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An Examination of Margins Needed to Ensure Conservative Application of T_0 to RPV Fracture Toughness

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ABSTRACT

Variation in fracture toughness of a heavy-section reactor pressure vessel (RPV) steel plate, forging or weld can be caused primarily by processing and chemical composition variation. Understanding the variation is paramount to enable application of the ASTM E1921 measured ductile-brittle transition temperature, T_0, to RPV integrity evaluations. Variation in toughness in thick section forgings and plates can be caused by carbon segregation and through thickness by the quenching process. Variation in toughness can also be caused by variation in chemical composition of the elements that enhance irradiation embrittlement, primarily copper and nickel. The geometric scale of these variations varies. For example, carbon segregation in a large ring forging might be limited to one region while it is well documented that toughness increases near the surface where the cooling rate was high when quenching. For welds, copper and nickel might vary within and between weld beads and at least a significant portion of the variation is captured in a typical set of toughness specimens used to determine T_0. This paper will look at many datasets where at least two sets of specimen tests from which T_0 can be calculated are available from the same heat of steel. It will be assumed that one T_0 measurement is used as the direct fracture toughness measurement and the 2nd (or more) are measurements from the irradiated RPV represented by the irradiated ductile-brittle transition temperature fracture toughness test results. One T_0 measurement will be adjusted to the condition of the 2nd (or more) measured dataset with assessment of the margin needed to ensure an evaluation of the RPV would be bounding. This information will enable development of necessary margins in applying unirradiated and irradiated master curve fracture toughness measurements to an RPV component using relatively small samples.

Keywords: RPV toughness, embrittlement, master curve

1. INTRODUCTION

As nuclear RPVs are being used for longer times, the beltline ferritic steel continues to accumulate damage from high energy neutron exposure from the nuclear core. The neutron exposure continues to shift the ductile to brittle transition temperature (DBTT) to higher temperatures. Using the traditional approach of determining unirradiated RT_{NDT} plus predicted embrittlement shift and adding uncertainties in some cases can challenge regulatory limits for postulated pressurized thermal shock (PTS) events and can limit plant operations during normal heat up and cooldowns [1, 2 and 3].

Therefore, the industry has advanced more accurate ways of measuring and statistically quantifying the DBTT through direct measurement of fracture toughness. A voluntary international consensus committee on fracture approved this measurement method starting in 1997 as captured in ASTM E1921 [4]. Use of this measurement methodology has been adopted into ASME Code and Section III [5], Section XI [6] and Code Case N-830 [7]. The United States Nuclear Regulatory Commission (NRC) has endorsed the use T_0 in Section XI [8]. However, in Section XI, the use of T_0 is "…subject to the approval of the regulatory authority having jurisdiction at the plant site." [6 and 7]

The Pressurized Water Reactor Owners Group (PWROG) has developed a methodology for applying direct fracture toughness, T_0, to RPV integrity evaluation [9] in which NRC-approval is sought as required in ASME Section XI, Appendix G, subsection G-2110 and ASME Code Case N-830 paragraph *(f)*.

2. METHODOLOGY

The evaluation herein generally follows the approach taken in PWROG-18068 [9], although certain simplifications are made due to lack of specific test data or other information as described in each evaluation section. PWROG-18068 is currently under review by the NRC. At a high level, the PWROG topical report is planned to be used for fracture toughness evaluation of RPV integrity for Heat-up/Cool-down curves meeting 10 CFR 50 Appendix G and for PTS evaluations according to 10 CFR 50.61. The methodology prescribes acceptable methods to:

- Generate unirradiated or irradiated master curve reference temperature (T_0) data according to ASTM E1921-20,
- Account for differences between the tested material and RPV component using the ASTM E900-15 [10] embrittlement trend curve,
- Account for test result uncertainty and material variability in the respective RPV component, and
- Apply the data in a manner consistent with precedent and ASME Section XI Code.

The method described herein is a general description of the methodology described in PWROG-18068 with Reference 9 containing the details of this method. However, the final NRC approved methodology may have some differences as NRC staff requests for additional information are addressed. The PWROG-18068 methodology can be described using equation (1).

$$Bounding\ adjusted\ T_0 = T_0 + adjustment + margin \qquad (1)$$

2.1 Generation of T_0

PWROG-18068 requires the use of ASTM E1921-20 which includes a screening procedure for assessing datasets to detect inhomogeneous scatter. Datasets that fail the screening may be representative of a macroscopically inhomogeneous material and might not be adequately described by the Weibull statistics used to determine the certainty bounds in E1921 that were developed for homogeneous material. Therefore, E1921-20 provides Appendix X5 for assessing materials screened as inhomogeneous which is used by PWROG-18068. For materials screened as inhomogeneous, T_{0IN} is a biased T_0 that conservatively accounts for the material inhomogeneity.

