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PWROG-18068, Revision 1-A
"Use of Direct Fracture Toughness for Evaluation of RPV Integrity"

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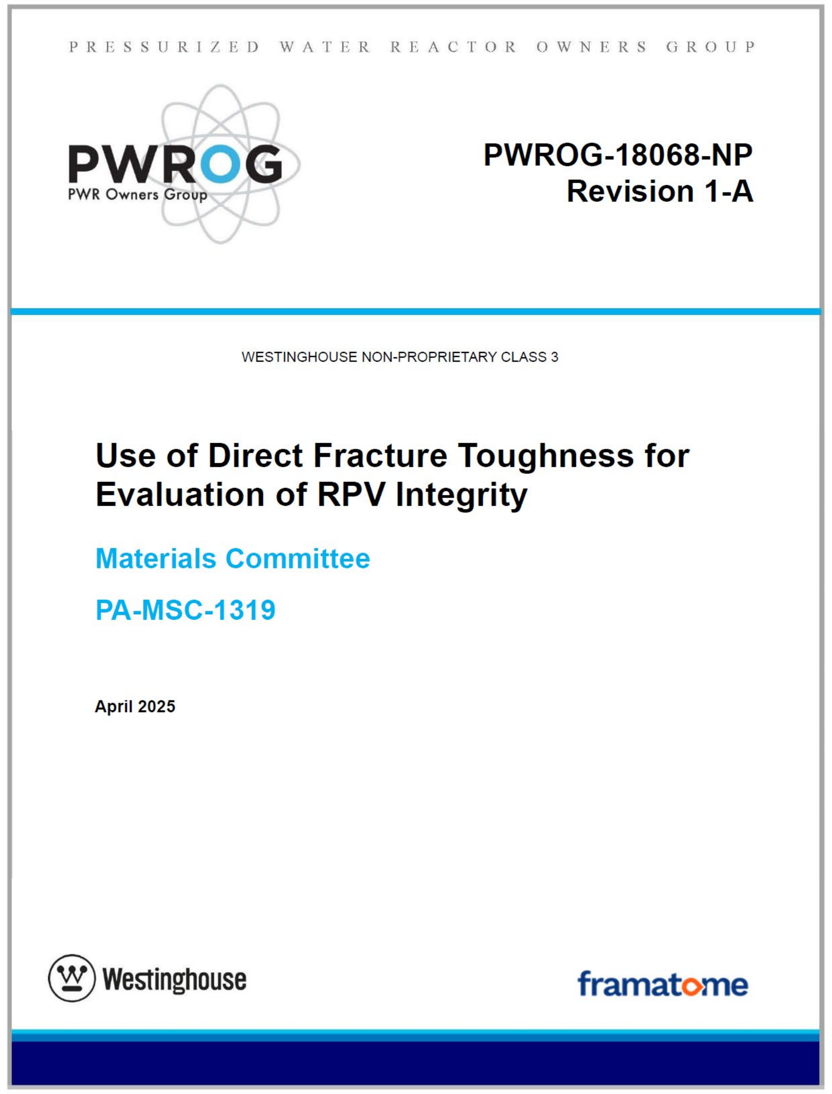
LWRS Spring meeting April 30, 2025

PWROG-18068-NP, Revision 1-A "Use of Direct Fracture Toughness for Evaluation of RPV Integrity"

- The methodology justifies the use of direct fracture toughness data to evaluate RPV integrity as an alternative to the requirements/methods of pressurized thermal shock (PTS) (10 CFR 50.61) and pressure-temperature (P-T) limit curves (10 CFR 50, Appendix G).
- The topical report describes a methodology to:
  - Generate irradiated or unirradiated ductile-brittle transition reference temperature (T_0) according to the industry consensus ASTM E1921-20 Standard Test Method
  - Adjust the data for differences between the tested material and RPV condition using industry consensus ASTM E900-15 Standard Guide for predicting embrittlement
  - Account for test result uncertainty and material variability
  - Apply the data using ASME Code NRC-endorsed methods


PRESSURIZED WATER REACTOR OWNERS GROUP

PWROG-18068-NP
Revision 1-A

WESTINGHOUSE NON-PROPRIETARY CLASS 3

Use of Direct Fracture Toughness for Evaluation of RPV Integrity

Materials Committee

PA-MSC-1319

April 2025

Westinghouse

framatome

Direct Fracture Toughness Activities

- PWROG-18068-NP,Rev. 1 submitted to NRC for review in July 2021
- Provides a methodology to use fracture toughness data as an alternative to specific sections of NRC-approved topical reports for generating pressure-temperature curves
    - WCAP-14040-A
    - BAW-10046A
- Applicable to all PWRs
- 25 multi-part requests for additional information received March 2022
    - A number of meetings and changes made to address NRC questions
    - Final RAI responses and PWROG-18068 markup submitted March 2024
    - Final safety evaluation (NRC method approval) received December 2024
- Parallel complimentary, different method proposed in ASME Code with ballot of Code Case N-914 – *Methods to account for embrittlement*
    - Basis in MRP-462, Rev. 1 Draft (Feb. ‘23)
    - Addressed reviewer comments; out for ballot

