{test} for both sets is 0.0,~~ the inequality from Equation 8~~7~~ ~~is~~ not being satisfied. Therefore, if any other materials from the same grouping which were irradiated in the BR2 irradiation, with Heat # 1P3571 as the validation set, the MTR adjustment from Equation 9~~8~~ would be used. For this example, Equation 9~~8~~ results in the following:

$$\text{Adjusted } T_{0\text{high flux}} = \left\{\frac{(276.4\cancel{5.7} - 271.6\cancel{0.9})}{234.5}\right\} \cdot \Delta T_{30\text{ RPV}\cancel{\text{high flux}}} + T_{0\text{high flux}}$$

Thus, the BR2 MTR irradiation should be increased by the above 2.1% to be representative of a PWR irradiation, and a material from the same Section 4.1 high Cu grouping could be used from this irradiation with the above MTR adjustment for an RPV integrity evaluation.

Table C-2: Validation of BR2 Irradiated RVSP Weld 1P3571 Against Capsule A-35

Input	**BR2-MTR**	**Capsule A-35**	**Source**
Cu (wt%)	0.351	0.351	WCAP-16609
Ni (wt%)	0.771	0.771	WCAP-16609
Mn (wt%)	1.380	1.380	WCAP-9875
P (wt%)	0.015	0.015	WCAP-9875
Fluence (E19 n/cm^2)	3.15	6.11	WCAP-16609
Temperature (°F)	550	532	WCAP-16609
Shift (°F)	234.5	313.6	ASTM E900-15 ETC*1.0
Adjustment (°F)	79.1	0.0	ETC_{PWRVM} - $ETC_{highfluxVM}$
Measured T_0 (°F)	192.6~~1.8~~	276.4~~57.7~~	Based on T_0
~~Charpy 3PB Bias (°F)~~	~~0.0~~	~~18.0~~	~~ASTM E1921-20~~
Adjusted T_0 (°F)	**271.6~~0.9~~**	**276.4~~5.7~~**	T_0 + Adjustment ~~+ Bias~~

As a second example for the purpose of demonstrating how multiple data sets would be considered, Table C-3 compares the Kewaunee RVSP weld (also weld Heat # 1P3571) irradiated in Kewaunee Capsules T and S to the BR2 MTR irradiation. In comparing the adjusted T_0 MTR data to Kewaunee Capsule T, the BR2 adjusted T_0 is lower than Capsule T T_0. ~~Since σ_{test} is 0°F for Capsule T and BR-2, t~~The inequality of Equation 8~~7~~ is not satisfied as it yields a result of 204.5~~3.8~~°F ≥ 230.5~~29.3~~°F. When considering Kewaunee Capsule S compared to BR-2, the Equation 8~~7~~ inequality is satisfied yielding 184.1~~3.4~~°F ≥ 163.8~~39.9~~°F. For the Maine Yankee Capsule A-35, the Equation 8~~7~~ inequality is not satisfied yielding 271.6~~0.9~~°F ≥ 276.4~~5.7~~°F. When adding these three inequalities together, the result is 660.2~~58.1~~°F ≥ 670.8~~44.9~~°F. The sum is nonconservative by 10.6°F. Dividing by 3 (to average for the number of PWR capsule comparisons) and by 234.5°F as per Equation 9 results in 1.5%. Therefore the Kewaunee average material data demonstrates that the BR2 irradiation is also nonconservative and increasing it by 1.5% would make it representative of a PWR irradiation.~~Thus, consideration of all the capsules together demonstrates that the BR2 irradiation is representative and no adjustment to the BR-2 data would be required if all the data is considered together.~~

~~In both the Table C-2 Capsule A-35 and the Table C-3 Kewaunee T and S comparisons, the BR2 irradiated adjusted result comes very close to the result from samples irradiated in PWRs.~~

Table C-3: Validation of BR2 Irradiated Weld 1P3571 Against Kewaunee Capsules T and S

Input	BR2-MTR	Kewaunee T	BR2-MTR	Kewaunee S	Source
Cu (wt%)	0.351	0.219	0.351	0.219	WCAP-16609
Ni (wt%)	0.771	0.724	0.771	0.724	WCAP-16609
Mn (wt%)	1.380	1.37	1.380	1.37	WCAP-14279 Table 4-1
P (wt%)	0.015	0.016	0.015	0.016	WCAP-14279 Table 4-1
Fluence (E19 n/cm^2)	3.15	5.62	3.15	3.67	WCAP-16609
Temperature (°F)	552	532	550	532	WCAP-16609
Shift (°F)	234.5~~0.4~~	246.4	234.5~~0.4~~	226.1	ASTM E900-15 ETC*1.0
Adjustment between BR2 and Kewaunee (°F)	11.9~~6.1~~	0.0	-8.4~~4.3~~	0.0	ETC_{PWRVM} - $ETC_{highfluxVM}$
Measured T_0 (°F)	192.6~~1.8~~	230.5~~11.3~~	192.6~~1.8~~	163.8~~45.5~~	Based on T_0
Adjusted T_0 (°F)	**204.5~~3.8~~**	**230.5~~29.3~~**	**18~~3.4~~4.1**	**163.8~~5~~**	T_0 + Adjustment ~~+ Bias~~