2.2 Adjustment to Another Condition

Tested specimens will rarely reflect the same irradiation conditions and chemical composition as the represented RPV material. Therefore, adjustments are necessary to compensate for differences between test samples and the actual RPV materials. The embrittlement trend curve (ETC) contained in ASTM consensus Standard Guide E900-15 [10] is the most recent internationally accepted consensus standard for predicting RPV embrittlement shift based on the transition temperature at which the Charpy impact test 41J of energy (T_{41J}). ASTM E900-15 is used to account for any differences as shown in Equation (2).

$$adjustment = \left(\Delta T_{30\ RPV} - \Delta T_{30\ Specimens}\right) \bullet (If\ BM, 1.1) \quad (2)$$

where:

- If base metal (BM), then multiply by 1.1
- $\Delta T_{30\ RPV}$ = predicted ΔT_{30} of the RPV material at the fluence of interest using the ASTM E900-15 ETC
- $\Delta T_{30\ Specimens}$ = predicted ΔT_{30} of the tested specimens using the ASTM E900-15 ETC

In some cases, there is a measured difference between the average embrittlement shift in ΔT_{41} and ΔT_0. Since the ETC model used is based on ΔT_{41}, this average difference is accounted for by using a 1.1 multiplier for base metals. Welds on average show no difference between ΔT_{41} and ΔT_0. There is no industry accepted ETC model based on ΔT_0 that could be used therefore ΔT_{41} is used with the multiplier. The basis for this multiplier is beyond the scope of this paper and is presented in NUREG-1807 [11] and MRP-462 [12].

The prediction of embrittlement shift according to ASTM E900-15 requires the following inputs: fluence, average irradiation temperature, and RPV steel chemical composition (Cu, Ni, Mn, P). Use of E900-15 is limited to the range of these parameters contained in the underlying database of power RPV steels and irradiation conditions.

2.3 Margin

A margin term is added to account for uncertainties in the measurement of T_0, the adjustment uncertainty, irradiation temperature and fluence uncertainty of RPV for unirradiated T_0 measurements as shown in Equation (3).

$$Margin = 2\sqrt{\sigma_{E1921}^2 + \sigma_{adjustment}^2 + \sigma_{tempRPV}^2 + \sigma_{fluenceRPV}^2} \qquad (3)$$

- σ_{E1921} is the measurement uncertainty on T_0 per ASTM E1921 and is a function of the number of specimens tested and average toughness
- $\sigma_{adjustment}$ is the uncertainty in the embrittlement prediction as defined in ASTM E1900-15 * (1.0 for welds and 1.1 for base metals) and is a function of product form and ΔT_{41J}
- $\sigma_{tempRPV}$ is the effect of the uncertainty of the RPV irradiation temperature on embrittlement using the ASTM E900-15 prediction * (1.0 for welds or 1.1 for base metals)
- $\sigma_{fluenceRPV}$ is the effect of the uncertainty of the RPV fluence on embrittlement using the ASTM E900-15 prediction * (1.0 for welds or 1.1 for base metals)

When adjusting from irradiated T_0 measurements the irradiation temperature and fluence uncertainty effect of the tested specimens are also included. $\sigma_{adjustment}$ for adjustment from irradiated condition is the proportion of the adjustment relative to the predicted E900-15 ΔT_{41J} to which adjustment is made with a minimum value imposed.

3. MARGIN ASSESSMENT METHODOLOGIES

Three approaches are taken to assess the adequacy of the approach taken in the above-described methodology. In all three approaches, a measured T_0 is adjusted to the condition of an irradiated T_0 with margin added. The *Bounding adjusted T_0* is compared to 25.4 mm (1 inch) thick irradiated fracture toughness measurements (K_{Jc1T}) or the irradiated T_0 measurement to assess conservatism. The irradiated K_{Jc1T} and T_0 is assumed to represent the irradiated RPV. Both measured T_0 values were determined from specimens machined from different pieces of material from the same heat of RPV steel, thereby introducing within heat material variability into the evaluation. Secondly, since both conditions being assessed are measured T_0 values the adjustment and margin using the Charpy ΔT_{41J} based ASTM E900-15 is also tested.

The first application is for various through wall thickness measurements of T_0 from the decommissioned Zion Unit 1 RPV wall. The second uses a large database of T_0 measurements in the unirradiated and irradiated conditions. The third approach looks in more detail at two weld heats that were irradiated in different reactors and conditions where unirradiated and irradiated T_0 measurements were made.