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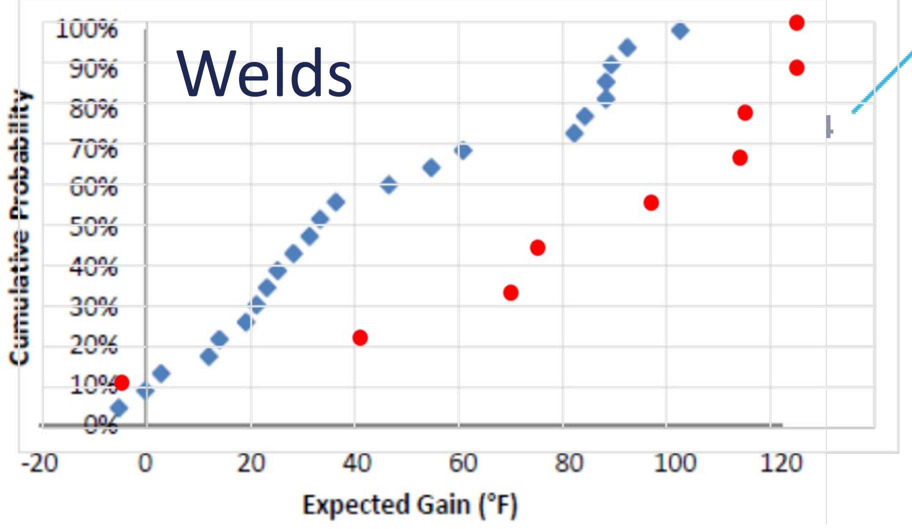
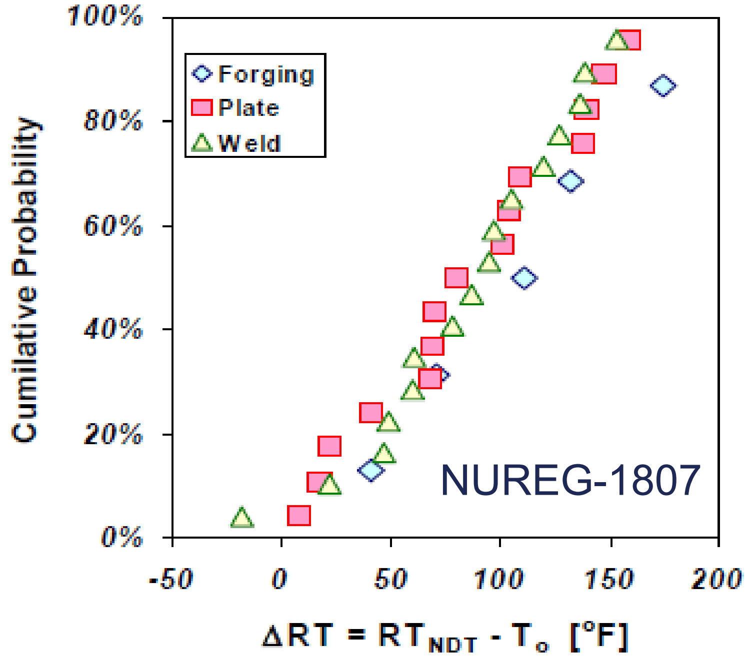
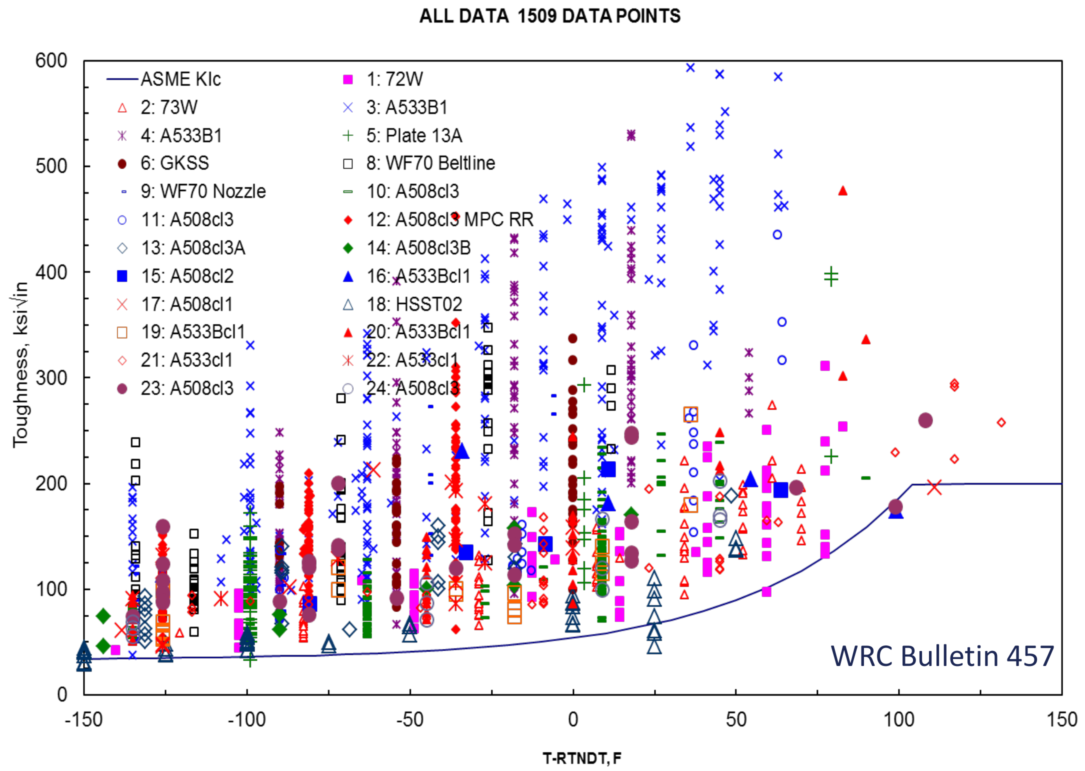
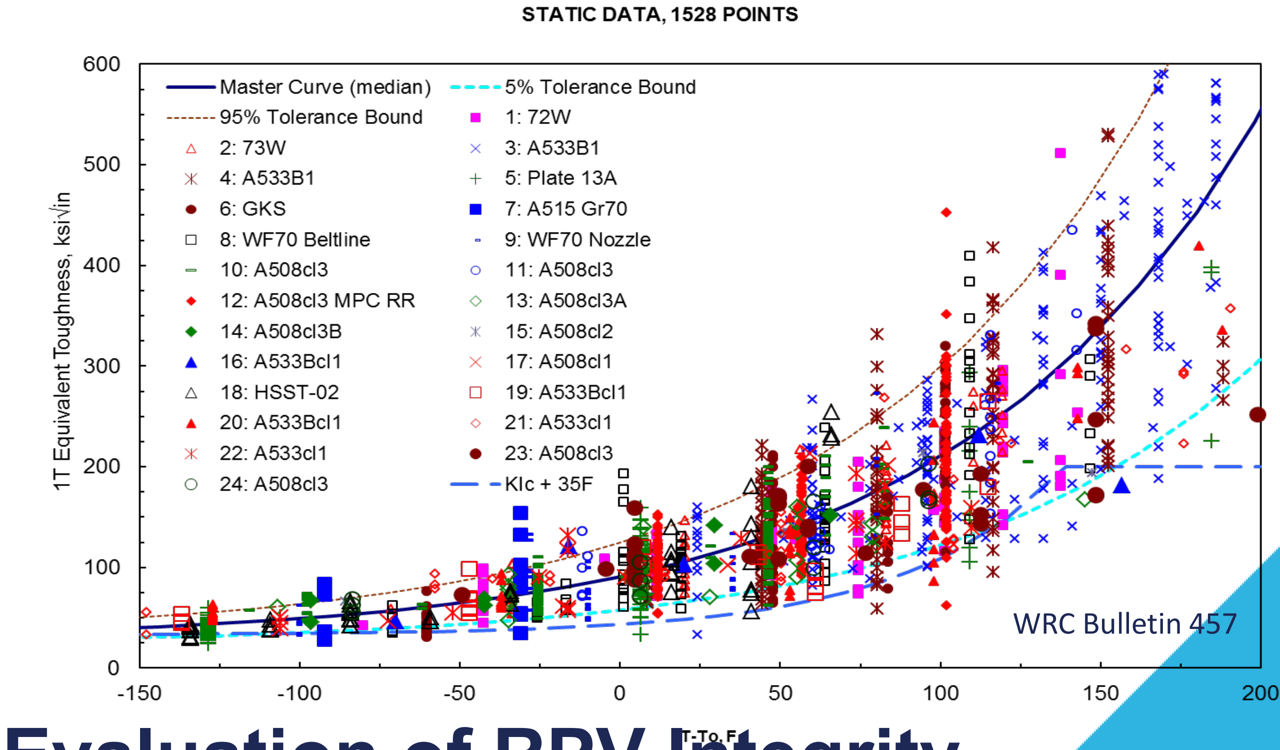
Why Direct Fracture Toughness

- **Master Curve**
  - Reduced uncertainty
  - Reduced inconsistency
  - Characterizes margin statistically
  - Based on actual fracture toughness measurement
- **Testing Irradiated Material**
  - Reduced embrittlement prediction uncertainty
  - Reduced embrittlement prediction error (bias)
    - e.g., RG1.99R2 high fluence non-conservatism
  - Uncertainties are accounted for explicitly









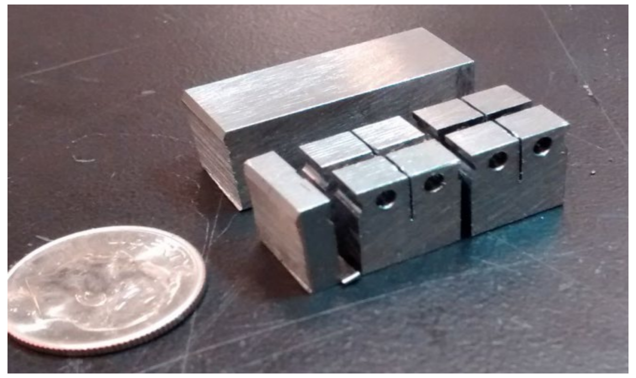
Methodology for Application of Master Curve Test Data

