Accounting for Uncertainty in Complex Relationships

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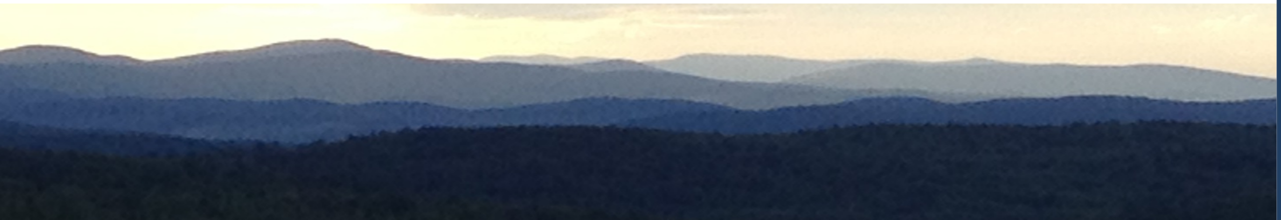


Phoenix Engineering Associates Inc.

Presentation Outline

START

Background: PFM codes and uncertainty treatment

Material property models and interrelationships

Appropriate treatment of uncertainty in interrelated material property models

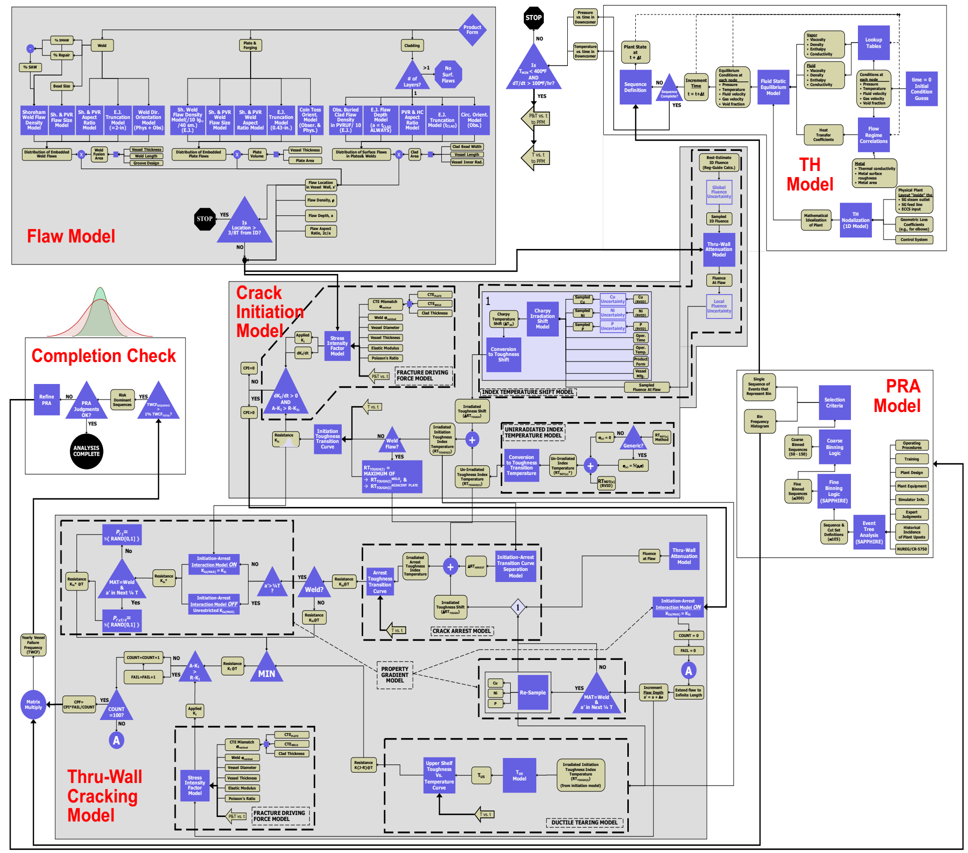
Uncertainty treatment in complex probabilistic code FAVOR

