PROPOSED ASME CC N-830-1

DIRECT USE OF FRACTURE TOUGHNESS FOR FLAW EVALUATIONS OF PRESSURE BOUNDARY MATERIALS IN CLASS 1 FERRITIC STEEL COMPONENTS

Working Group Members

Marj Erickson, PEAI
erickson@peaiconsulting.com

Mark Kirk, PEAI

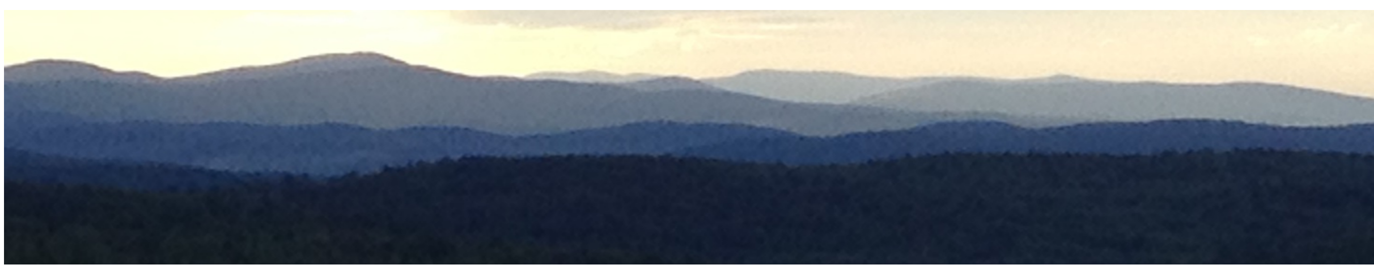
Tim Hardin EPRI

Bill Server, ATI

Russ Cipolla, Intertek

Brian Hall, Westinghouse

Meeting with USNRC
January 13, 2020



OUTLINE

- Background
- Summary of CC N-830-1
- Summary of MRP 418 (Rev 0 and Rev 1)
- NRC Comments
- Changes Made to Address NRC Comments
- Summary

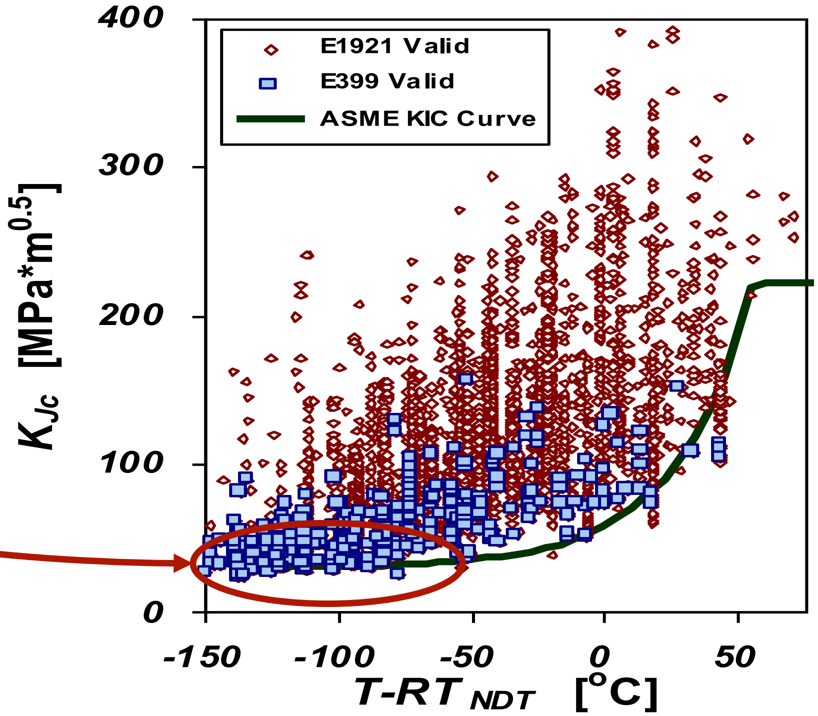
Motivation for CC N-830-1

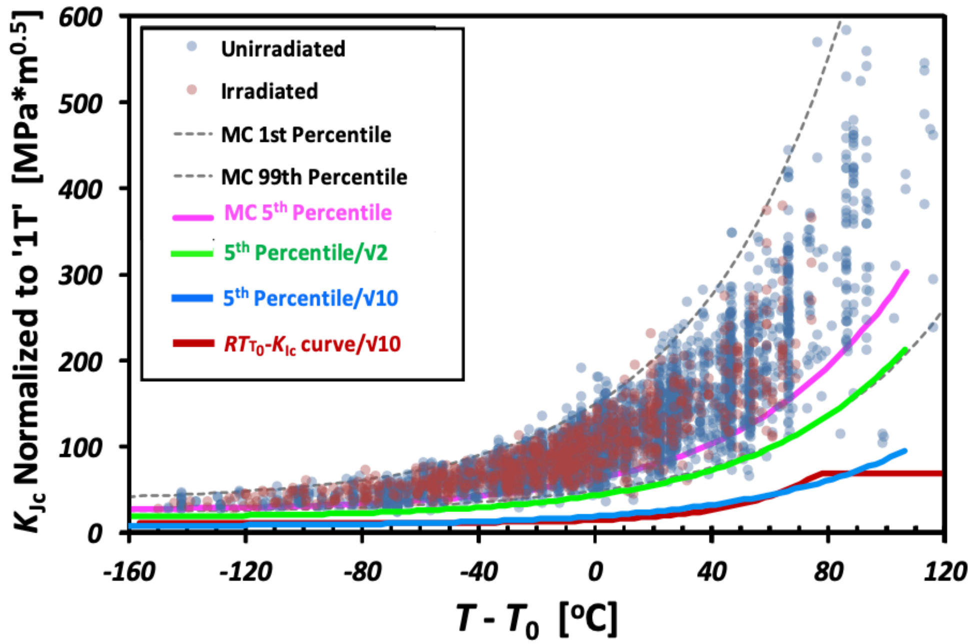
RT_{NDT} does not position the K_{Ic} curve consistently relative to the data

- The K_{Ic} curve is a conservative lower bound to a majority of the toughness data
- The K_{Ic} curve is non-conservative on the lower shelf compared to measured toughness values