The chemistry and irradiation conditions of the irradiated specimens and RPV at the fluence of interest are different. The irradiated specimen source chemistry and RPV weld best estimate chemistry are shown in Table C-4. The average irradiation temperature, EFPY, and fluence of the specimens and the RPV at 51 EFPY are also shown in Table C-4. These inputs are used to make an ETC predicted shift for the tested material and the RPV weld of interest using ASTM E900-15. The difference in ΔT_{30} between the irradiated samples and the RPV is multiplied by the $\Delta T_0/\Delta T_{30}$ slope in subsection 4.3.5 of this topical report (for welds slope = 1.0) and is then used as the adjustment as shown in Table C-4. The adjustment of each test material to the RPV consists of the difference between the RPV prediction and the test material predicted shift as discussed in Section 4.3 of this topical report. ~~For the purposes of this example, the 2% increase from the Capsule A-35 validation is utilized as though the Capsule A-35 data were the only data available. As previously discussed, when all of the capsule data was considered together,~~ The BR2 material gets an additional adjustment for the MTR effect when it was compared to the A-35 capsule of 1.5% of the predicted high flux (MTR) shift.~~the BR-2 irradiation was considered representative and no MTR increase is required.~~

Table C-4: Adjustment to Kewaunee Circumferential Weld 1P3571

	Capsule T	**Capsule S**	**Capsule A-35**	**BR2-MTR**	**RPV Weld**	**Source**
Cu (wt%)	0.219	0.219	0.351	0.351	0.287	WCAP-16609
Ni (wt%)	0.724	0.724	0.771	0.771	0.756	WCAP-16609
Mn (wt%)	1.370	1.370	1.380	1.380	1.370	WCAP-9875, WCAP-14279 Table 4-1
P (wt%)	0.016	0.016	0.015	0.015	0.016	WCAP-9875, WCAP-14279 Table 4-1
Fluence (E19 n/cm^2)	5.62	3.67	6.11	3.15	4.70	WCAP-16609
Temperature (°F)	532	532	532	550	532	WCAP-16609
Predicted ΔT_{30} (°F)	246.4	226.1	313.6	234.5*1.0~~2~~15	297.4	ASTM E900-15 ETC*1.0
Adjustment (°F)	51.0	71.3	-16.2~~9.5~~	59.4~~7.9~~		ETC_{RPV} - $ETC_{Specimen}$

Since T_{0IN} for the Capsule T, A-35, and BR2 data sets is greater than T_{0max}, then σ_{test} = 0°F, while the homogenous Capsule S data set includes the E1921-20 prescribed $\sigma_{test.}$ For three of the four capsules, the adjustment is greater than σ_{ETC}; therefore, $\sigma_{\cancel{additional}adjustment}$ is included in the margin as well as shown in Table C-5. Since Kewaunee Capsules T and S were irradiated in the Kewaunee RPV, the irradiation temperature is controlled by the cold leg temperature, the same as the RPV and therefore, $\sigma_{tempspecimens}$ = 0 for these two capsules. For Capsule A-35 irradiated in the Maine Yankee RPV, an uncertainty for this independent irradiation temperature is included. For the BR2 irradiation, the uncertainty of the irradiation temperature was reported as 5°C (9°F). The Capsules S and T fluence uncertainty is obtained from Table A-6 of WCAP-16641 [77] and the RPV fluence uncertainty is obtained from page 6-8 of [77]. The Capsule A-35 fluence uncertainty is obtained from page 6-10 of [75]. The BR2 fluence uncertainty is assumed to be 8%. Each of the uncertainties identified in Table C-5 are combined using the SRSS and then multiplied by two to determine the total margin for ~~a capsule~~each measurement (shown in the last row of Table C-5).

Table C-5: Margins for Kewaunee Circumferential Weld 1P3571

Uncertainty	Kewaunee T	Kewaunee S	MY A-35	BR2-MTR	Uncertainty Basis, Section 4.4
σ_{test} (°F)	0.0	11.8	0.0	0.0	Subsection 4.4.1
$\sigma_{adjustment\cancel{additional}}$ (°F)	3.3~~1.2~~	3.4~~1.7~~	0.~~0~~6	3.3~~1.5~~	~~If adjustment exceeds σ_{ETC} = 34.8°F, then c~~Calculated per subsection 4.4.2
$\sigma_{tempspecimens}$ (°F)	0.0	0.0	6.4	19.9	Kewanee capsules 0°F, 2°F for MY A-35 and 9°F for BR2
$\sigma_{tempRPV}$ (°F)	6.0	6.0	6.0	6.0	2°F
$\sigma_{fluencespecimens}$ (°F)	3.3	2.6	4.6	2.6	6%, 6%, 8%, 8% [77 and 75]
$\sigma_{fluenceRPV}$ (°F)	6.2	6.2	6.2	6.2	13% [77]
Total Margin (°F)	19.7~~8.6~~	30.5~~29.9~~	23.4	44.1~~3.7~~	2*SRSS

The measured irradiated reference temperature adjusted to the peak fluence location for the Kewaunee Heat # 1P3571 circumferential weld including ~~bias and~~ margin ensures a bounding result as shown in Table C-6. Each result is considered bounding and the weighted average ~~may be~~is used, since there is more than one capsule (~~four~~three PWR irradiations in this case). ~~Alternatively, the Capsule A-35 results could be used alone, since the irradiation conditions most closely match the RPV irradiation as evidenced by the closest ETC prediction to the RPV ETC prediction in Table C-4.~~ For Code Case N-830 the adjusted T_0 plus Total Margin is used, and for RT_{T0}, 35ºF is added for use with 10 CFR 50.61 and ASME Section XI, Appendix G evaluations.