Summary & Conclusions

END

Probabilistic Models & Codes

- **Probabilistic codes are comprised of:**
  - a set of models & sub models
  - linked by a framework that enables sampling
    - on distributed input variables and model parameters
    - to account for uncertainty contributions from various sources directly and explicitly.
- **Appropriate treatment of uncertainties is key to interpreting the outcomes**
  - Information flow through a code controls the cumulative impact of various sources of uncertainty on failure probabilities.
  - Sub-models must be linked together appropriately to ensure that there is no distortion of the flow of information
    - Avoid double counting of uncertainty contribution from key factors
    - Appropriately account for model bias



PFM Codes

- Involve models to describe:
  - Crack driving force defined by
    - environment
    - loading
    - geometry
    - manufacturing
  - Material crack resistance defined by
    - strength
    - toughness
    - fatigue
    - SCC
  - Treatment of uncertainties

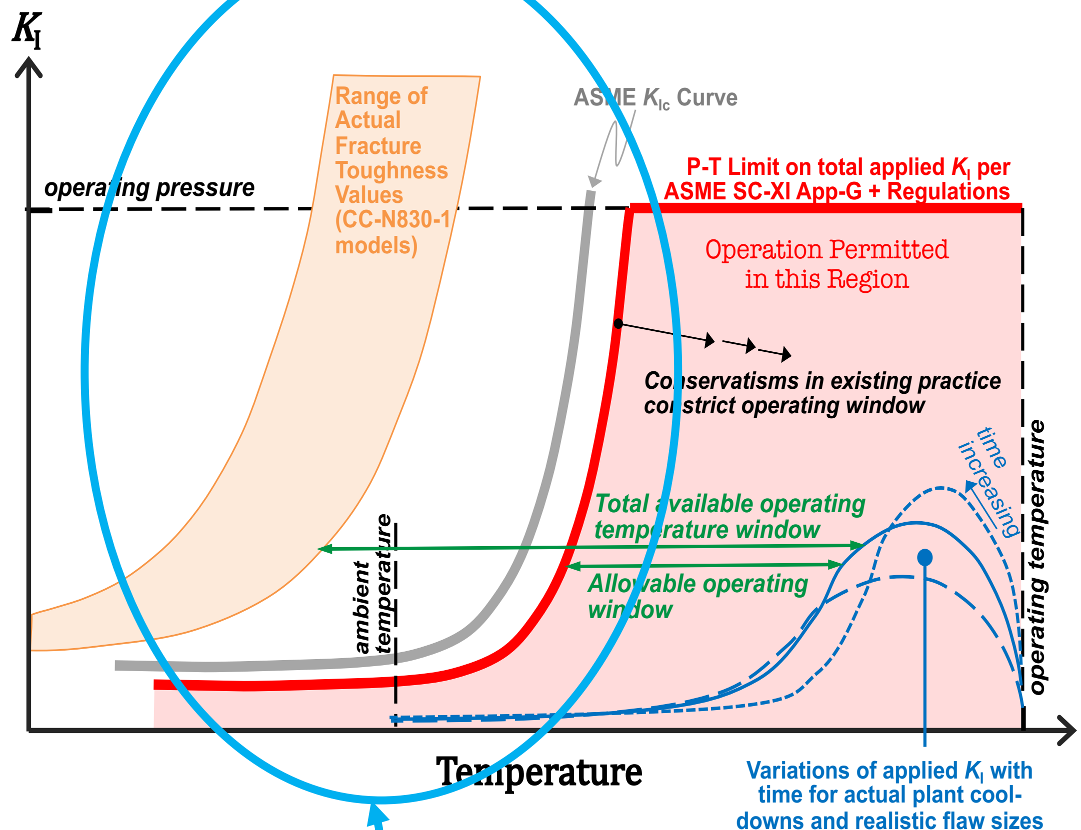
  that represent some phenomena of interest