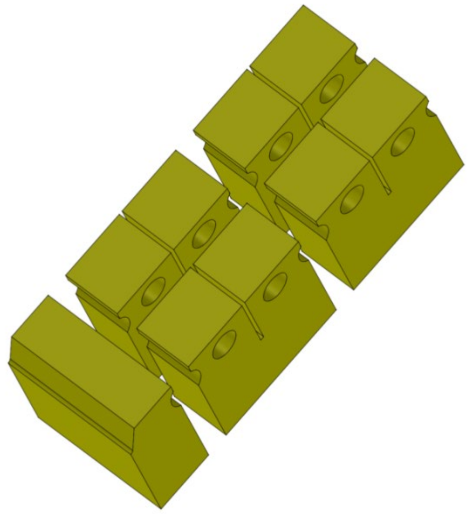
- For PTS evaluations, the following is used:

$$RT_{PTS} = RT_{T0} + \textit{adjustment} + \textit{margin}$$

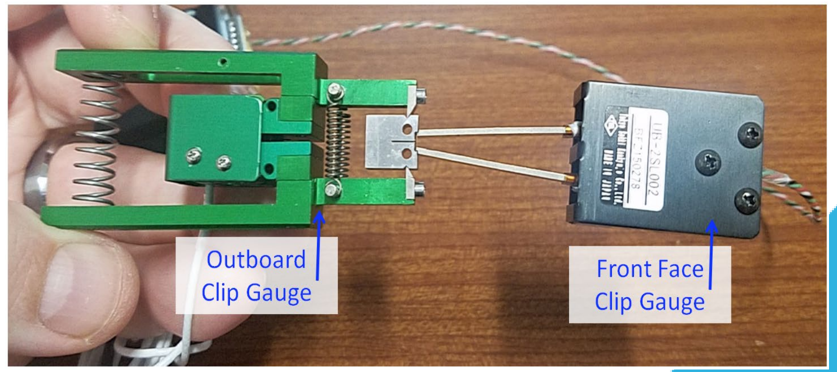
- Using ASME Section XI, Appendix G 2013
  - $K_{Ic} = 33.2 + 20.734 \exp[0.02\,(T - \{RT_0 + \textit{adjustment} + \textit{margin}\})]$ **(K_{Ic} curve with RTT_0)**
    - $RT_0 = T_0 + 35°F$
- OR
- Using Code Case N-830-0 as modified by the NRC condition
  - $\mathbf{K_{Jc\text{-}lower95\%}} = 22.9 + 33.3 \exp[0.0106\,(T - \{T_0 + \textit{adjustment} + \textit{margin}\})]$
- This topical report provides a methodology to determine the *adjustment* and *margin* terms

Generation and Validation of T_0 Data





- **ATM E1921, T_0 can be obtained by**
  - Using existing test data
  - Testing specimens machined from unirradiated archive material
  - Testing specimens machined from material irradiated in a PWR surveillance capsule, or
    - E1921 compliant mini-C(T) 4mm thick specimens are approved for use
      - 8 mini-C(T) specimens can be machined from a broken irradiated Charpy specimen
  - Irradiating specimens in at high flux & testing; e.g. material test reactor (MTR)
    - MTR irradiation must include similar validation material also irradiated in a PWR
    - Ensures that MTR irradiated specimens are representative of PWR irradiated specimens
      - Potential Flux effect
      - Other differences: spectrum, temperature, unknown
      - Ensures well-designed MTR irradiation of specimens



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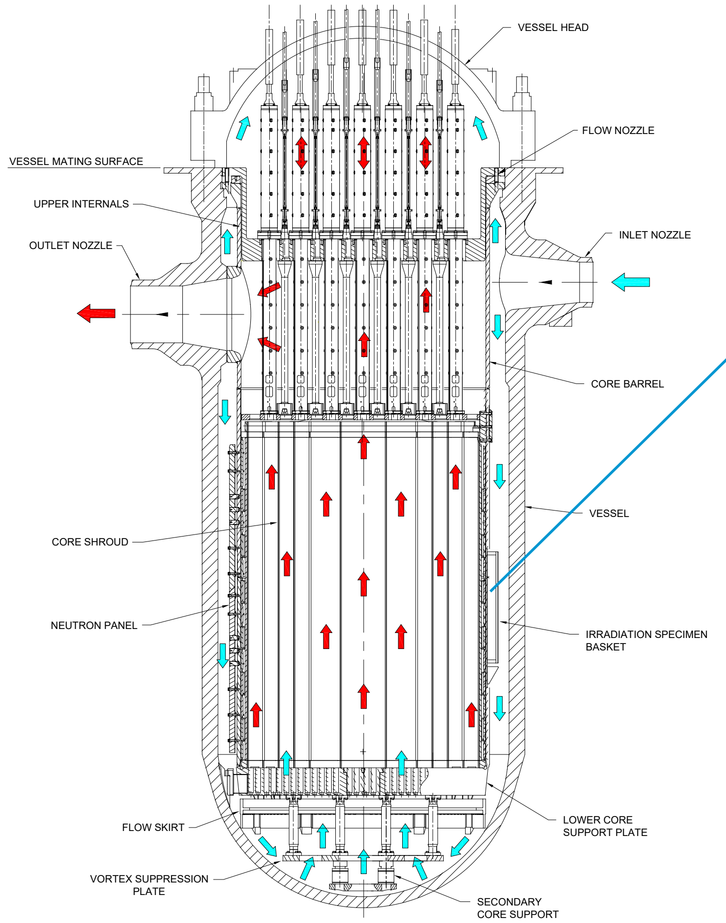
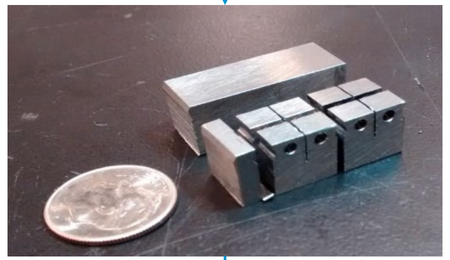
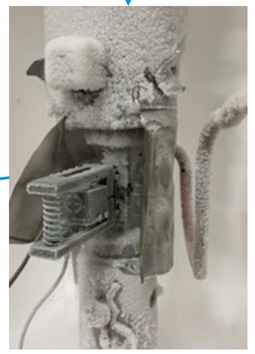
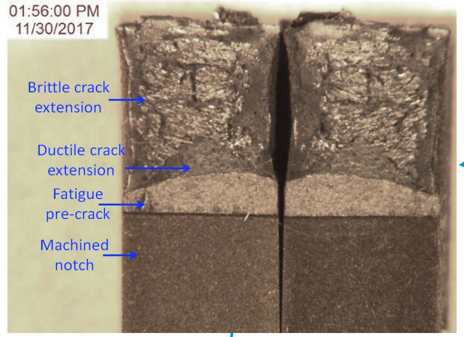
Specimen Testing

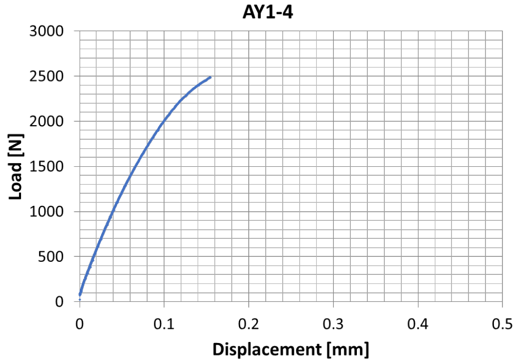
- **Testing of the same heat of material is required to evaluate the RPV material of interest, except**
  - Generic unirradiated T_0 method is described
    - Minimum 4 valid T_0 from same type, manufacturer, or class
    - 95/95 one-sided tolerance limit factor (k1) margin is used rather than 2 which is typically used for large populations
- **Testing in accordance with ASTM E1921-20**
  - Data sets are screened for inhomogeneity in accordance with 10.6 of ASTM E1921-20
  - Data sets that fail the screening criterion are evaluated in accordance with Appendix X5 “Treatment of Potentially Inhomogeneous Data Sets,” of ASTM E1921-20 with T_{0IN} (as calculated in Appendix X5) substituted for T_0.
  - Any geometry that meets ASTM E1921-20
    - A 10°C bias is added for the SEB Charpy size (10x10mm) specimen (ASTM E1921)