The results from Table C-6 are compared to the Kewaunee NRC approved method with the new capsule data obtained from WCAP-16609 [78]. The NRC method used shift predictions in RG 1.99, Revision 2 [21]. As expected, the adjustment differs using the ASTM E900-15 ETC versus the RG 1.99, Revision 2 method used in the NRC approved Kewaunee method [78]. For the methodology in this topical report, the PCVN bias is larger than the value used in the NRC approved methodology (8.5ºF), while the margin term is smaller in this example. However, there is more margin in the methodology in this topical report due to the use of the T_{0IN} values. In total, ~~on~~ the weighted average~~, the~~ RT_{T0} value of 318.5~~20.0~~°F is considerably larger (more conservative) than the updated results using the NRC approved Kewaunee method, which resulted in an RT_{T0} value of 291.1°F. The individual capsule by capsule results are also conservative compared to the NRC approved method in WCAP-16609-NP [78].

As an example, Table C-6a shows the calculation of w_i for the Kewaunee capsule T according to Equation 4a. The ASTM E900-15 shift is calculated for the RPV, except that each of the ASTM E900-15 inputs is changed to the test material condition one input at a time to calculate each individual input effect on the shift. The bold inputs in Table C-6a are changed to Capsule T, the other inputs are the RPV best-estimate condition. The ASTM E900-15 calculated shift described above is subtracted from the RPV condition, then the absolute values of each difference are summed. The process shown in Table C-6a is done for the other two PWR irradiation conditions with the w_i values shown in Table C-6. Since there is PWR irradiated T_0 data, the BR2-MTR data should not be used with the weighting factor set to 0. To calculate the weighted average each w_i is multiplied by each T_{0i} (or RT_{T0i}) + $adjustment_i$ + $margin_i$ value and divided by the sum of w_i values according to Equation 4b.

Table C-6: Kewaunee Circumferential Weld 1P3571 Application of Direct Fracture Toughness

Input	Kewaunee T	Kewaunee S	MY A-35	BR2-MTR	Source
T_{0IN} or T_0 ~~+ Bias~~ (°F)	230.5~~29.3~~	163.8~~5~~	276.4~~5.7~~	192.6~~1.8~~	Table C-1
Adjustment (°F)	51.0	71.3	-16.2	59.4~~7.9~~	Table C-4
Total Margin (°F)	19.7~~8.6~~	30.5~~29.9~~	23.4	44.1~~3.7~~	Table C-5
T_{0i} + Adjustment$_i$ + Margin$_i$ (°F)	301.2~~298.9~~	265.6~~4.7~~	283.7~~2.9~~	296.1~~3.5~~	Code Case N-830
RT_{T0i} + Adjustment$_i$ + Margin$_i$ (°F)	336.2~~3.9~~	300.6~~299.7~~	318.7~~7.9~~	331.1~~28.5~~	Section XI, Appendix G
Weighting (w_i)	0.76	0.76	0.95	0.0	Table C-6a & Equation 4a
Bounding RT_{T0} for RPV Weld 1P3571	318.5~~320.0~~				Weighted Average
NRC Method $ART_{T0\text{-}X\text{-}Y\text{-}cap}$	302.1	293.3	277.8	NA	WCAP-16609-NP
Average	291.1				

Table C-6a: Kewaunee Capsule T Weighting Factor Calculation

(**bold text** = Capsule T value; normal text = RPV value)

Input	Cu	Ni	Mn	P	Fluence	Temperature
Cu (wt%)	**0.219**	0.287	0.287	0.287	0.287	0.287
Ni (wt%)	0.756	**0.724**	0.756	0.756	0.756	0.756
Mn (wt%)	1.370	1.370	**1.370**	1.370	1.370	1.370
P (wt%)	0.016	0.016	0.016	**0.016**	0.016	0.016
Fluence (1E19 n/cm^2)	4.70	4.70	4.70	4.70	**5.62**	4.70
Temperature (°F)	532	532	532	532	532	**532**
ETC ΔT_{30} (°F)	240.6	293.1	297.4	297.4	306.6	297.4
Difference from RPV shift Table C-4 (°F)	56.8	4.3	0.0	0.0	-9.2	0.0
Sum of absolute differences = 70.2 °F						
Divide by the RPV shift in Table C-4 and subtract from one: w_i = 1 – 70.2 / 297.4 = 0.76						

When using T_{0IN} with σ_{test} = 0 for the Capsule T data set and the 5% lower bound curve (labelled as N-830 Capsule T), all the data is bounded as shown in Figure C-1. By "bounded" it is meant that the curve falls "below" all the data points obtained from testing. Each N-830 curve is shown for each respective data set with the corresponding σ_{test} per Table 3 in subsection 4.4.1. In each case, all the data is bounded by the N-830 curve showing the robustness of the methodology. The ASME Section XI, Appendix G RT_{T0} and K_{Ic} curve also bounds the data.