CC N-629/631 (now in Code) allows use of RT_{T0} in lieu of RT_{NDT} to reduce conservatism, but use with the K_{Ic} curve still provides inconsistent representation of the toughness data

CC N-830 provides for use of T_0 to position the 5TH% LB ASTM E1921 fracture toughness curve (MC) but does not address arrest toughness or upper shelf toughness

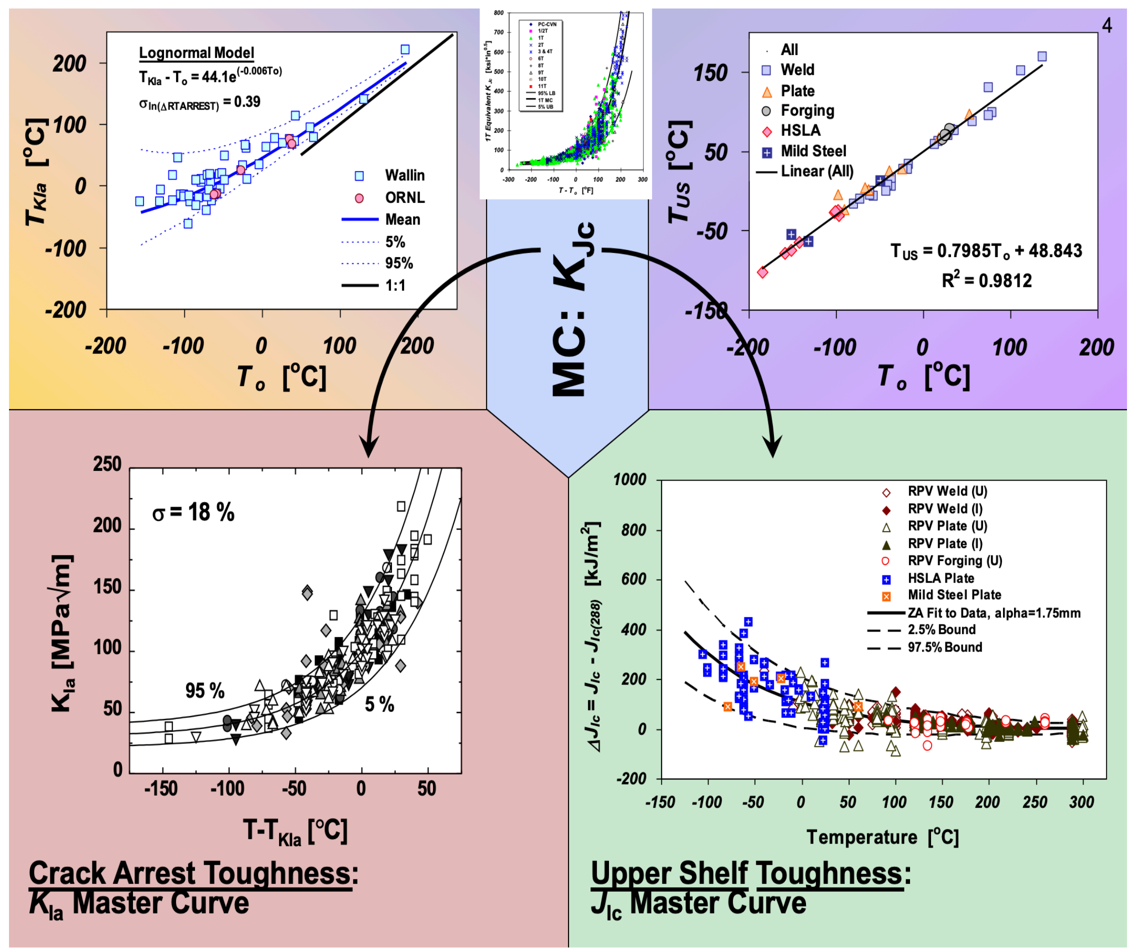




Basis & Benefits of ASME CC N-830-1

A complete & self-consistent suite of best estimate models, all linked to a single parameter, T_0, provides tremendous advantages over the current ASME Code models for fracture toughness:

- Linked toughness models account for hardening effects on inter-relationship of toughness metrics
- Full description from lower transition to upper shelf toughness (i.e., K_{Jc}, K_{Ia}, $J_{Ic}/J_{0.1}/J\text{-}R$)
- Manages transition from LEFM to EPFM analysis organically
- Supports both deterministic and probabilistic assessments



N-830-1

Proposed Code Case N-830-1

Inquiry

What current best-estimate (alternative) fracture toughness models and relationships may be used for flaw evaluations performed in accordance with Nonmandatory Appendix A and/or Nonmandatory Appendix K in lieu of the current requirements of these Appendices to determine values of K_{Ic}, K_{Ia}, J_{Ic}, $J_{0.1}$, and J-R?

Response

It is the opinion of the Committee that the fracture toughness models based on the Master Curve Method in accordance with ASTM E-1921 may be used in lieu of the current requirements of Nonmandatory Appendices A or K when determining values for K_{Ic}, K_{Ia}, J_{Ic}, $J_{0.1}$, and J-R using the procedures and equations given below.

CC N-830-1 Structure

Article	Article Title	Detail
1000	Scope	Defines the variation of fracture toughness as a function of temperature over the entire material toughness range of interest to operating Division 1, Class 1 vessels (lower shelf, transition and upper-shelf).
2000	Reference Toughness Temperature (input)	Defines $T_{0(adj)}$ used to index all fracture toughness curves accounting for uncertainty in knowledge of T_0
3000	Toughness Variability	Provides for using 5% LB curves to account for toughness variability
4000	Toughness Curves (output: K_{Jc}, K_{Ia}, J_{Ic}, J_{xx})	Provides equations describing the temperature dependence and variability associated with cleavage and ductile crack initiation toughness, and of cleavage crack arrest toughness.
5000	Applicability Limits	Provides the limits over which the curves of -4000 can be applied
6000	Applications	Provides guidelines on bounding percentiles to use in flaw tolerance, and acceptable toughness calculations performed according to the provisions of the ASME Code.
7000	Unit Conversions	SI to US Customary
8000	Nomenclature	Defines symbols and abbreviations used in Code Case.