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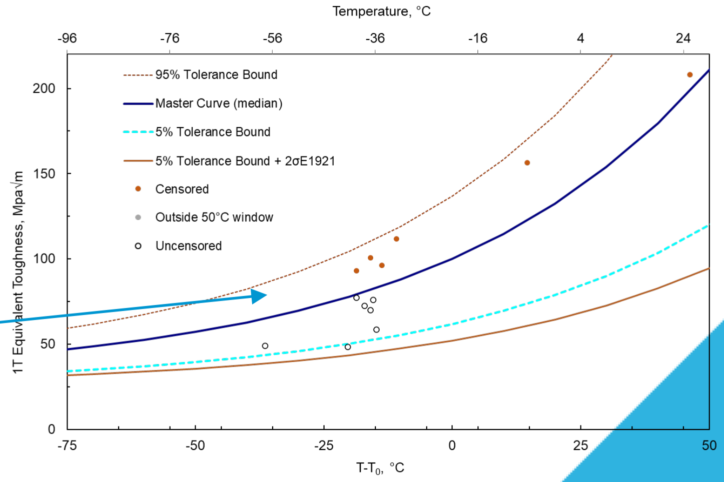

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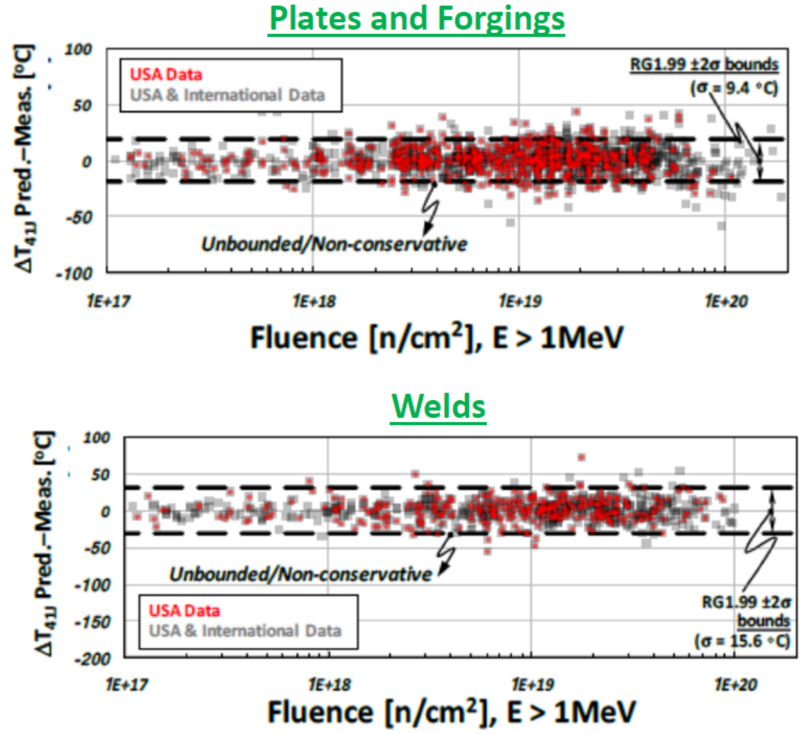
Data Adjustment

- **Tested specimens will rarely reflect the exact same irradiation conditions and chemistry as the represented RPV material**
  - Adjustments presented herein are made using the embrittlement trend curve (ETC) in ASTM E900-15 (other ETCs could also be used)

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

  - Best-estimate inputs are used for the irradiated data adjustments
    (Cu, Ni, Mn, P, Temp., Fluence)
  - An NRC-approved method of fluence evaluation consistent with the plant licensing basis, or another NRC-approved method of fluence evaluation
  - Weld = 1.0 and Base metal = 1.1

- Comparisons based on ASTM E900-15 ETC
- The NRC staff found that the ASTM E900-15 ETC provided the most accurate characterization of this database*



*"Basis for a Potential Alternative to Revision 2 of Regulatory Guide 1.99," TLR-RES/DE/CIB-2020-11, ML20345A003

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United States Nuclear Regulatory Commission
Protecting People and the Environment

ML21270A002 NRC presentation, Oct. 2021

Margin Term

$$Margin = 2\sqrt{\sigma^2_{E1921} + \sigma^2_{adjustment} + \sigma^2_{tempspecimen} + \sigma^2_{tempRPV} + \sigma^2_{fluencespecimen} + \sigma^2_{fluenceRPV}}$$

- **Accounts for uncertainties**
  - Uncertainty of **E1921** T_0 measurement
  - Uncertainty of **adjustment**
  - **Irradiation temperature** (effect of uncertainty on embrittlement using the ETC)
    - Test specimens; 0 if irradiated in assessed RPV
    - RPV; (2°F can conservatively be used)
  - **Fluence** (effect of uncertainty on embrittlement using the ETC)
    - Test specimens (0 if unirradiated)
    - RPV projection

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

Determination of σ_{E1921}

- **Uncertainty of T_0 measurement**
  - σ_{E1921} is calculated in accordance with ASTM E1921
- **Uncertainty includes screening for material variability**
  - In 2019, a homogeneity screening procedure was added to ASTM E1921, Appendix X5
    - Identifies datasets which do not follow expected normal material Weibull distribution and the 95% lower bound curve would not bound 95% of data
    - Inhomogeneity can result from initial toughness variation (i.e. segregation) or uneven embrittlement due to chemical composition variation