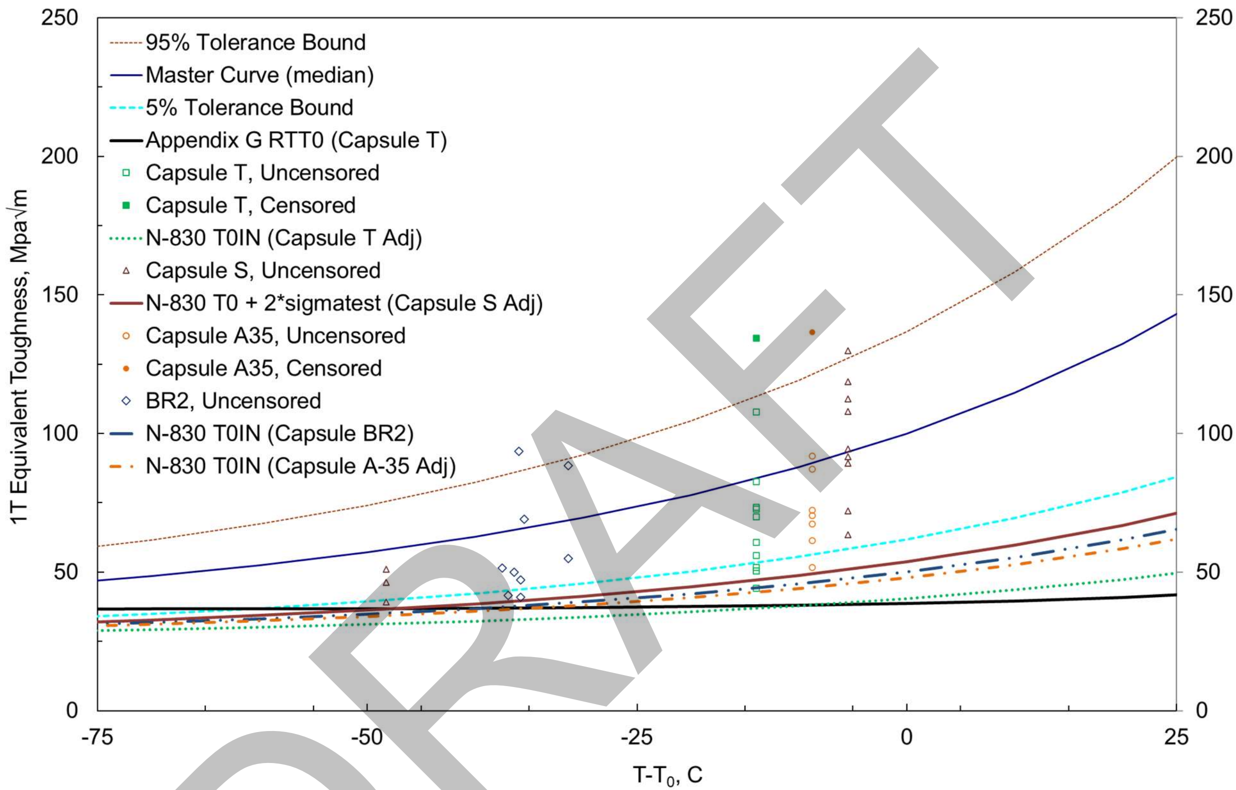

Figure C-1: Kewaunee Heat 1P3571 Irradiated Toughness Data Showing Bounding Curves Developed Using ASTM E1921-20 and ASME Section XI

C.2 LINDE 80 WELD HEAT 72105

An example is presented for the Linde 80 weld wire Heat 72105 weld Flux 8669 combination, identified as WF-70. This weld heat was used in the Crystal River Unit 3 (CR-3) upper-shell to lower-shell circumferential RPV weld. This heat was also used in the Midland Unit 1 RPV for the beltline and nozzle course circumferential welds [65], which~~. This RPV~~ was never in operation and ORNL removed sections of the beltline and nozzle course welds both fabricated with WF-70. The range and average Cu content of the beltline and nozzle course welds are significantly different (Table 2 [65]), but both are in the high Cu category per the criterion presented in Section 4.1. Since they are in the same Cu category, one could be used as a validation material for the other, as if they were from different heats. ORNL irradiated fracture toughness specimens from both welds in the Michigan's Ford Nuclear Reactor to an approximate fluence of 1 x 10^{19} n/cm^2 in two capsules, which is the equivalent of 0.5 EFPY.

C.2.1 Nozzle Course Weld MTR Validation

The WF-70 Midland Unit 1 nozzle dropout (ND) WF-70 weld was irradiated in CR-3 in a supplemental capsule. This is the same weld as the nozzle course irradiated in the Ford MTR and tested by ORNL.

There were 30 tests performed on the nozzle course weld irradiated in the Ford MTR by ORNL (Table 15 [65]). T_0 for all the data is 140.3~~2.0~~ºF and is homogeneous; therefore, σ_{test} = 9.5ºF per ASTM E1921-20 (see Section 4.4 and Table C-7). Since there are 30 tests, the results can be broken into two smaller groups to evaluate the typical number of irradiated specimens tested (~8-20). Both of the smaller group results are within $2\sigma_{test}$ of the "All Data" data set as expected (Table C-7) and all pass the homogeneity screening criterion. The T_0 calculation and screening result for the same nozzle course weld irradiated in the B&W CR-3 capsule is shown in Table C-7. The Cu level of the nozzle course (Cu = 0.39%) is above the saturation level (Cu ~ 0.28%); therefore, any variation in Cu content does not cause varying embrittlement effects. This explains why all the nozzle course data sets were determined to be homogenous.