3.1 Application to Zion Unit 1 RPV

A full thickness section of the RPV beltline plate (A533B2) of the decommissioned Zion Unit 1 was obtained by Oak Ridge National Laboratory (ORNL) [13, 14]. Zion Unit 1 had been operated for 25 years (15 effective full power years) and was shut down in 1998. Central Research Institute of Electric Power Industry (CRIEPI) tested mini-CT (4mm thick) specimens from several thickness locations of the irradiated RPV plate [15]. The test result obtained from the ¼ thickness (1/4T) location was adjusted to other thickness locations for which T_0 was measured and where the fluence was different due to neutron attenuation from the inside surface. Measurement of T_0 from the ¼ (or ¾) thickness is required in PWROG-18068 for base metals consistent with ASTM E185 [16] and ASME Section III, NB-2300. Equation (4) was used for fluence attenuation, which is consistent with Regulatory Guide 1.99, Rev. 2 [2].

$$fluence_x = fluence_{surface} \bullet e^{-\frac{0.24}{25.4}x} \quad (4)$$

Where x is the distance from the inside surface in mm.

The through wall fluence is shown in Figure 1. The adjustment includes margins as described previously. In every case the 1/4T adjusted + margin value is conservative relative to measured T_0 values at the other locations in the RPV plate as shown in Figure 1. The *Bounding adjusted T_0* (red lines) is more conservative than each measured T_0 (purple circles). Two of the datasets (19 mm and 29 mm) were screened as inhomogeneous according to ASTM E1921-20. Even the more conservative T_{0IN} values are below the *Bounding adjusted T_0* values. The approach to calculate the margin contributes to the conservatism in these cases, but also the plate toughness is higher (lower T_0) near the surfaces of the plate due to the faster cooling rate during the quenching process which also adds to the margin/conservatism. This is expected and typical for thick-section RPV plates. One can conclude that use of the 1/4T thickness toughness provides added margin for locations closer to the inside and outside surfaces of plates. Thick-section RPV forgings also exhibit increased toughness near the surfaces [17].

Figure 2 shows the 1T equivalent fracture toughness values compared to the bounding curves adjusted from the ¼ T location. For simplification since the five-bounding adjusted T_0 values 70 mm and closer to the inside surface are similar, the red bounding curve is shown for the 39 mm location. This curve bounds all but one datapoint. The two adjusted T_0 values that are near the outside surface of the plate are also similar with the bounding purple curve bounding all the 192 mm and 201 mm points. The one nonbounded point amounts to 99% of the 119 measured fracture toughness values being bounded by the adjusted tolerance bound curves.

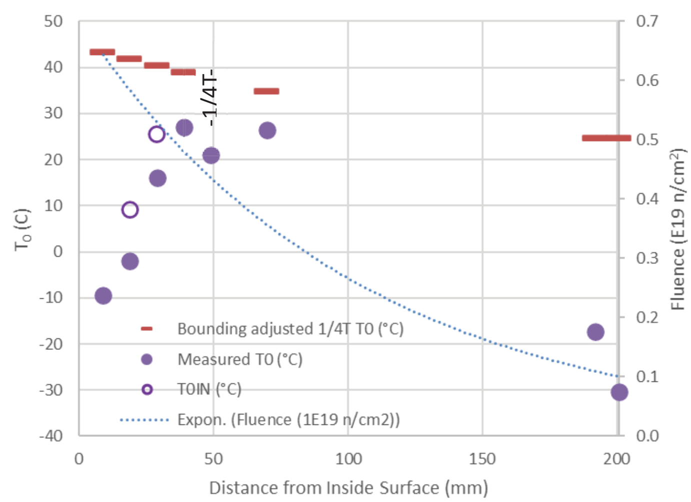

Figure 1 Comparison of Measured 1/4 Thickness T_0 Adjusted to Fluences at other Locations Compared to Measured T_0 Values for Zion Unit 1 RPV Plate

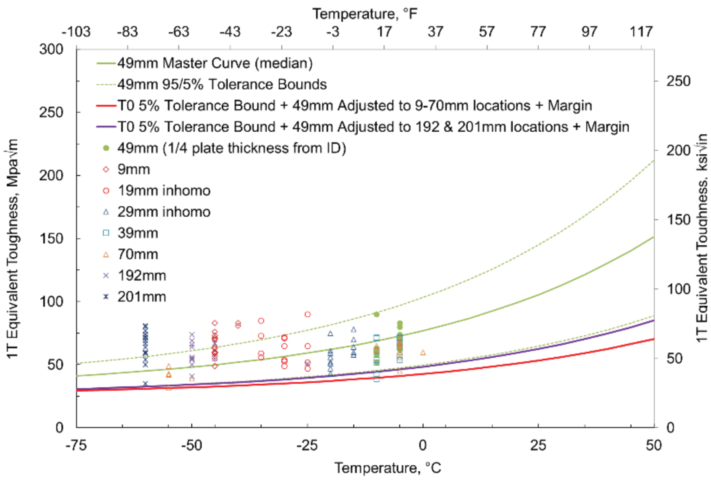

Figure 2 Comparison of Fracture Toughness Values to Bounding Curves (Censored Values not Shown)