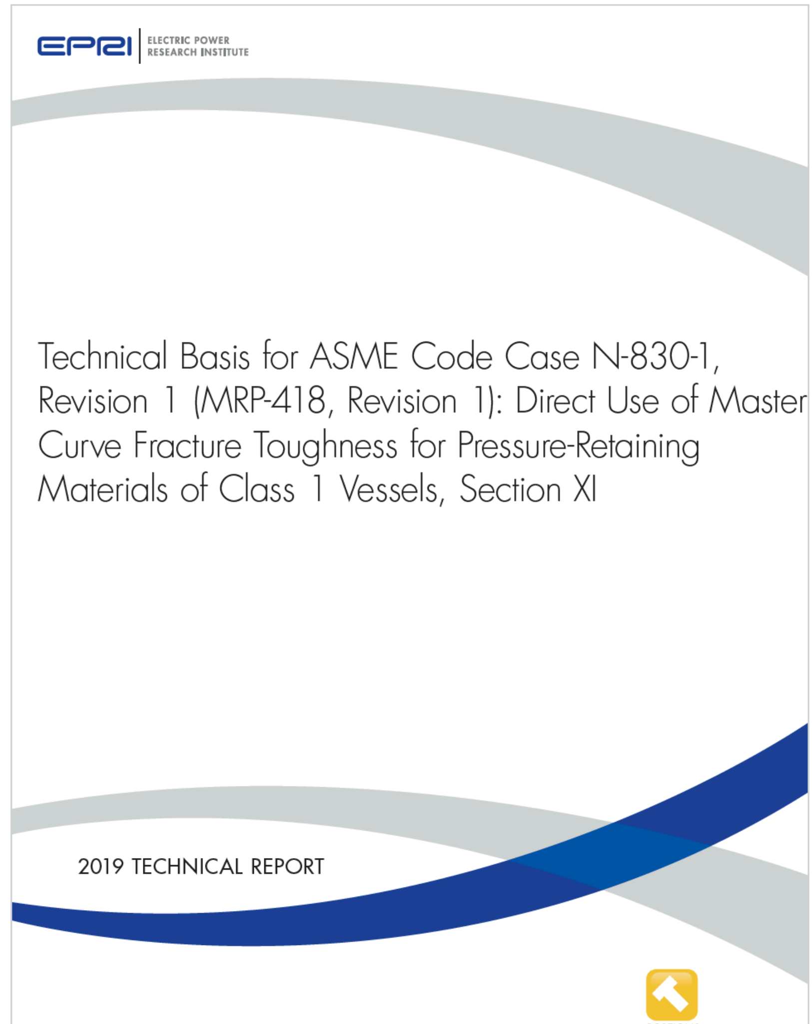
N-830-1

Benefits of CC N-830-1

- **The level of margin / level of safety achieved is much more consistent between various plants when using CC N-830-1 models than is possible using current correlative methods.**
  - Future applications of CC N-830-1 models will likely be situations where licensees have been unable to demonstrate compliance using current methods
  - It is most important in these situations to have consistent, calculable margins
  - This is where the CC N-830-1 models provide their greatest benefit relative to existing models
- **The theoretical framework underlying the CC N-830-1 models, that includes the physical assumptions upon which the models are based and an understanding of the aleatory and epistemic uncertainties inherent to the models, is a key feature that current correlative Code methods lack.**
- **This theoretical framework provides the context for:**
  - Defining the full range of applicability and limitations of the models
  - Consistent assessment of margins to account for uncertainties

CC N-830-1 Technical Basis Document
Issued Oct 27, 2017
Rev 1 Issued November 19, 2019

https://www.epri.com/#/pages/product/000000003002016008/



Contains a summary of all direct and linkage models that includes:

- Theoretical basis
- Empirical basis
- Validation
- Limitations

Contains a Chapter describing current, and proposed methods for accounting for uncertainty in flaw evaluations

Includes potential applications of CC N-830-1

Includes Sample Problem results summary

Includes Proposed CC N-830-1

Includes NRC Comments and Working Group responses

N-830-1

NRC Comments

- **41 detailed comments from review of MRP-418 Rev 0 received April 2018**
- **Most pertained to the technical basis report and supporting documents, some pertained directly to the proposed CC N-830-1**
- **NRC subdivided the comments into**:
  - General Code Case Issues (21 comments),
  - Issues of Medium Significance (18 comments),
  - Editorial Issues (2 comments)
  - Comments covered all models but were ***primarily focused on upper shelf and linkage models, and uncertainty treatment***
- **The WG subdivided the questions into additional categories**
  - **Specifying Code use** for only deterministic assessment using bounding curves (#'s 1, 3, 4)
  - **Model validation** (#'s: 1, 5, 8, 10, 13, 17, 21, 25, 30, 31)
  - **Accounting for uncertainty** (#'s: 6, 9, 11, 12, 39)
  - **Clarification** (#'s: 2, 7, 14-16, 18-20, 22-24, 26-29, 32-41)

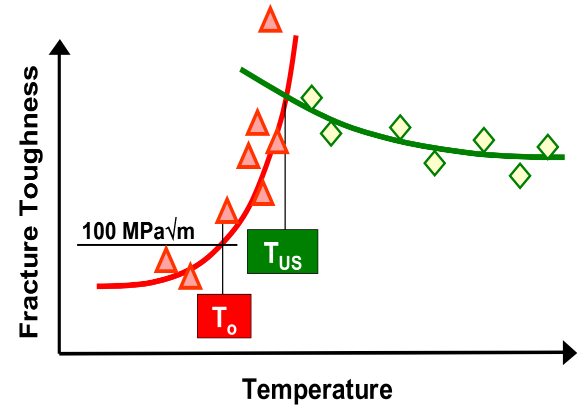
N-830-1

Major Differences Between MRP 418 Rev 0 and Rev 1

- **Background sections discussing Appendix K added to Chapter 1**
- **How uncertainties are accounted for was revisited and additional validation studies were performed**
  - T_0 changed to $T_{0(adj)}$ in Chapter 3 with definition added to Section 5.5 and to Article 4000 in CC N-830-1
  - Methods to account for uncertainty discussion and validation added to Chapter 5 (Section 5.5)
- **J_{Ic}/*J-R* model was revisited to provide stronger physical basis, recalibration of parameters, and validation**
  - Moved to Chapter 3 since J_{Ic}/*J-R* is a primary model
  - Validation added for T_0 to J_{Ic} (Section 3.3.6 and Section 4.1.4)
  - Validation added for T_0 to *J-R* (Section 3.4.5)
- **Additional statistical analysis to address NRC concerns resulted in modification to T_{US} model (Section 4.1)**