- Material crack resistance is the focus of this presentation

Driving force ≤ material resistance

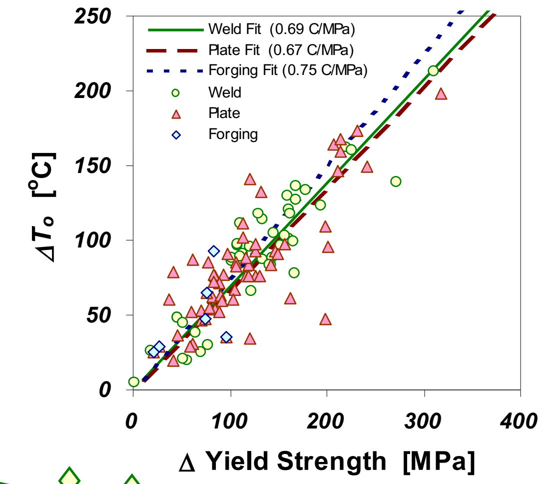
or

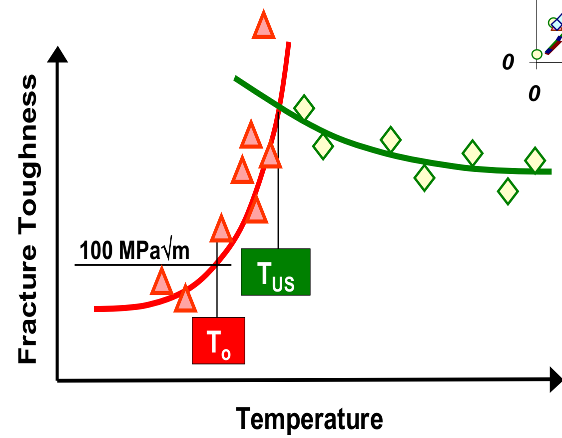
$T_{operating} \geq T_{cleavage\ toughness}$

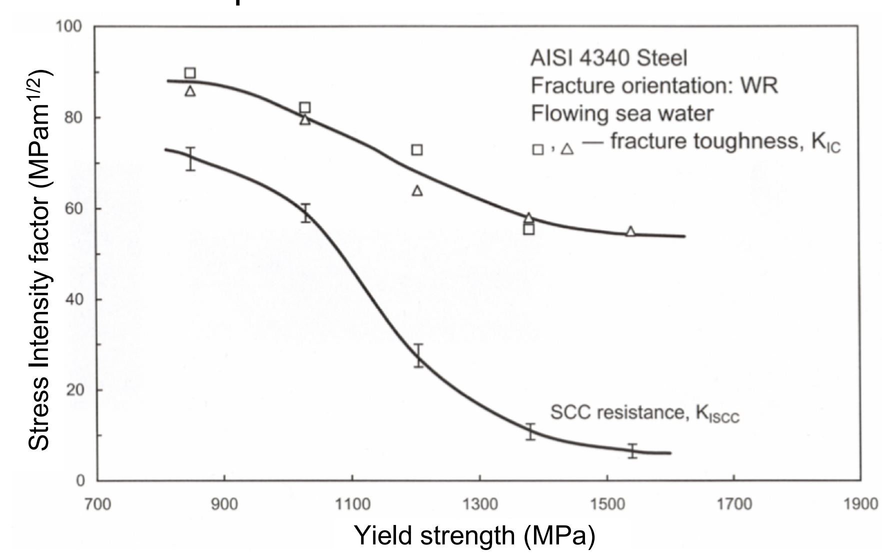


Models of Material Resistance to Failure

- Material resistance to through-wall cracking is characterized by various material properties:
  - Strength
  - Fracture toughness
  - Fatigue and SCC initiation and growth rates
- All of these properties are uncertain/distributed
- Many of these properties are correlated & the correlations are uncertain
- Models of properties and correlations should capture the uncertainty inherent in the data