3.2 Application to Database of T_0 Measurements

A significant database of master curve reference temperature data was collected and reported in NUREG/CR-6609 [18]. In addition, power reactor irradiated data was added from four other sources published since NUREG/CR-6609 to increase the size of the database [19, 20, 21 and 22]. The compiled database included 28 heats of base metal with 69 irradiated T_0 measurements and the weld database included 24 heats with 50 irradiated T_0 measurements.

The method used to calculate T_0 (T_{100} is the designation used in NUREG/CR-6609) was reported as being calculated according to ASTM E1921-97 which is nearly the same as that used in ASTM E1921-20, although there are some differences of note:

- Since the 1997 edition, the Poisson's ratio was added to the conversion from J_e to K_{Jc}. Due to this change, the ASTM E1921-97 calculated K_{Jc} values could be slightly higher than ASTM E1921-20. However, in this case comparisons between two T_0 values are being made using the same calculational methodology so there would be no significant resulting difference.
- ASTM E1921-20 recommends adding an 18°F (10°C) bias to T_0 for three-point bend specimens due to the effect of the difference in constraint. If the geometry between the two T_0 values compared were different then a conservative or non-conservative bias of 10°C could be introduced. If there were no change in geometry, then there would be no effect in this comparison.
- Due to the effect of loading rate on T_0 for ferritic materials, the allowable K_{rate} was tightened by ASTM E1921-05 reducing the effect on T_0.
- ASTM E1921-20 requires that datasets be screened for inhomogeneous scatter. Datasets that fail the screening may be representative of a macroscopically inhomogeneous material which might not be adequately described by the certainty bounds in ASTM E1921 which is meant for homogeneous materials.

Differences in specimen geometry and loading rate will add to the scatter (uncertainty) in comparing specimens tested at one condition and comparing to the *Bounding adjusted T_0* at another irradiation condition. The specimen geometry and loading rate was not reported in NUREG/CR-6609. In addition, uncertainty in the measured T_0 which is a function of number of specimens tested and the average specimen toughness was also not reported. Therefore, reasonably conservative simplifications were made regarding the number of specimens tested and the average specimen toughness in performing this evaluation.

The NUREG/CR-6609 T_0 database included some steels that are not within the range of commercial RPV steels and irradiation conditions included in the database used to develop the ASTM E900-15 embrittlement correlation. Since this method adjusts the measured T_0 data using ASTM E900-15, steels not within its applicability were excluded. The steels excluded had either a high Cu (0.43%) weld, advanced CrNiMoV RPV steel, lab melted plates, VVER steel, or high fluence rate non-commercial reactor irradiated specimens. The irradiation temperature required by ASTM E900-15 was also not reported in NUREG/CR-6609. When unavailable from accessible source references, the irradiation temperature of 288°C was assumed.

The T_0 database included unirradiated and irradiated T_0 values along with material chemical composition and fluence. This information, along with irradiation temperature discussed above was used as inputs to ASTM E900-15 to calculate the adjustment and $\sigma_{adjustment}$. Since σ_{E1921} is not available a conservative low value of 5°C was used assuming a relatively large dataset. The uncertainty of irradiation temperature and fluence were also not available, therefore 2°C uncertainty on irradiation temperature and 20% uncertainty on fluence were assumed to be typical and the effect of these input uncertainties on ASTM E900-15 ΔT_{41J} predictions were used for $\sigma_{tempRPV}$ and $\sigma_{fluenceRPV}$.

The *Bounding adjusted T_0*, calculated from unirradiated T_0 measurements, is compared to measured irradiated T_0 values as shown in Figure 3 for welds and for base metals in Figure 4. The highlighted heats are assessed in more detail in a later section. All of the measured data are bounded by the *Bounding adjusted T_0* values for the welds and 98% is bounded for the base metals. For a datapoint that falls exactly on the 1:1 line with construction of the 95% lower bound curve, it can be expected that 95% of the K_{Jc1T} data would be bounded for a homogeneous material.