N-830-1

Code Case Changes



- **Explicitness in accounting for uncertainty**
  - **The value of T_0 shall be adjusted to account for the effects of epistemic uncertainty by adding the 2σ, where the uncertainty, σ, on T_0 is given in ASTM E1921:**

$$\sigma = \sqrt{\left(\frac{\beta^2}{r} + \sigma_{exp}^2\right)} \qquad T_{0(ADJ)} = T_0 + 2\sigma$$

  - **5% LB curve taken to describe all toughness values (K_{Jc}, K_{Ia}, J_{Ic}/$J_{0.1}$/J-R)**
    - "Bounding toughness curves for a deterministic analysis shall be generated from the equations in -4000 by using the values of p=0.05 and M_p =1.64."
    - "The values of p and M_p should be applied consistently to all toughness curves."
  - **Mean values of linkage models (T_{US} and $T_{K_{Ia}}$) are used**
- **A product form-dependent intercept was adopted into the T_{US} model**

N-830-1

Uncertainty Treatment

- **Both the index temperatures (T_0, T_{KIa}, T_{US}) and the toughness metrics (K_{Jc}, K_{Ia}, and J_{Ic}/*J-R*) *reflect the same uncertainties***
  - associated with experimental error (epistemic) and
  - material variability (aleatory)
- **Therefore, care must be taken in accounting for these uncertainties when the models are used together to avoid the possibility of '*double counting*,' which would produce *unrealistic and non-physical* estimates of fracture toughness.**
- **The approach adopted to date in proposed CC N-830-1 is as follows:**
  - **Account** for the experimental error and material variability in the toughness vs. temperature models by using a 5th percentile lower-bounding curve and $T_{0(adj)}$
  - **Do not account** for experimental error and material variability in the linkage models that relate the index temperatures (T_0, T_{KIa}, T_{US}), which themselves are determined from the K_{Jc}, K_{Ia}, and J_{Ic}, toughness vs. temperature data.

N-830-1

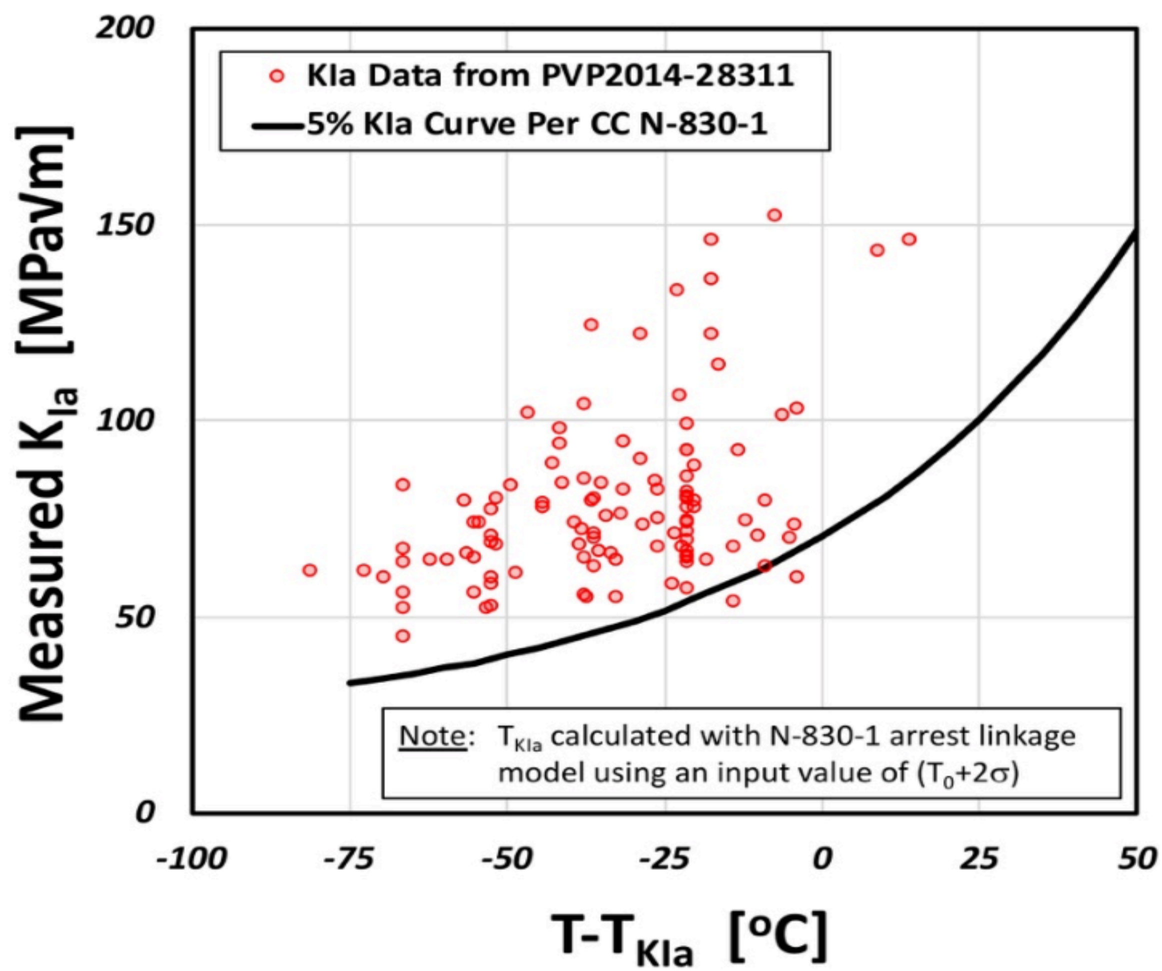
Validation of Uncertainty Treatment: T_0-K_{Ia}