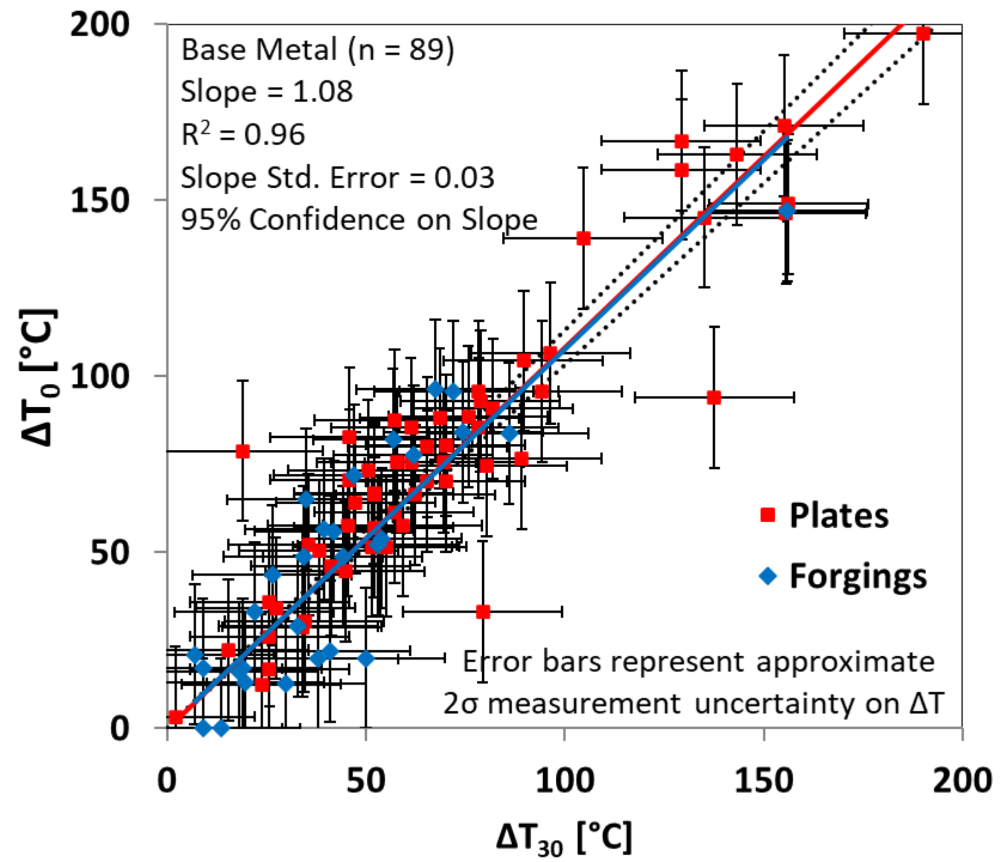
Determination of $\sigma_{adjustment}$

- $\sigma_{adjustment}$ **is proportional to ASTM E900-15 σ with a minimum value of 9°C**

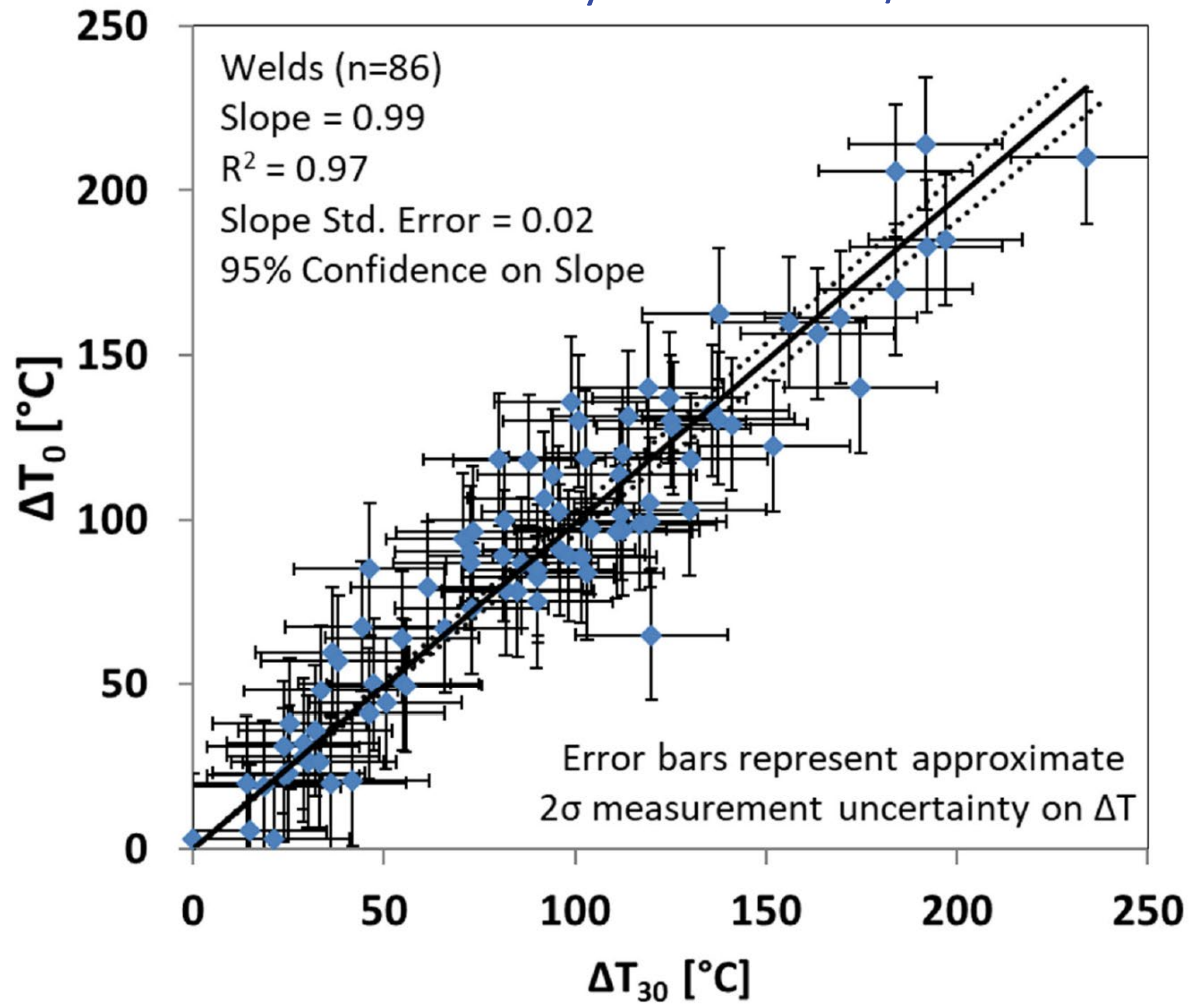
$$\sigma_{adjustment} = \boldsymbol{max}\left[9°\mathrm{C}, \{\boldsymbol{C} \bullet ([If\ BM, 1.1] \bullet \Delta T_{30RPV})^{\boldsymbol{D}}\} \bullet \frac{|adjustment\ |}{(If\ BM, 1.1) \bullet \Delta T_{30\ RPV}}\right]$$

  - Adjustment from unirradiated results in use of full σ_{E900}
  - With small adjustments, the 9°C is the value used

- **9°C uncertainty due to material variability**
  - Typical σ_{E1921} ranges from 6 to 8°C
  - Typical σ_{41J} ranges from 4 to 10°C
  - $\sqrt{T_{0init}^2 + T_{0irr}^2 + T_{30init}^2 + T_{30irr}^2}$ = $\boldsymbol{\sqrt{6^2 + 8^2 + 4^2 + 10^2}}$ **= 14.4°C**
  - Standard Deviation on Fit Residuals = 17°C for BM and Welds
  - $\boldsymbol{\sqrt{17^2 - 14.4^2}}$ **= 9°C (material variability)**



Data is mostly from NUREG/CR-6609



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Basis: J. B. Hall, B. Golchert, and D. Simpson, "An Examination of Margins Needed to Ensure Conservative Application of T0 to RPV Fracture Toughness,"

ASME PVP2024-125225

Margin Evaluation

- **Method was used with measured fracture toughness data to evaluate if margin is sufficient**
  - Unirradiated T_0 was adjusted to irradiated T_0 with margin added from same heat (irradiated T_0 as if from RPV assessed)
  - Adjustment from unirradiated results in use of full σ_{E900}
- **98% of the data is bounded for base metals**
- **100% is bounded for welds**
- **Data is mostly from NUREG/CR-6609**