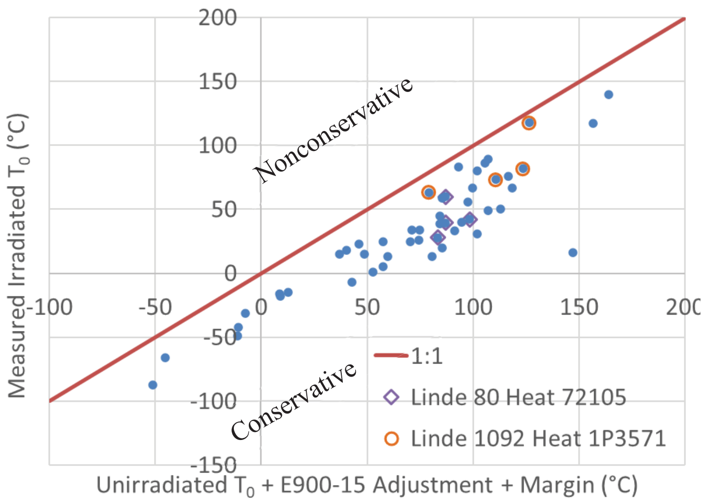

Figure 3 Bounding Adjusted T_0 Compared to Measured Irradiated T_0 for Weld Metals

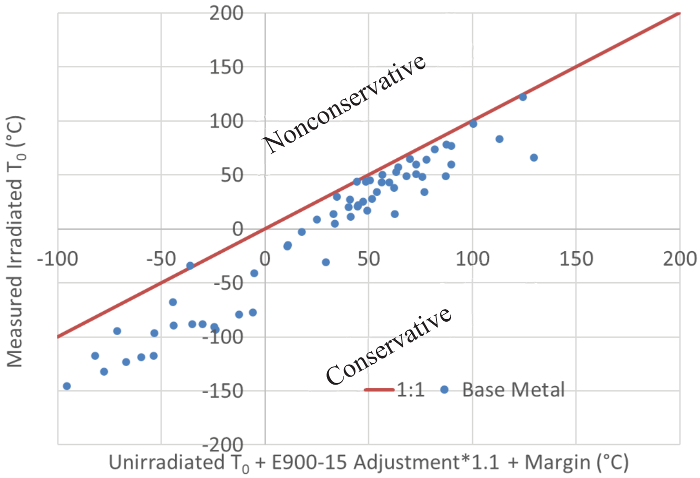

Figure 4 Bounding Adjusted T_0 Compared to Measured Irradiated T_0 for Base Metals

Several materials in the database had irradiated T_0 measured at two or more fluence levels. For these cases, *Bounding adjusted T_0* values were determined by adjusting from typically lower fluence T_0 to the higher fluence T_0. The margin term includes additional terms since there is added uncertainty with the irradiation temperature and calculated fluence values of the irradiated specimens that did not exist when adjusting from an unirradiated T_0. As before, 2°C uncertainty on irradiation temperature and 20% uncertainty on fluence were assumed to be typical and the effect of these input uncertainties on ASTM E900-15 ΔT_{41J} predictions were used for $\sigma_{temp\ specimen}$ and $\sigma_{fluence\ specimen}$. These were included in the margin term in addition to the uncertainties used when adjusting from unirradiated T_0 shown in Equation (3).

Originally, the *Bounding adjusted T_0* calculated from the irradiated T_0 measurements was compared to measured irradiated T_0 values. It was found that 92% of data was bounded by the *Bounding adjusted T_0* values for the welds and 93% is bounded for the base metals. It was felt that not enough of the data was bounded, so a minimum value of 9°C was imposed on $\sigma_{adjustment}$ as shown in Figure 5 for welds and for base metals in Figure 6 increasing the amount of data bounded such that 97% of the irradiated T_0 measurements for weld and base metal are bounded by the *Bounding adjusted T_0* values. The 9°C value is also supported by evaluating the residual error of a large population of ΔT_0 vs. ΔT_{30} data, subtracting the measurement and correlation uncertainty with the remaining uncertainty representing material variability which resulted in 9°C for both welds and base metals.

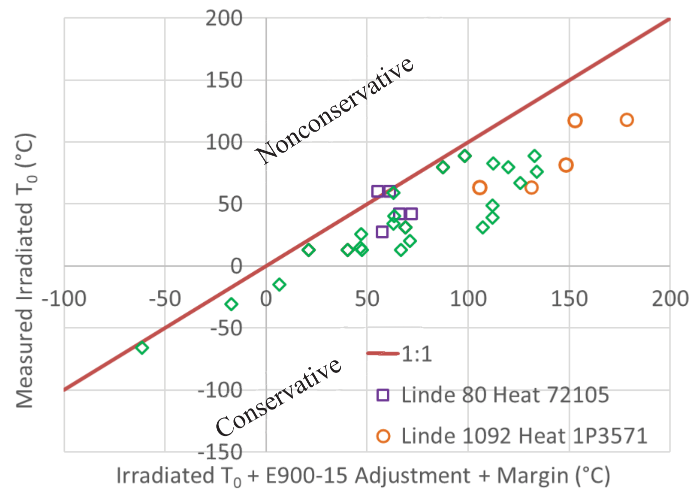

Figure 5 Bounding Adjusted T_0 Compared to Measured Irradiated T_0 for Weld Metals