111 measured K_{Ia} values plotted as a function of T-T_{KIa}, where T_{KIa} is estimated from measured T_0 values as follows:

$$T_{0(ADJ)} = T_0 + 2\sigma$$

$$T_{KIa} = T_{0(ADJ)} + 44.97exp[-0.00613T_{0(ADJ)}]$$

Approximately 95% Bounding is achieved using the mean linkage Models: T_0 - K_{Ia}



Validation of Uncertainty Treatment: T_0-J_{Ic}

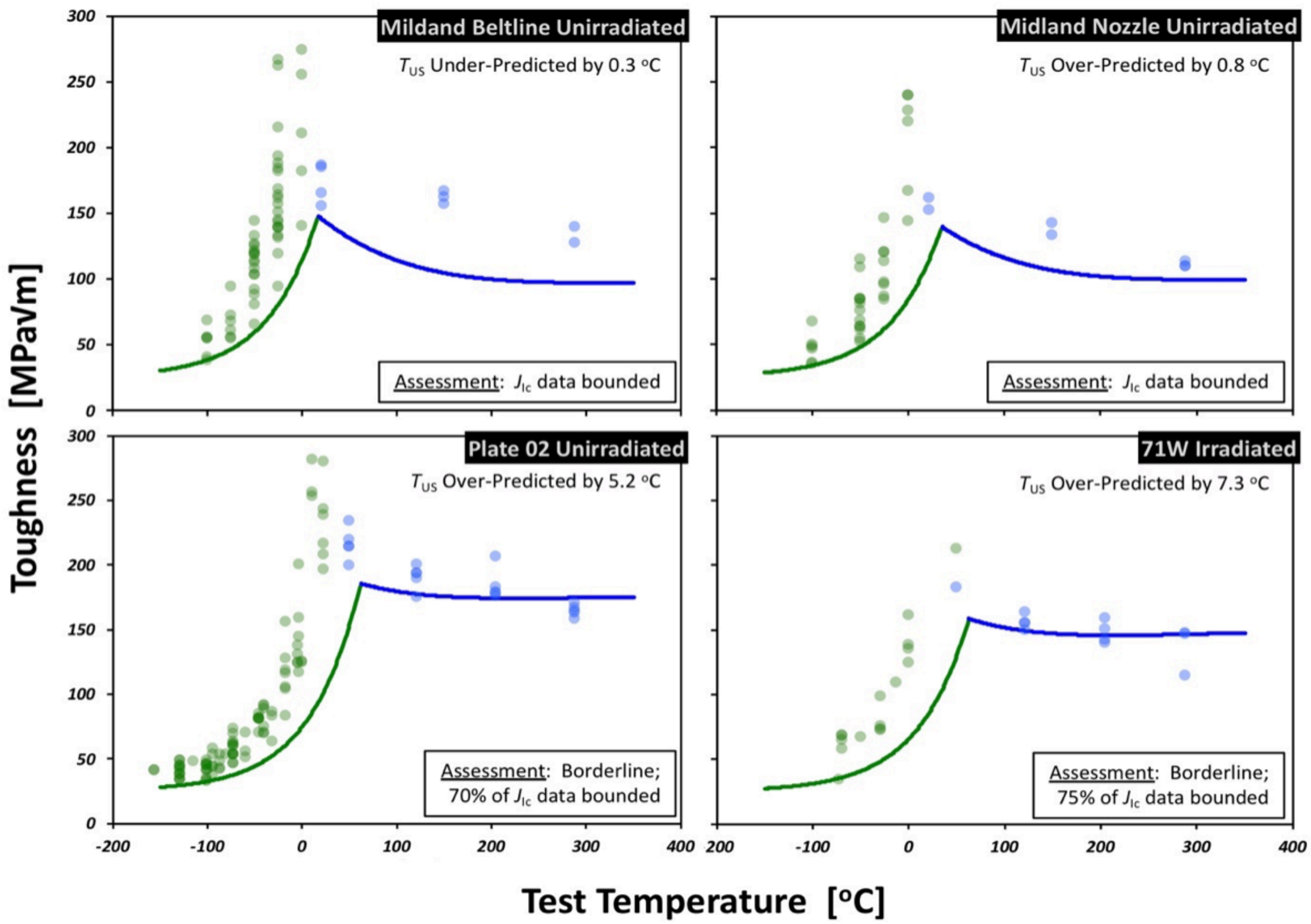
Four data sets with large number of both K_{Jc} and J_{Ic} data are examined to validate the T_0 – J_{Ic} uncertainty treatment:

- Midland Beltline (Unirradiated). T_{US} under-predicted by 0.3 °C.
- Midland Nozzle (Unirradiated). T_{US} over-predicted by 0.8 °C.
- Plate 02 (Unirradiated). T_{US} over-predicted by 5.2 °C.
- Weld 71W (Unirradiated). T_{US} over-predicted by 7.3 °C.

T_{US} over-prediction is of concern because it has the potential to produce over-estimates of J_{Ic}.

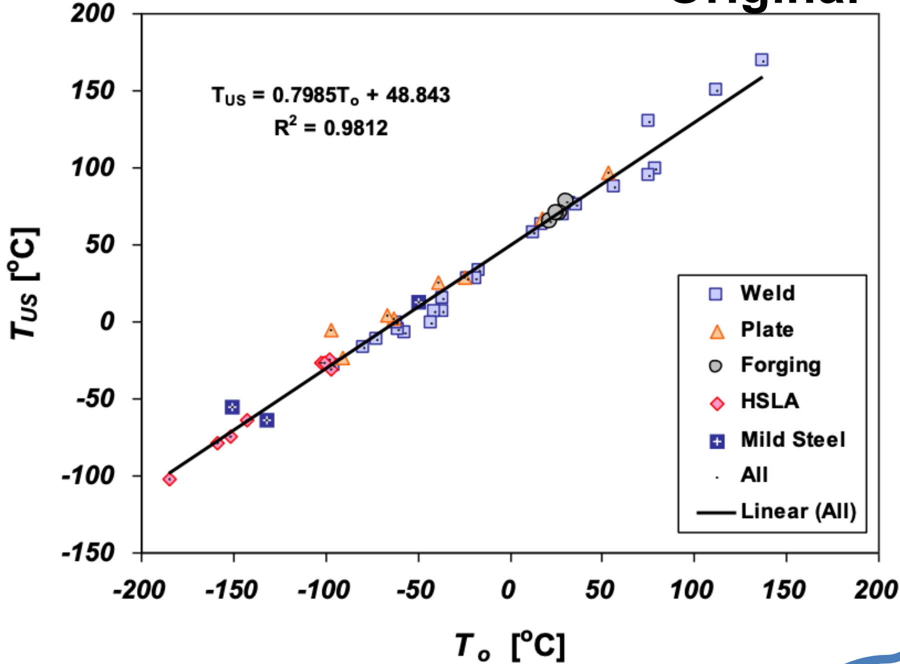
Approximately 95% bounding is achieved using the mean linkage Models: T_0 – J_{Ic}