Table C-7: Calculation of T_0 per ASTM E1921-20 for Midland Nozzle Course Weld

	ORNL Ford Reactor All Data	**ORNL Ford Reactor Subset with Test Temps. 65ºC & 75ºC**	**ORNL Ford Reactor Subset with Test Temps. 25ºC & 45ºC**	**B&W CR-3 Capsule**
Toughness Data Source	Table 15 [65]	Table 15 [65]	Table 15 [65]	Table D-4 [31]
Number of Tests	30	12	16	10
T_0 (ºF)	140.3~~32.0~~	147.0~~6.6~~	135.6~~23.3~~	~~67.6~~82.0
Valid per ASTM E1921-20 paragraph 10.5	Yes	Yes	Yes	Yes
T_{0scrn} per ASTM E1921-20 paragraph 10.6 (ºF)	140.0~~37.7~~	147.0~~6.6~~	135.6~~23.3~~	~~69.8~~88.3
Screening Criterion ASTM E1921-20 paragraph 10.6.3 (ºF)	8.8	13.5	12.2	15.4~~5~~
Homogeneous	Yes	Yes	Yes	Yes
T_{0IN} Calculation ASTM E1921-20 Appendix X5	Not applicable	Not applicable	Not applicable	Not applicable
T_{0IN} (ºF)	Not applicable	Not applicable	Not applicable	Not applicable
T_{0max} (ºF)	Not applicable	Not applicable	Not applicable	Not applicable
σ_{test} per Section 4.4 (ºF)	9.5	11.8	11.1	12.9
T_{0IN} or T_0 + Bias (ºF)	140.3~~37.8~~	147.0~~6.6~~	135.6~~3.4~~	82.0~~78.4~~

Next, the ETC predicted shift is calculated for each material from Table C-7 using the source average chemistry for the irradiated samples so that the MTR irradiation can be validated against the B&W PWR irradiation. The adjusted T_0 comparing the Ford MTR WF-70 Nozzle Course Weld irradiation to the B&W CR-3 Capsule irradiation results in a higher adjusted T_0 for the Ford MTR irradiation (Table C-8). Therefore, the Ford MTR irradiation is conservative, and a similar material can be used from this irradiation without any flux effect adjustment for RPV integrity evaluation. The fracture toughness specimen average fluence was 1.35 x 10^{19} n/cm^2 at 556ºF for the CR-3 irradiation. The set irradiated to 1.59 x 10^{19} n/cm^2 does not have enough specimens for a valid T_0; therefore, even though the fluence of the other set is lower at 1.19 x 10^{19} n/cm^2, they are combined for the purposes of this example to provide a larger number of specimens to provide a higher confidence in T_0.

Table C-8: Validation of Ford MTR Irradiated WF-70 Nozzle Course Weld

Input	Ford Reactor MD1 Nozzle Course	CR-3 Irradiated MD1 ND	Source [65 and 79]
Cu (wt%)	0.396	0.390	NUREG/CR-5736 / ANP-2650
Ni (wt%)	0.572	0.580	NUREG/CR-5736 / ANP-2650
Mn (wt%)	1.590	1.630	NUREG/CR-5736 / ANP-2650
P (wt%)	0.015	0.018	NUREG/CR-5736 / ANP-2650
Fluence (E19 n/cm^2)	1.00	1.35	NUREG/CR-5736 / ANP-2650
Temperature (°F)	550	556	NUREG/CR-5736 / ANP-2650
Shift (°F)	189.5	183.7	ASTM E900-15 ETC*1.0
Adjustment (°F)	-5.9	0.0	ETC_{PWRVM} - $ETC_{highfluxVM}$
Measured T_0 (°F)	140.3~~32.0~~	~~67.6~~82.0	Based on T_0
Adjusted T_0 (°F)	134.5~~32.0~~	~~78.4~~82.0	T_0 + Adjustment ~~+ Bias~~

C.2.2 Beltline Weld MTR Validation

Fracture toughness tests were performed on the Midland Unit 1 beltline weld irradiated in the Ford MTR. Combined, there were 111 tests conducted originally by ORNL (Table 14 [65]) and more recently a round robin was conducted with four participating laboratories on the same material using mini-C(T) specimens [56, 68, and 80] machined from the broken Charpy specimens. T_0 for the whole data set was determined to be inhomogeneous per ASTM E1921-20, paragraph 10.6.3: T_{0IN} = 103.1~~98.6~~ºF and σ = 8.3ºF per ASTM E1921-20, Section 10.9. Since there are 111 tests, the results were broken into several smaller groups for the purposes of this example to evaluate the typical number of specimens which might be irradiated and tested. Any group could be used in an assessment, if other specimens were not available. Most groups were identified as non-homogenous. Using the methodology described in Sections 4.2 and 4.4.1, the values in **bold** in Table C-9 are combined with ~~Charpy bias and~~ $2\sigma_{test}$ and shown in the last column of the table. Each T_0 ~~+ bias~~ + $2\sigma_{test}$ subset is within $2\sigma_{E1921}$ of "All data" except for one data set which is very conservative; thus, demonstrating the success of the methodology in producing consistent results with varying data sets (Table C-9).