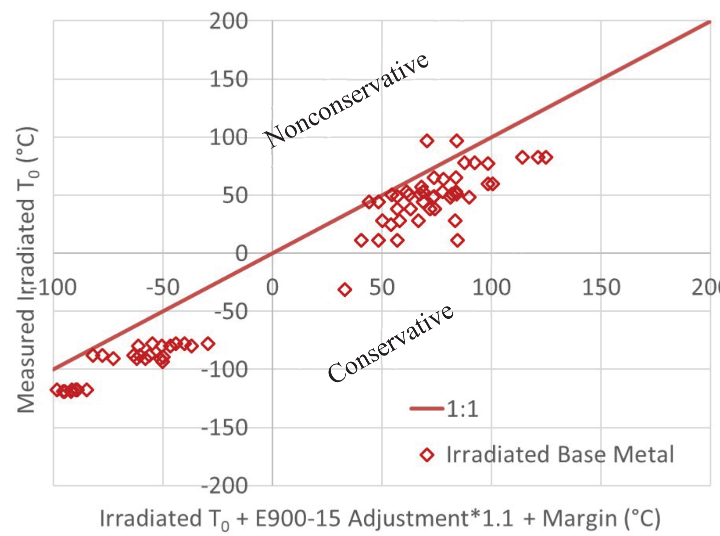

Figure 6 Bounding Adjusted T_0 Compared to Measured Irradiated T_0 for Base Metals

3.3 Detailed Examples

The first example is for the Kewaunee circumferential RPV Linde 1092 flux weld wire Heat # 1P3571. Three sets of specimens tested on Heat # 1P3571 for T_0 were irradiated in a PWR and one set was irradiated in a material test reactor (MTR). Unirradiated archive Maine Yankee RPV surveillance Heat # 1P3571 mini-CT specimens were irradiated in the Belgium BR2 MTR, returned to Westinghouse, and tested for T_0 [9]. The PWR irradiations included Palisades Capsule A-35, Kewaunee Capsule T and Kewaunee Capsule S [23, 24 and 25]. The baseline T_0 [23] test data was screened as homogeneous and was adjusted to the fluence and irradiation temperature of each capsule using the weld Heat # 1P3571 best-estimate chemistry. The standard approach taken in the US is to adjust for embrittlement using the heat best estimate chemistry and the RPV projected fluence and irradiation temperature. With margin added as described previously, all but 1 of the K_{Jc1T} values are bounded by the respective *Bounding adjusted* 5% tolerance bound curve as shown in Figure 7 resulting in 98% of the data being bounded. The Capsule S data was screened as homogeneous, while the other 3 irradiated datasets were inhomogeneous. The Capsule S data is the closest 1P3571 data point to the 1:1 line shown in Figure 3.

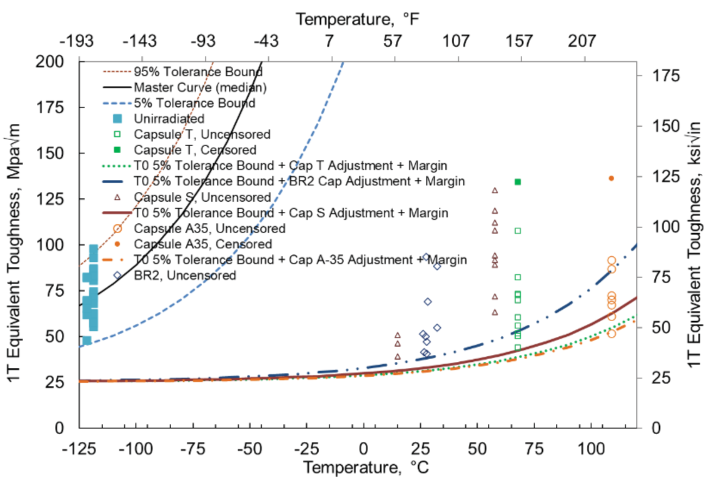

Figure 7 Comparison of Fracture Toughness Values to Bounding Curves for Weld Heat 1P3571 Adjusted from Unirradiated T_0

Next, the Capsule S data was adjusted to the other 3 irradiated conditions in a similar manner as the unirradiated data. However, in this case since there is uncertainty with the fluence and irradiation temperature of the Capsule S specimens, 1°C uncertainty on irradiation temperature and 8% uncertainty on fluence were used to determine the effect of these input uncertainties on ASTM E900-15 ΔT_{41J} predictions were used for $\sigma_{\text{temp specimen}}$ and $\sigma_{\text{fluence specimen}}$. These were included in the margin term. The data relative to each respective *Bounding adjusted* 5% tolerance bound curve are shown in Figure 8. All the measured data are bounded by each respective curve.