Uncertainty treatment was also validated for T_0 to *J-R* predictions with similar results

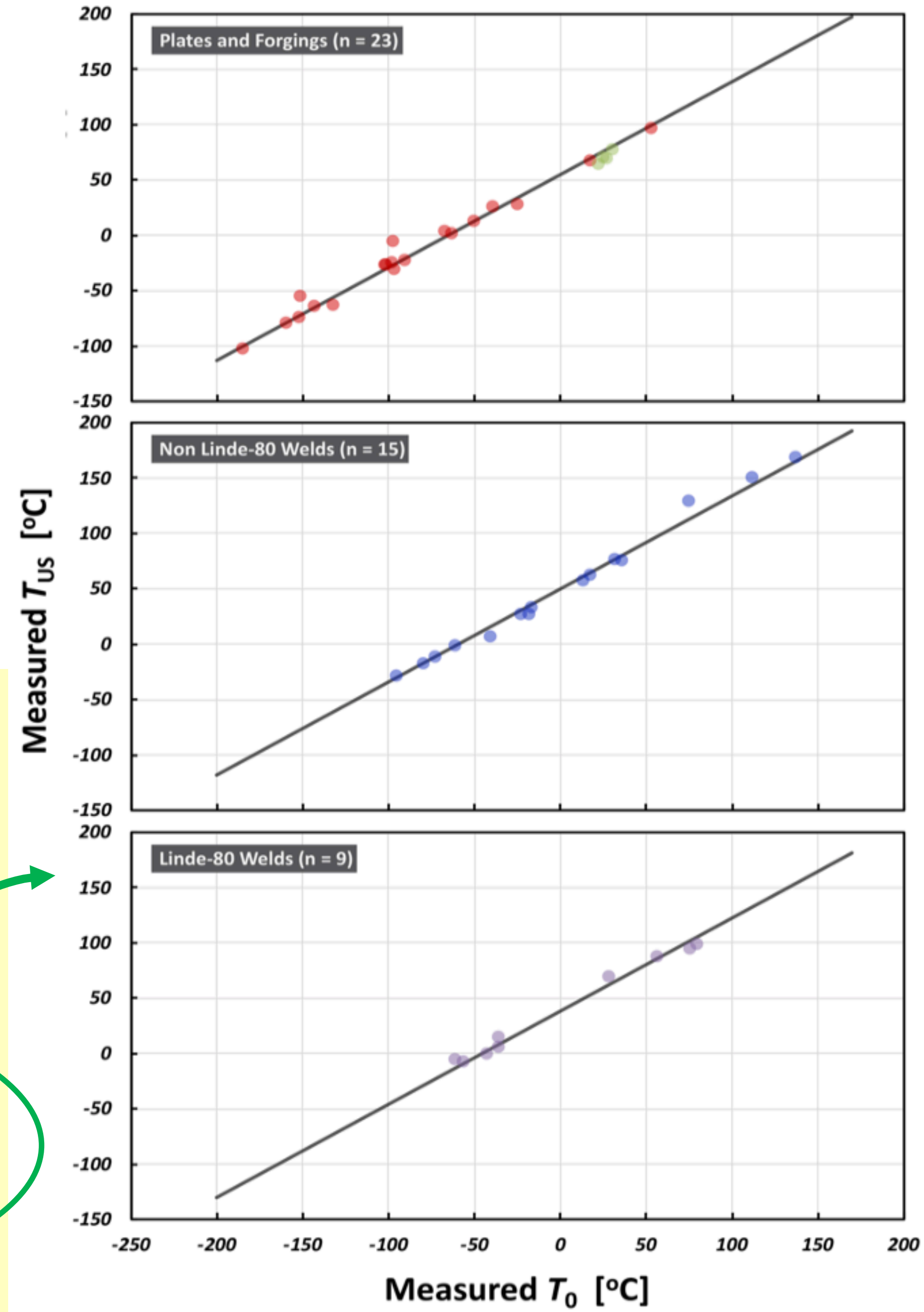


Changes to the T_{US} Linkage Model

Original



Re-assessment



- Effect of product form not assessed in model development resulted in:

$$T_{US} = 48.843 + 0.7985T_0$$

- Statistical reassessment of product form:

$$T_{US} = b_{PF} + 0.84T_0$$

where b_{PF} has units of °C and has the following values:

+54.5 °C for plates and forgings
+49.5 °C for non-Linde 80 welds
+38.0 °C for Linde 80 welds

J_{Ic}/*J-R* from T_0 Model Validation

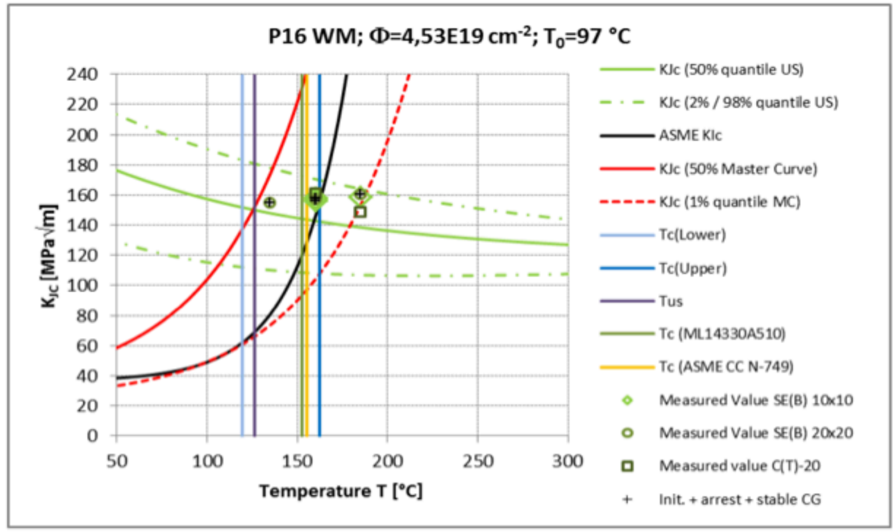
From the CARINA/CARISMA/CAMERA* program:

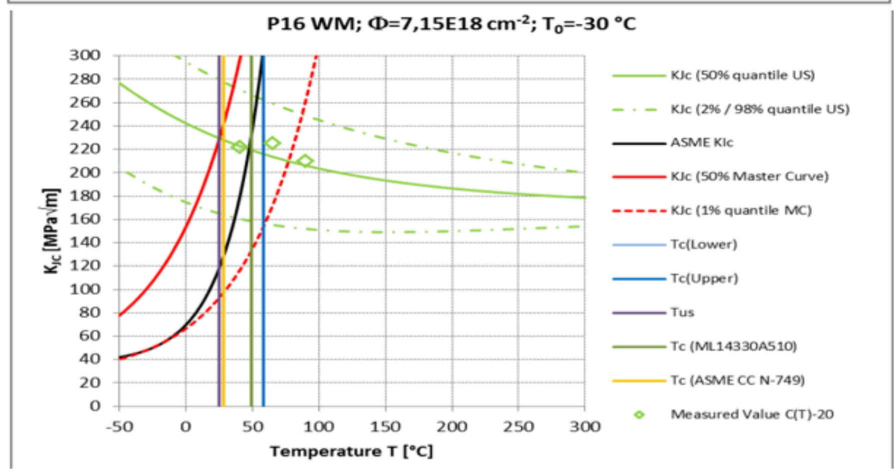
K_{Jc} and *J-R* tests were conducted on 7 materials in the unirradiated and irradiated conditions

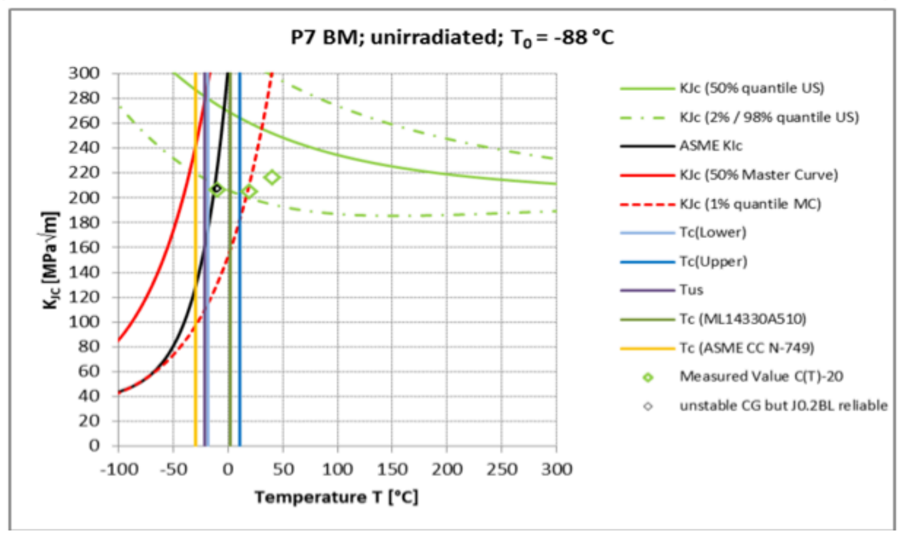
- The measured/calculated J_{Ic} data was compared to J_{Ic} predicted from T_0 using the N-830-1 procedure (T_{0mean} and the original T_{US} equation)
- The onset of upper shelf was compared to various T_{US} models including that of N-830-1

Study Conclusions:

- The upper shelf model of N-830-1 predicted the upper shelf test data well, including *T*-dependence.
- CC N-830-1 T_0-J_{Ic} predictions **bound** all of the data
- CC N-830-1 tended to underpredict J_{Ic} toughness.
- **Using T_{0adj} and the T_{US} with PF bias would tend to decrease J_{Ic} predictions**





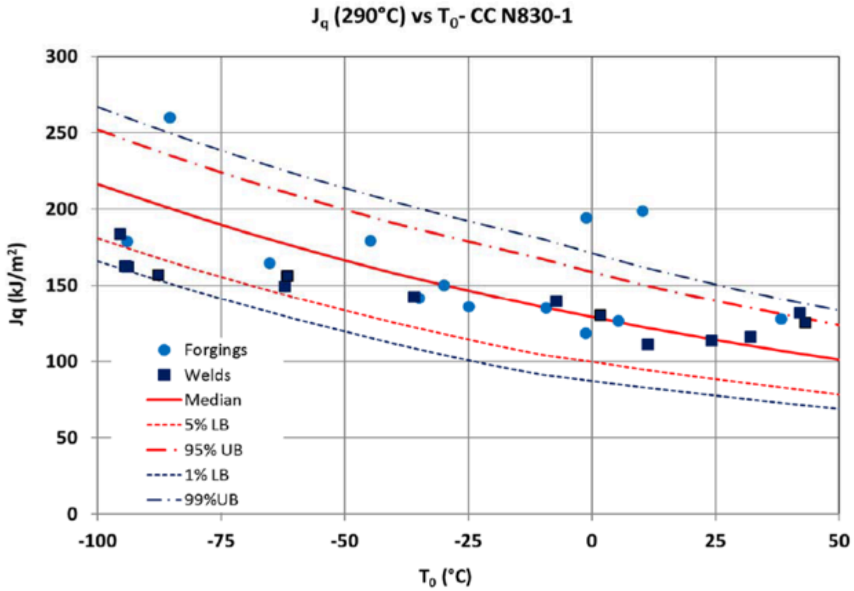


*Description of the entire fracture toughness curve including upper shelf on the basis of empirical T_0 correlation within the project CAMERA