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

Midland Unit 1 Beltline Weld	#	Homo-geneous	T_0 (ºF)	σ_{E1921} (ºF)	T_{0IN} (ºF)	T_{0max} (ºF)	σ_{test} (ºF)	T_0 or T_{0IN} ~~+ Bias~~ + $2\sigma_{test}$ (ºF)
All data	111	No	~~59.0~~60.9	8.3	**~~98.6~~103.1**	-	**8.3**	119.7~~8.1~~
Lab A mini-C(T) [68]	13	Yes	**94.~~6~~9**	14.7	~~-~~94.9	~~82.6~~-	**14.7**	124.3~~.9~~
Lab B mini-C(T) [68]	13	-	Invalid	-	-	-	-	-
Lab C mini-C(T) [80]	12	No	58.5~~2~~	14.0	**83.8~~5~~**	108.3	**12.2~~4~~**	108.3
Lab D mini-C(T) [56]	13	No	94.7~~3~~	13.5	**127.6~~2~~** *	133.1	**2.8~~9~~**	133.1
>50ºC 1TC(T) [65]	27	No	80.8~~4~~	12.5	**~~93.4~~96.1**	112.7	**~~9~~8.3~~.6~~**	112.7
35ºC & 20ºC [65] 1TC(T) & 1/2TC(T)	12	Yes	**87.9~~5~~**	11.8	~~-~~95.0	-	**11.8**	111.5~~1~~
22ºC 1TC(T) & 3PB Charpy [65]	13	No	~~76.8~~95.7	13.5	**~~105.4~~122.5**	~~107.1~~ 125.1	**~~0.9~~1.3**	125.1~~120.9~~
0ºC 3PB Charpy [65]	8	Yes	**~~105.6~~123.9**	14.7	~~-~~132.4	~~95.9~~-	**14.7**	153.3 ~~152.9~~

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

When using the lowest T_0 ~~+ bias~~ + $2\sigma_{test}$ subset (least conservative) from Table C-9 and the 5% lower bound curve, 96~~8~~% of the data is bounded. Figure C-2 demonstrates how well the ASME XI, N-830, and RT_{T0} curves bound the data. The other data sets in Table C-9 have higher T_0 + ~~bias +~~ $2\sigma_{test}$ values and are therefore more conservative than where the 5% lower bound curve is shown demonstrating the robustness of the methodology.

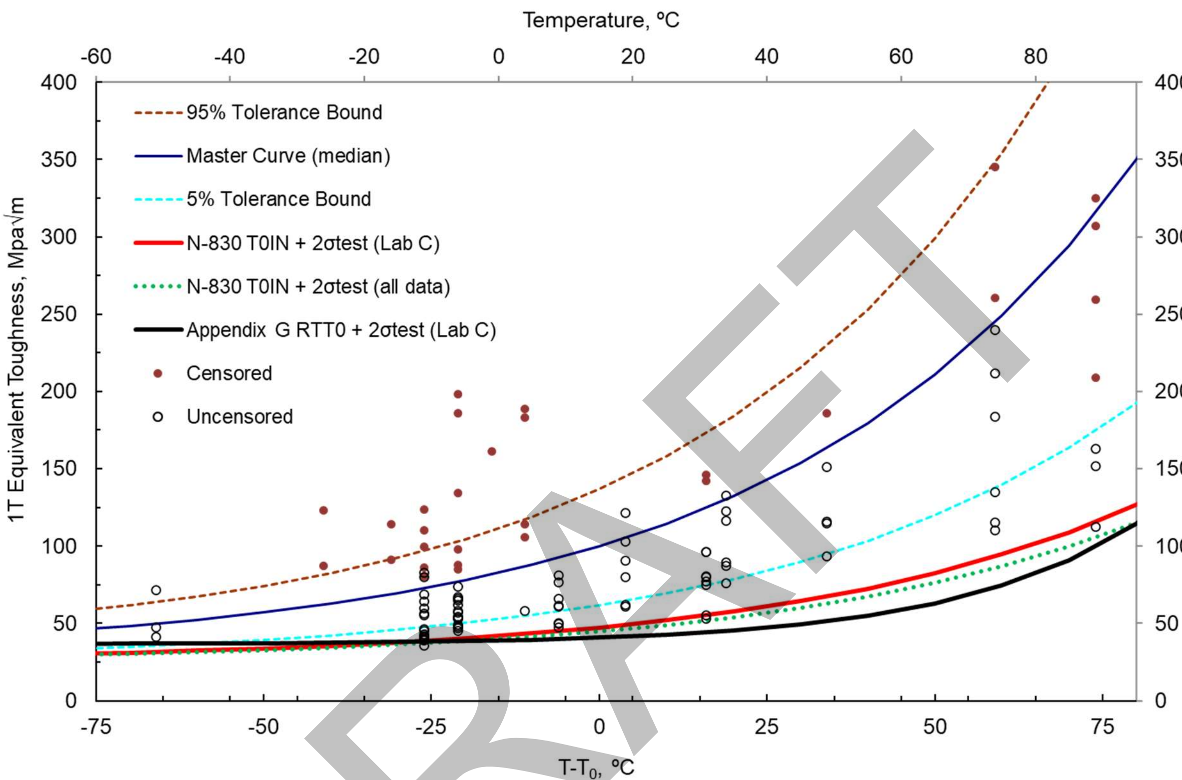

Figure C-2: Irradiated WF-70 Midland Beltline Weld Toughness Data Showing Bounding Curves Developed Using ASTM E1921-20 and ASME Section XI