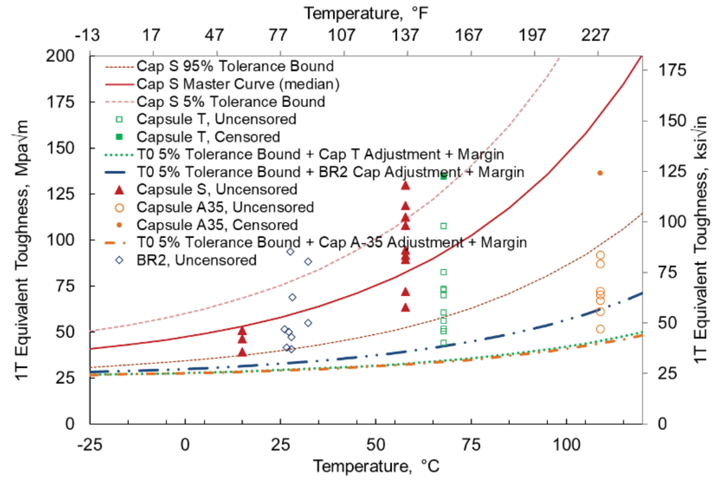

Figure 8 Comparison of Fracture Toughness Values to Bounding Curves for Weld Heat 1P3571 Adjusted from Capsule S T_0

For the next detailed example, Linde 80 weld flux, wire Heat 72105 was evaluated. Linde 80 weld flux, wire Heat 72105, Flux lot 8669 combination identified as WF-70 was used in construction of several RPVs including the Midland Unit 1 (MD1) RPV which was never operated. ORNL removed sections of the beltline and nozzle elevation (referred to nozzle dropouts, ND) welds both fabricated with WF-70 [26]. The range and average Cu content of the beltline (0.25) and nozzle (0.39%) course welds are significantly different (Table 2 [26]), but both are composed of the same wire heat and are considered high Cu welds. The weld wire was copper coated which varied in thickness which resulted in different Cu contents of the fabricated welds. 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, for 0.5 EFPY. Specimens were also irradiated in a Crystal River Unit 3 Capsule to 1.35 x 10^{19} n/cm^2 and the Zion Unit 1 Capsule X to 1.9 x 10^{19} n/cm^2. There were 148 specimens tested to determine the unirradiated T_0 for this heat [27]. This T_0 was adjusted using the heat best estimate chemistry and the fluence and irradiation temperature of each capsule and margin added. The data relative to each respective *Bounding adjusted* 5% tolerance bound curve are shown in Figure 9. All the data are bounded by each respective curve by a significant margin as would be expected since the Linde 80 points in Figure 3 are not near the 1:1 line.

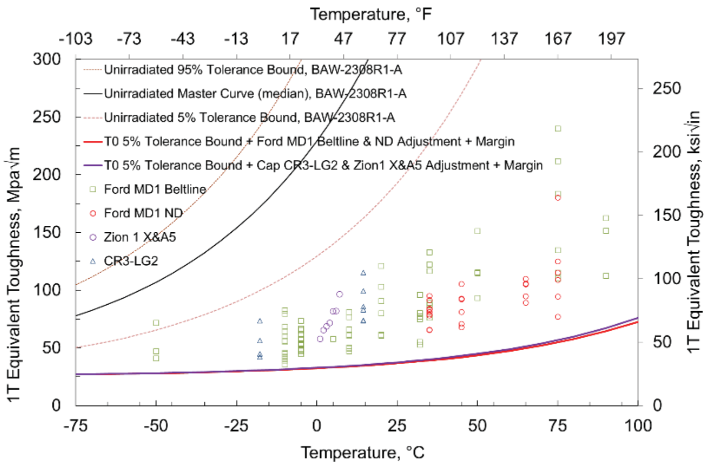

Figure 9 Comparison of Fracture Toughness Values to Bounding Curves for Weld Heat 72105 Adjusted from Unirradiated T_0

Next, the Ford reactor beltline weld T_0 was adjusted to the other 3 irradiated conditions in a similar manner as the unirradiated data. However, in this case since the uncertainty with the power reactor fluence and irradiation temperature are relatively low, 1°C uncertainty on irradiation temperature and 8% uncertainty on fluence were used to determine the effect of these input uncertainties on ASTM E900-15 ΔT_{41J} predictions for $\sigma_{temp\ specimen}$ and $\sigma_{fluence\ specimen}$. These were included in the margin term.