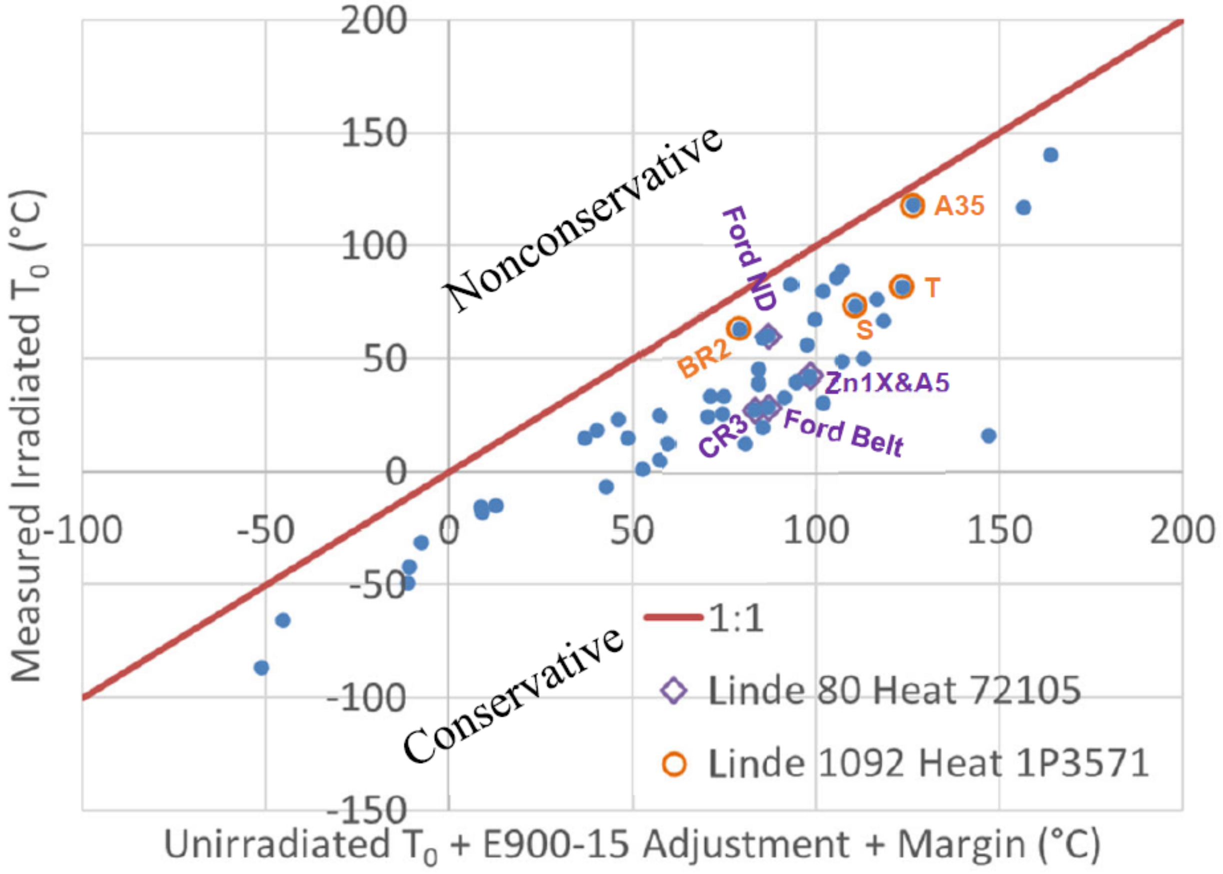

Figure 3 Bounding Adjusted T_0 Compared to Measured Irradiated T_0 for Weld Metals (labels are capsule names which are referenced later)

Does the method bound measured T_0 at 2nd condition?

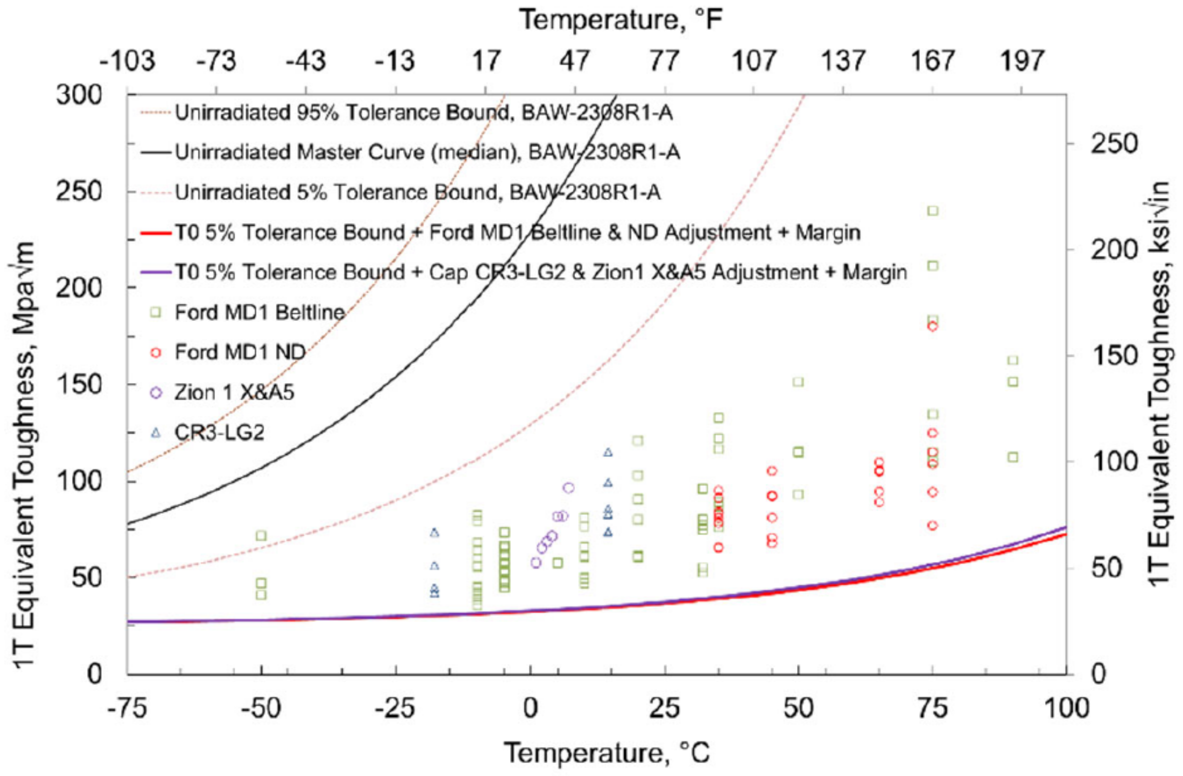

Figure 9 Comparison of Fracture Toughness Values to Bounding Curves for Weld Heat 72105 Adjusted from Unirradiated T_0