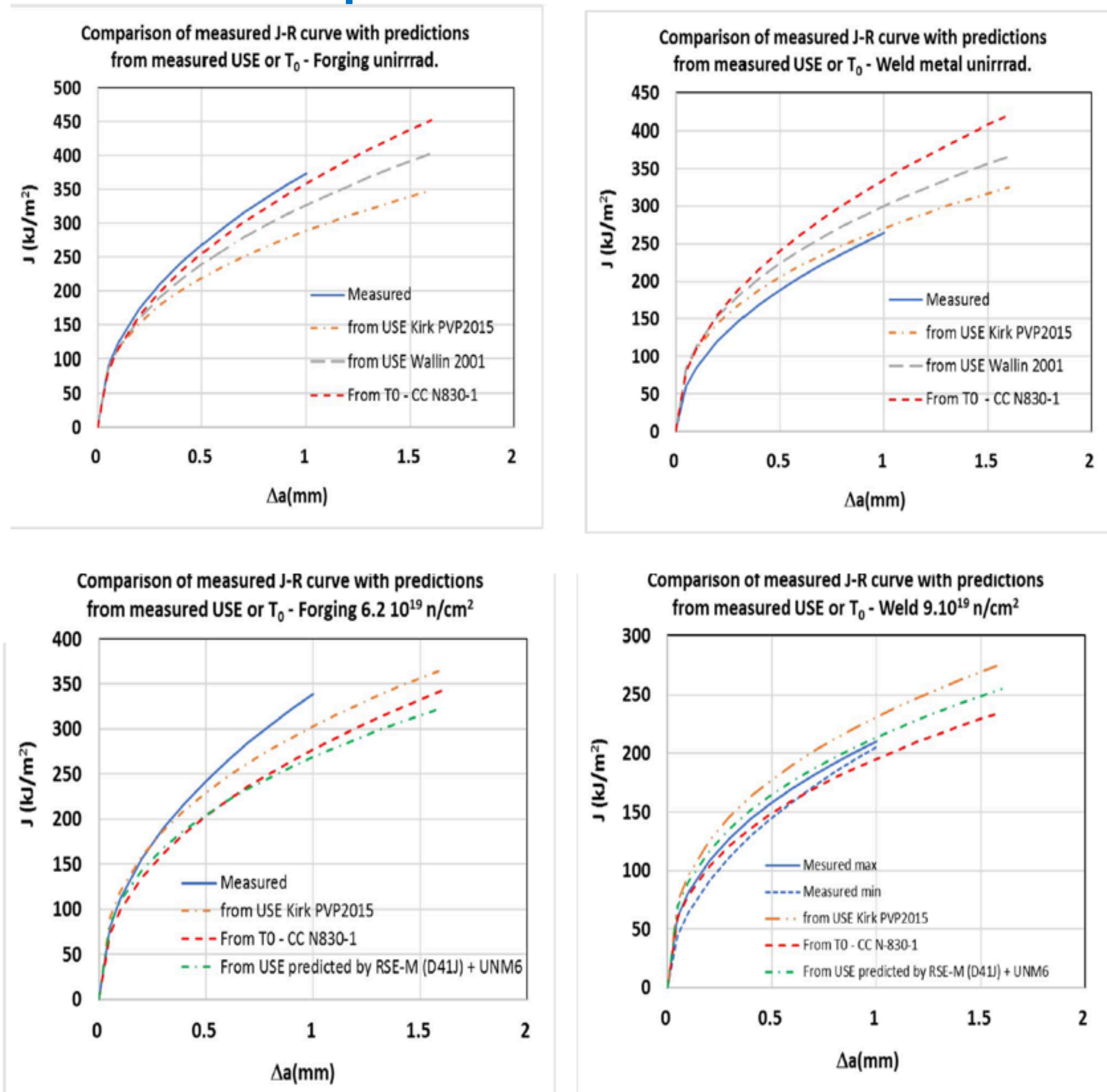
Kobiela, May, Keim, Jong, Efsing and Hein
FONTEVRAUD 9 | 17-20 September 2018 | Avignon, France

J_{Ic}/*J-R* from T_0 Model Validation

J_q compared to J_{Ic} predicted from N-830-1



Examples of *J-R* Curves



Studies by Gerard et al. on Belgian RPV steels show that:

- In some cases N-830-1 models over predict J_q and in others J_q is underpredicted, ***but***
- In all cases the data is within the N-830-1 predicted scatter.
- Modifications to N-830-1 eqns. would correct PF bias noted in this study

Irradiation Effects on Upper Shelf Energy and J-R Curves of Belgian RPV Steels, R.Gerard, W. De Koster, R. Chaouadi, D. Bertolis, D. Martens, **FONTEVRAUD 9 | 17-20 September 2018** | Avignon, France

N-830-1

Summary

ASME CC N-830-1 presents a complete & self-consistent suite of best estimate models, all linked to a single parameter, T_0, provides tremendous advantages over the current ASME Code models for fracture toughness:

- Linked toughness models account for hardening effects on inter-relationship of toughness metrics
- Full description from lower transition to upper shelf toughness (i.e., K_{Jc}, K_{Ia}, $J_{Ic}/J_{0.1}/J\text{-}R$)
- Uncertainties well-understood and consistently treated
- Models supported by strong theoretical and empirical bases
- Manages transition from LEFM to EPFM analysis organically
- Supports both deterministic and probabilistic assessments

MRP 418 Rev 1 provides comprehensive descriptions of all models from development through validation, including limitations and how uncertainties are accounted for.

The Code Case development process, that included detailed NRC Staff review, provided clear benefit to both the CC N-830-1 and the technical basis document.

- How uncertainties are accounted for was revisited and additional validation studies were performed
- $J_{Ic}/J\text{-}R$ model was revisited to provide stronger physical basis, recalibration of parameters, and validation
- Additional statistical analysis to address NRC concerns resulted in modification to T_{US} model

N-830-1

Are there Questions on specific ASME Working Group responses to NRC Comments?????