There were 111 tests conducted by multiple test labs on the Ford reactor irradiated beltline weld using different specimen sizes including mini-CT specimens [26, 28, 29 and 30]. Overall, the dataset is inhomogeneous. The dataset was broken into 7 subsets of 8 to 27 specimens some of which were homogeneous, others inhomogeneous [9]. The least conservative subset T_0 (or T_{0IN} for inhomogeneous datasets) was used to adjust from the Ford irradiated beltline weld.

The data relative to each respective *Bounding adjusted* 5% tolerance bound curve are shown in Figure 10. One of the Ford irradiated beltline tests lies below the 5% tolerance bound with margin added using the least conservative T_{0IN} described above. This one has no adjustment with only margin added. All the data for the other irradiations is adjusted and bounded by each respective curve even with the significant differences in source Cu chemistry. The red circles in Figure 10 corresponds to the purple data point in Figure 5 which is on top of the 1:1 line and all this data is bounded. In all, over 99% of the data is bounded in Figure 10. For Figure 11 the curves are adjusted from CR3-LG2 MD1 ND irradiated measurement and compared to the other irradiations with adjustment and margin. There is one point in Figure 11 (red point relative to the red curve) not bounded for the Ford irradiated MD1 ND which corresponds to the purple nonconservative point shown in Figure 5.

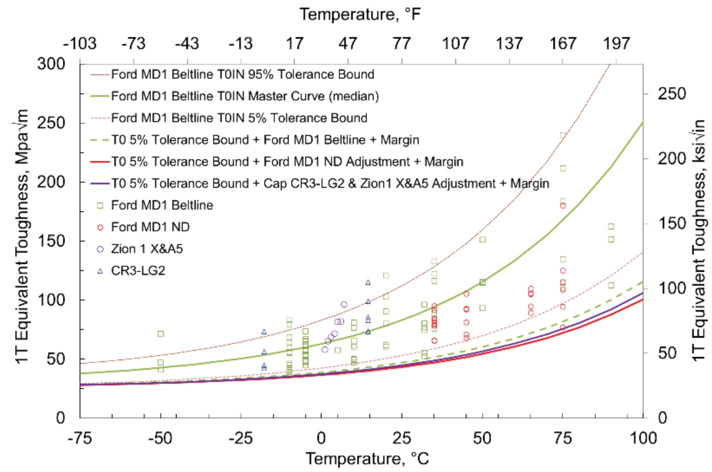

Figure 10 Comparison of Fracture Toughness Values to Bounding Curves for Weld Heat 72105 Adjusted from Ford Reactor MD1 Beltline T_{0IN}

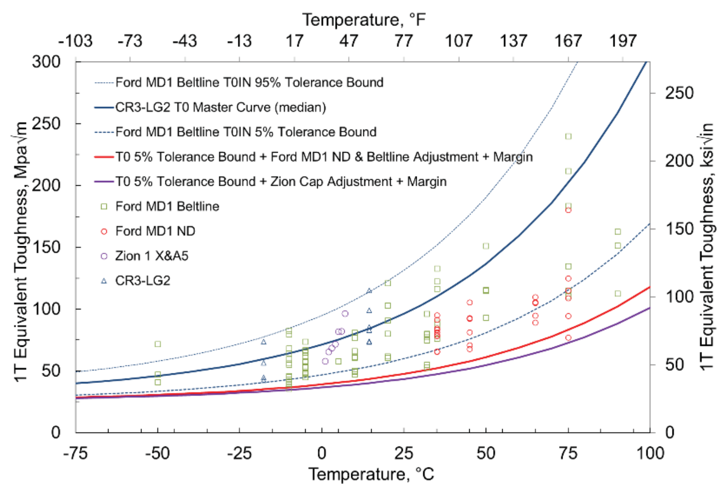

Figure 11 Comparison of Fracture Toughness Values to Bounding Curves for Weld Heat 72105 Adjusted from CR3-LG2 MD1 Nozzle Dropout T_0

4 CONCLUSION

A substantial amount of fracture toughness data has been compared using the described methodology in which T_0 values are adjusted to the irradiated condition of interest with uncertainty margin added and compared to measured irradiated T_0 values and measured fracture toughness data. In all cases, at least 95% of the data is bounded. The described methodology provides conservative margin for the application of direct fracture toughness using either unirradiated or irradiated T_0 data for the application to RPV integrity evaluations.

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use of direct fracture toughness in the evaluation of RPV integrity.

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