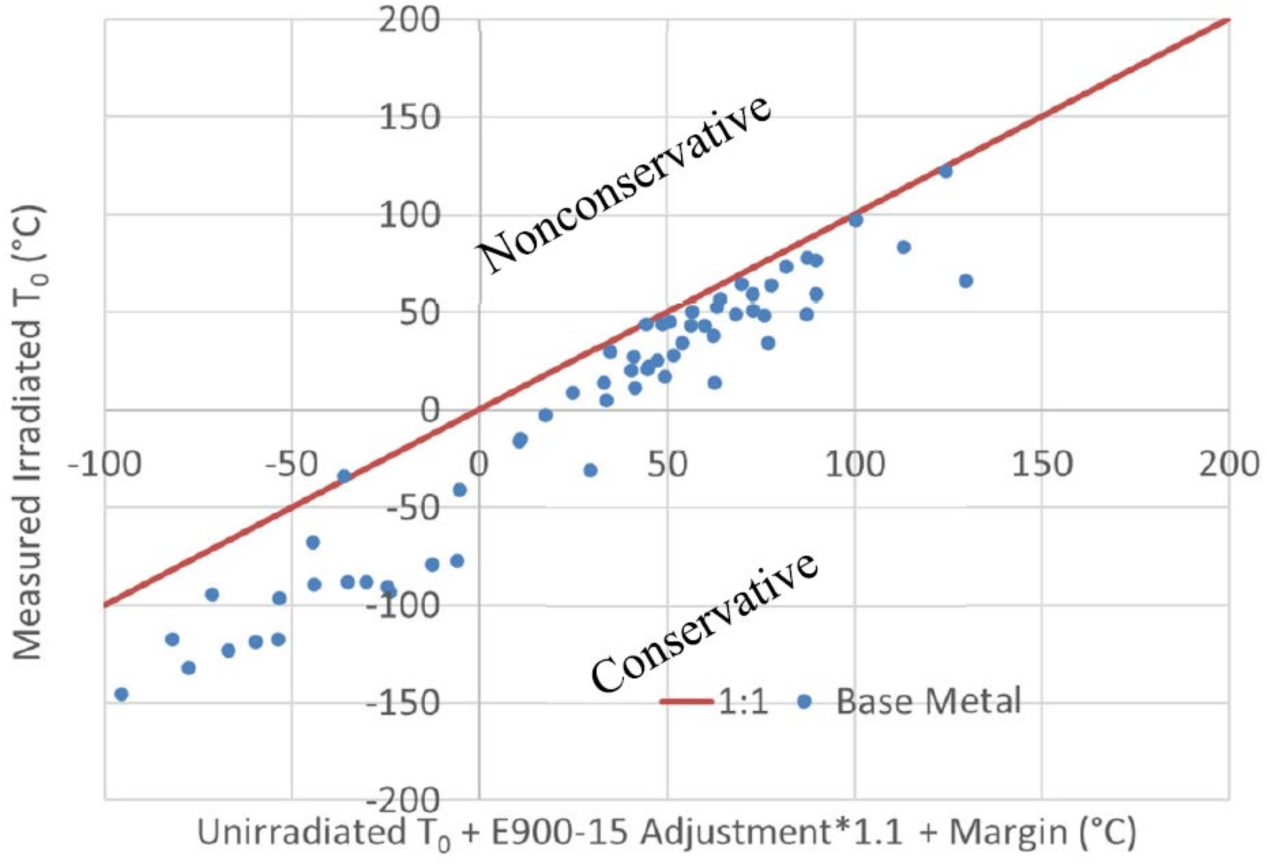

Figure 4 Bounding Adjusted T_0 Compared to Measured Irradiated T_0 for Base Metals

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

Margin Evaluation

- **Method was used with measured fracture toughness data to evaluate if margin is sufficient**
  - Irradiated T_0 was adjusted to another irradiated T_0 with margin added from same heat (2nd irradiated T_0 as if from RPV assessed)
  - With small adjustments, the 9°C is the value used for $\sigma_{adjustment}$
- **97% of the data is bounded**

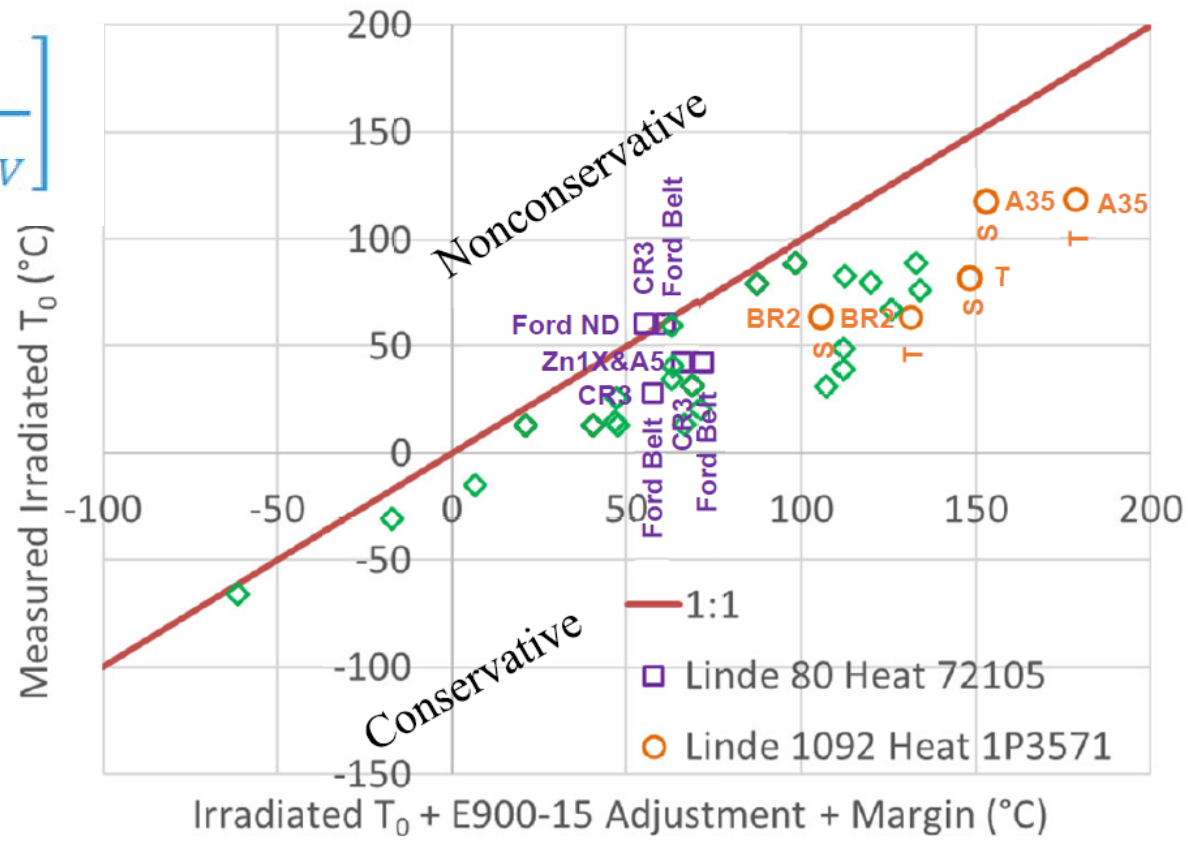

Figure 5 Bounding Adjusted T_0 Compared to Measured Irradiated T_0 for Weld Metals (horizontal labels indicate capsule names showing measured T_0; vertical labels indicate capsules from which measured T_0 was adjusted and margin added)