The WF-209-1 weld (Heat # 72105 weld flux Lot 8773 combination) was irradiated in the Zion Unit 1 RPV surveillance program in Capsule X and additionally irradiated in a supplemental capsule with the fracture toughness specimen fluence of 1.897 x 10^{19} n/cm^2 at an average temperature of 547ºF (547°F is not the time weighted average, but is sufficient for use as an example). The T_0 calculation result for WF-209-1 is shown in Table C-10.

Table C-10: Calculation of T_0 per ASTM E1921-20 for Linde 80 Beltline Weld 72105

	ORNL Ford Reactor All Beltline Data	Capsule X Zion 1 RVSP WF-209-1
Toughness Data Source	Table 14 [65]	Table D-4 [31]
Number of Tests	111	7
T_0 (ºF)	~~59.0~~60.9	~~90.0~~108.4
Valid per ASTM E1921-20 paragraph 10.5	Yes	Yes
T_{0scrn} per ASTM E1921-20 paragraph 10.6 (ºF)	103.1~~98.6~~	112.3~~94.3~~
Screening Criterion ASTM E1921-20 paragraph 10.6.3 (ºF)	5.9	18.4
Homogeneous	No	Yes
T_{0IN} Calculation ASTM E1921-20 Appendix X5	X5.2.2	Not applicable
T_{0IN} (ºF)	103.1~~98.6~~	Not applicable
T_{0max} (ºF)	Not applicable	Not applicable
σ_{test} per subsection 4.4.1 (ºF)	8.3	14.7
~~Charpy 3PB Bias (ºF)~~	~~18*18/111 = 2.9~~	~~18~~
T_{0IN} or T_0 ~~+ Bias~~ (ºF)	103.1~~01.5~~	108.4~~0~~

The adjusted T_0 values comparing the Ford MTR irradiation of the WF-70 beltline weld to the Zion Unit 1 Capsule X and supplemental capsule irradiation shows a higher adjusted T_0 for the Ford MTR irradiation (Table C-11) when using all the data. Therefore, the result of the Ford MTR irradiation is conservative, demonstrating that similar materials (high Cu) can be used from this irradiation without an MTR adjustment for an RPV integrity evaluation. This is the same conclusion reached when comparing the PWR and Ford MTR irradiation of the nozzle course weld at the end of Section C.2.1.

Table C-11: Validation of Ford MTR Irradiated WF-70 Beltline Weld

Input	Ford Reactor MD1 Beltline	Zion 1 RVSP WF-209-1	Source [65, 79, and 31]
Cu (wt%)	0.256	0.250	NUREG/CR-5736 / ANP-2650
Ni (wt%)	0.574	0.540	NUREG/CR-5736 / ANP-2650
Mn (wt%)	1.607	1.480	NUREG/CR-5736 / ANP-2650
P (wt%)	0.017	0.019	NUREG/CR-5736 / ANP-2650
Fluence (E19 n/cm^2)	1.00	1.90	NUREG/CR-5736
Temperature (°F)	550	547	NUREG/CR-5736
Shift (°F)	172.1	182.2	ASTM E900-15 ETC*1.0
Adjustment (°F)	10.1	0.0	ETC_{PWRVM} - $ETC_{highfluxVM}$
Measured T_0 (°F)	~~98.6~~103.1	~~90.0~~108.4	Based on T_{0IN} / T_0
~~PCCVN Bias (°F)~~	~~2.9~~	~~18~~	~~ASTM E1921-20~~
Adjusted T_0 (°F)	113.2~~1.7~~	108.4~~0~~	T_0 + Adjustment ~~+ Bias~~

The WF-70 weld is contained in the CR-3 RPV upper-shell to lower-shell circumferential weld. The methodology in this topical report is applied to this weld as an example. A projected fluence of 1.56×10^{19} n/cm^2 at 54 EFPY for 60 years is used for this example.

All four irradiations with T_0 values presented in Table C-8 and Table C-11 are adjusted to the CR-3 best estimate chemistry and irradiation conditions for the RPV weld as shown in Table C-12.