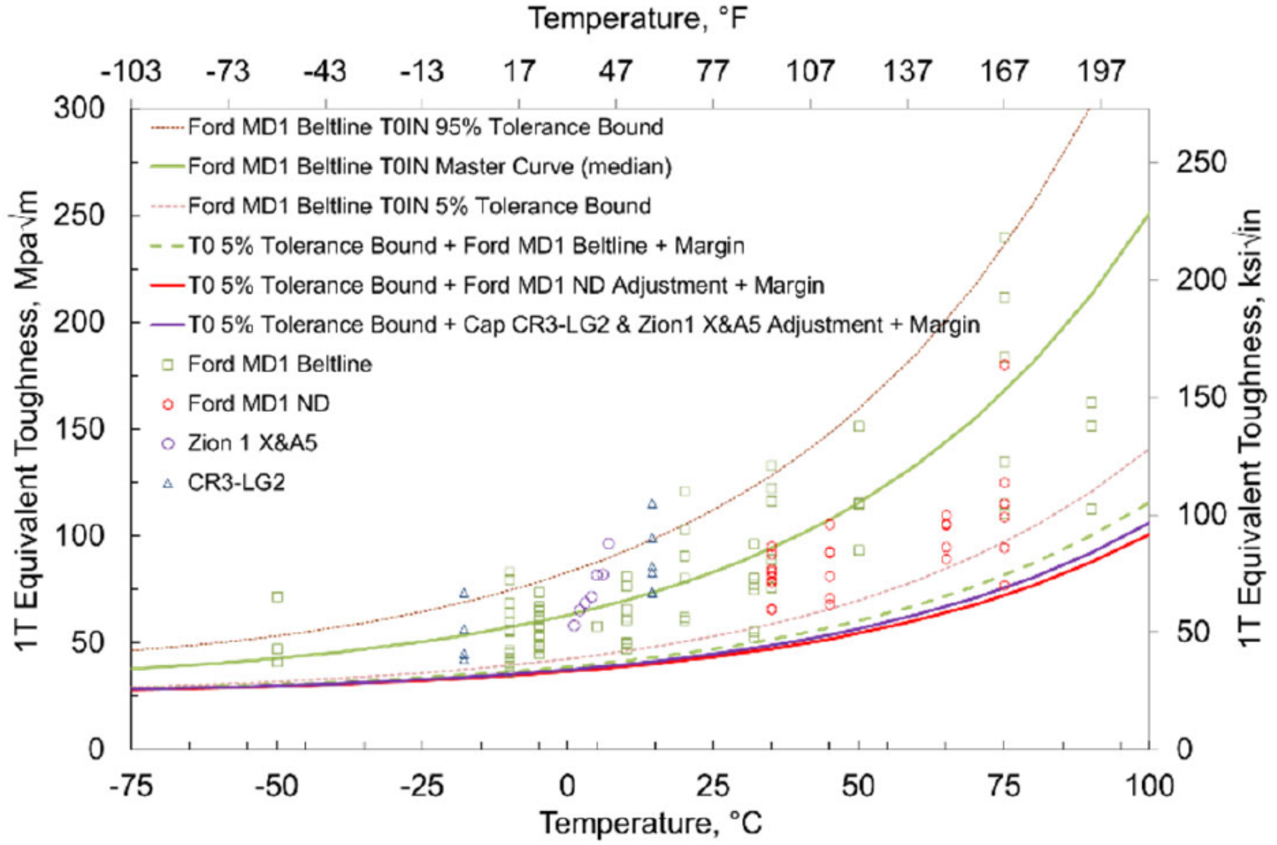

Figure 10 Comparison of Fracture Toughness Values to Bounding Curves for Weld Heat 72105 Adjusted from Ford Reactor MD1 Beltline T_{0IN}

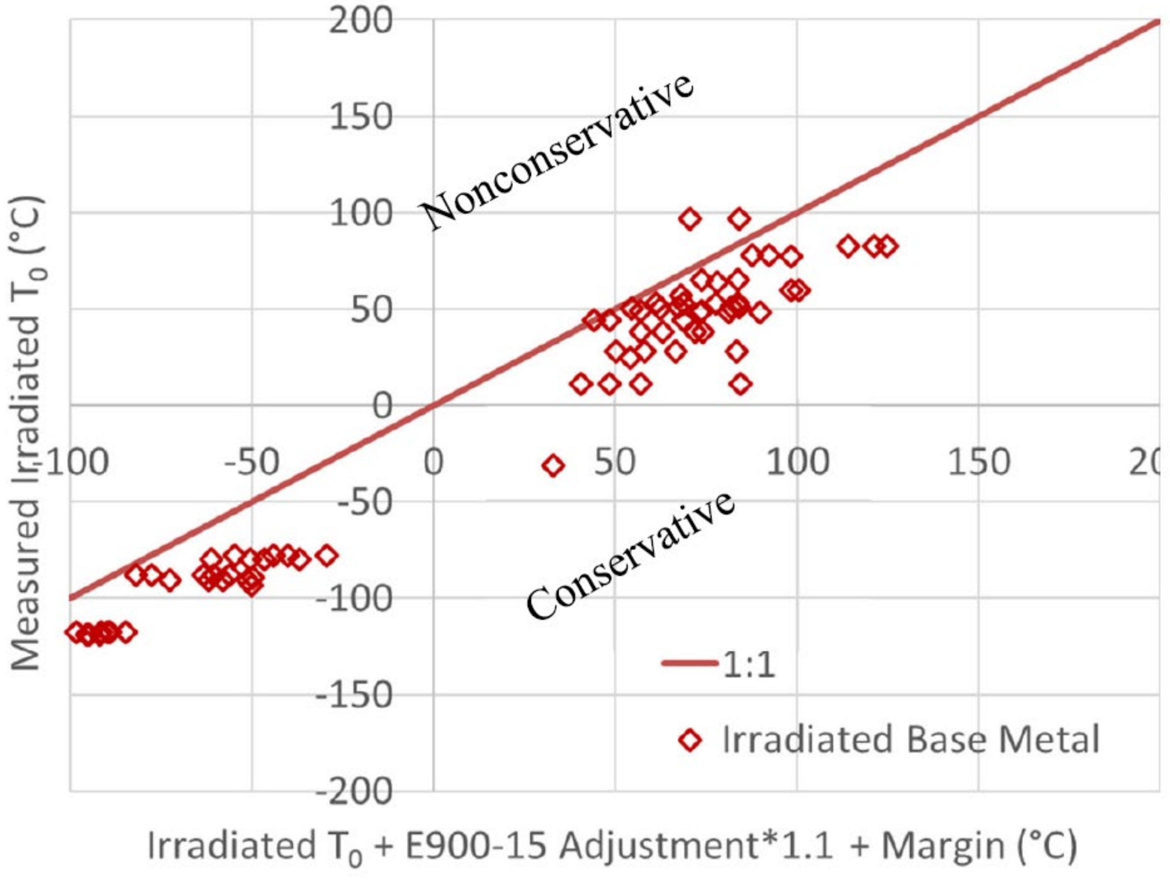

Figure 6 Bounding Adjusted T_0 Compared to Measured Irradiated T_0 for Base Metals

Basis: J. B. Hall, B. Golchert, and D. Simpson, "An Examination of Margins Needed to Ensure Conservative Application of T0 to RPV Fracture Toughness,"

ASME PVP2024-125225

PWROG-18068 Summary

The benefits of an irradiated direct fracture toughness data evaluation methodology are:

- Establishes a robust fracture toughness basis ensuring public health and safety by reducing uncertainty and enabling a statistical understanding of the actual irradiated RPV fracture toughness
- 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, adjustment and input uncertainties and material variability in the respective RPV component
    - Apply the data using the ASME Section XI Code.

Next Steps

- Application of approved PWROG-18068
  - Initiated PWROG project
    - Support submittal of 3 pilot plant evaluations using existing T_0 data
    - Develop detailed test matrix
      - Select limiting materials most likely to benefit most PWROG plants
      - Balance irradiated material testing cost vs. unirradiated vs. benefit
  - Extend life, license renewal
  - Uprates, 2-year cycles, fuel management changes, other increase in fluence to RPV
  - Extend P-T curve applicability or open operating window
  - Mitigate new surveillance data or other new potential information

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Collaboration Activities

- **Recent**
  - Dr. Chen and Sokolov have attended PWROG materials committee meetings to listen to ongoing activities and present LWRS work
  - ORNL provided archive Palisades pressurizer weld for use in plant SLR application of direct fracture toughness
  - PWROG provided unirradiated archive Zion Unit 1 weld and plate to ORNL so that irradiated RPV beltline test results could be compared
  - Palisades high fluence capsule was withdrawn, shipped, disassembled with specimens sent to ORNL for testing
  - Provided unirradiated archive Palisades weld and plate to ORNL so that irradiated high fluence capsule test results could be compared
- **Future possibilities**
  - Test Zion Unit 1 surveillance capsule materials for T_0 to compare to RPV shell test results
  - Testing and expertise to help resolve observed ductile instabilities (test record crack jumps) when testing irradiated stainless and RPV steel on upper-shelf

Questions?

The Materials Committee is established to provide a forum for the identification and resolution of materials issues including their development, modification and implementation to enhance the safe, efficient operation of PWR plants.