Table C-12: Adjustment to CR-3 Upper-Shell to Lower-Shell Circumferential WF-70 Weld

Input	Ford Reactor MD1 Nozzle Course	CR-3 Irradiated MD1 ND	Ford Reactor MD1 Beltline	Zion 1 RVSP WF-209-1	CR-3 US to LS Circ. Weld	Source [65, 79, and 31]
Cu (wt%)	0.396	0.390	0.256	0.250	0.320	NUREG/CR-5736 / ANP-2650
Ni (wt%)	0.572	0.580	0.574	0.540	0.580	NUREG/CR-5736 / ANP-2650
Mn (wt%)	1.590	1.630	1.607	1.480	1.630	NUREG/CR-5736 / ANP-2650
P (wt%)	0.015	0.018	0.017	0.019	0.018	NUREG/CR-5736 / ANP-2650
Fluence (E19 n/cm^2)	1.00	1.35	1.00	1.897	1.56	NUREG/CR-5736 / ANP-2650
Temperature (°F)	550	556	550	547	556	NUREG/CR-5736 / BAW-2308R1
Predicted ΔT_{30} (°F)	189.5	183.7	172.1	182.2	186.7	ASTM E900-15 ETC*1.0
Adjustment (°F)	-2.9	3.0	14.6	4.5	-	ETC_{RPV} - $ETC_{Specimen}$

There is a σ_{test} for all four data sets per subsection 4.4.1. ~~No adjustment is larger than the σ_{ETC} therefore $\sigma_{additional}$ = 0.~~ Since the MD1 ND was irradiated in the CR-3 RPV, the irradiation temperature is controlled by the cold leg temperature, the same as the RPV and therefore $\sigma_{tempspecimens}$ = 0 for this capsule. For the Ford MTR irradiation, the temperature standard deviation is reported in Table D2 [65] and varies by location, and is approximately 1°C; therefore, 2°F is used as the uncertainty for this independent irradiation temperature. The PWR capsule and the Ford MTR irradiation fluence uncertainty is not reported; therefore, for this example 7% is assumed. Likewise, the fluence uncertainty of the RPV calculation is not available; therefore, the maximum allowed by RG 1.190, which is 20%, is assumed. The effect of these uncertainties is determined using the ETC independently at each material chemistry and irradiation condition. The results are shown in Table C-13. Each of the uncertainties identified in Table C-13 is combined using the SRSS.

Table C-13: Margins for CR-3 Upper-Shell to Lower-Shell Circumferential WF-70 Weld

Uncertainty	Ford Reactor MD1 Nozzle Course	CR-3 Irradiated MD1 ND	Ford Reactor MD1 Beltline	Zion 1 RVSP WF-209-1	Uncertainty Basis Section 4.4
σ_{test} (°F)	9.5	12.9	8.3	14.7	Subsection 4.4.1
$\sigma_{adjustment\cancel{additional}}$ (°F)	~~0.0~~1.4	0.~~0~~2	~~0.0~~2.4	~~0.0~~3.3	~~Only needed if adjustment exceeds σ_{ETC} = 35.6°F per~~S~~s~~ubsection 4.4.2
$\sigma_{tempspecimens}$ (°F)	3.7	0.0	3.4	3.6	CR-3 capsule 0°F, 2°F for all others
$\sigma_{tempRPV}$ (°F)	3.6	3.6	3.6	3.6	2°F
$\sigma_{fluencespecimens}$ (°F)	2.7	1.4	2.5	1.8	7% assumed
$\sigma_{fluenceRPV}$ (°F)	4.1	4.1	4.1	4.1	20% assumed
Total Margin (°F)	23.9~~7~~	28.2	22.2~~1.6~~	33.1~~2.4~~	2*SRSS

The measured irradiated reference temperature adjusted to the peak fluence location for the CR-3 circumferential weld, including ~~bias and~~ margin, ensures a bounding result as shown in Table C-14. Each result is considered bounding and the weighted average ~~may be~~is used since multiple data sets are available. Since there is PWR irradiated T_0 data, the MTR data should not be used with the weighting factor set to 0. For Code Case N-830 the adjusted T_0 plus Total Margin is used, and for RT_{T0}, 35ºF is added for use in 10 CFR 50.61 and ASME Section XI, Appendix G evaluations. The bounding RT_{T0} for the RPV weld is compared to the CR-3 license renewal application 60-year RT_{PTS} in Table C-14.

Table C-14: Application of Methodology to the CR-3 Upper-Shell to Lower-Shell Circumferential WF-70 Weld

Input	Ford Reactor MD1 Nozzle Course	B&W Plant Irradiated MD1 ND	Ford Reactor MD1 Beltline	Zion 1 RVSP WF-209-1	Source
T_{0IN} or T_0 ~~+ Bias~~ (ºF)	140.3~~37.8~~	82.0~~78.4~~	103.1~~1.5~~	108.~~0~~4	Tables C-7 and C-10
Adjustment (°F)	-2.9	3.0	14.6	4.5	Table C-12
Total Margin (°F)	23.~~7~~9	28.2	22.2~~1.6~~	33.1~~2.4~~	Table C-13
T_0 + Adjustment + Margin (°F)	161.3~~58.7~~	113.2~~09.6~~	139.9~~7.8~~	146.0~~4.9~~	Code Case N-830
RT_{T0} + Adjustment + Margin (°F)	196.3~~3.7~~	148.2~~4.6~~	174.9~~2.8~~	181.0~~79.9~~	Section XI, Appendix G
Weighting (w_i)	0.0	0.98	0.0	0.75	Equation 4a and 4b
Bounding RT_{T0} for RPV Weld (°F)	162.4~~72.7~~				Average
CR-3 60-Year RT_{PTS} (°F)	253.8				License Renewal Application, Table 4.2-5 [81]