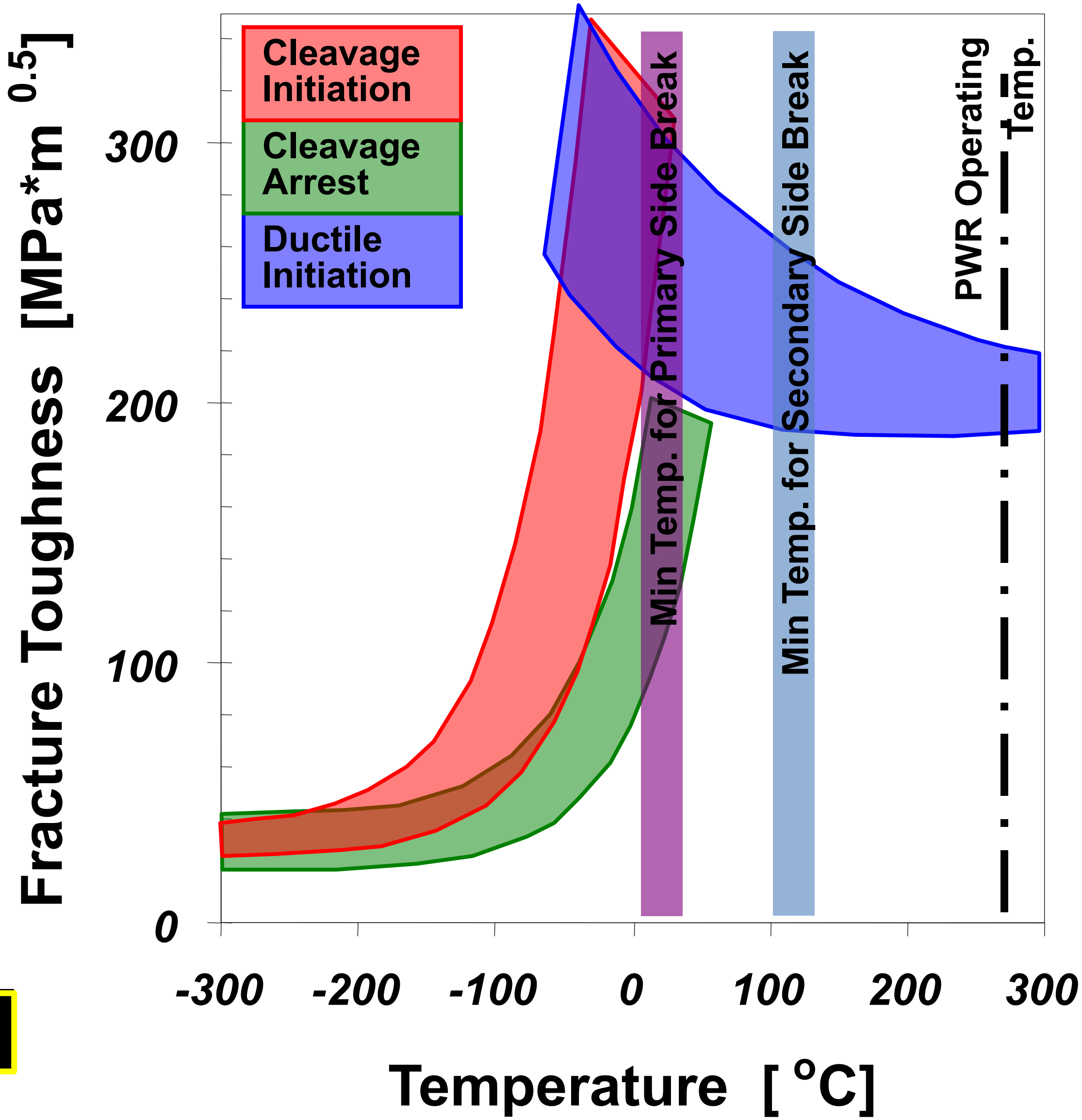


Focusing on Fracture Toughness:
An Illustration of Linked Toughness Distributions

- The behavior of ***all*** toughness properties of interest with hardening/ embrittlement is related and can be characterized by the reference temperature (T_o)
  - Cleavage crack initiation (transition)
  - Stopping (arresting) a running cleavage crack
  - Ductile crack initiation (upper shelf)

- Example: Toughness curves for the most embrittled axial weld in a highly embrittlement plant
  → At beginning of life

T_o= +126°C



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- Example: Toughness curves for the most embrittled axial weld in a highly embrittlement plant
  - → At beginning of life
  - → At 40 years

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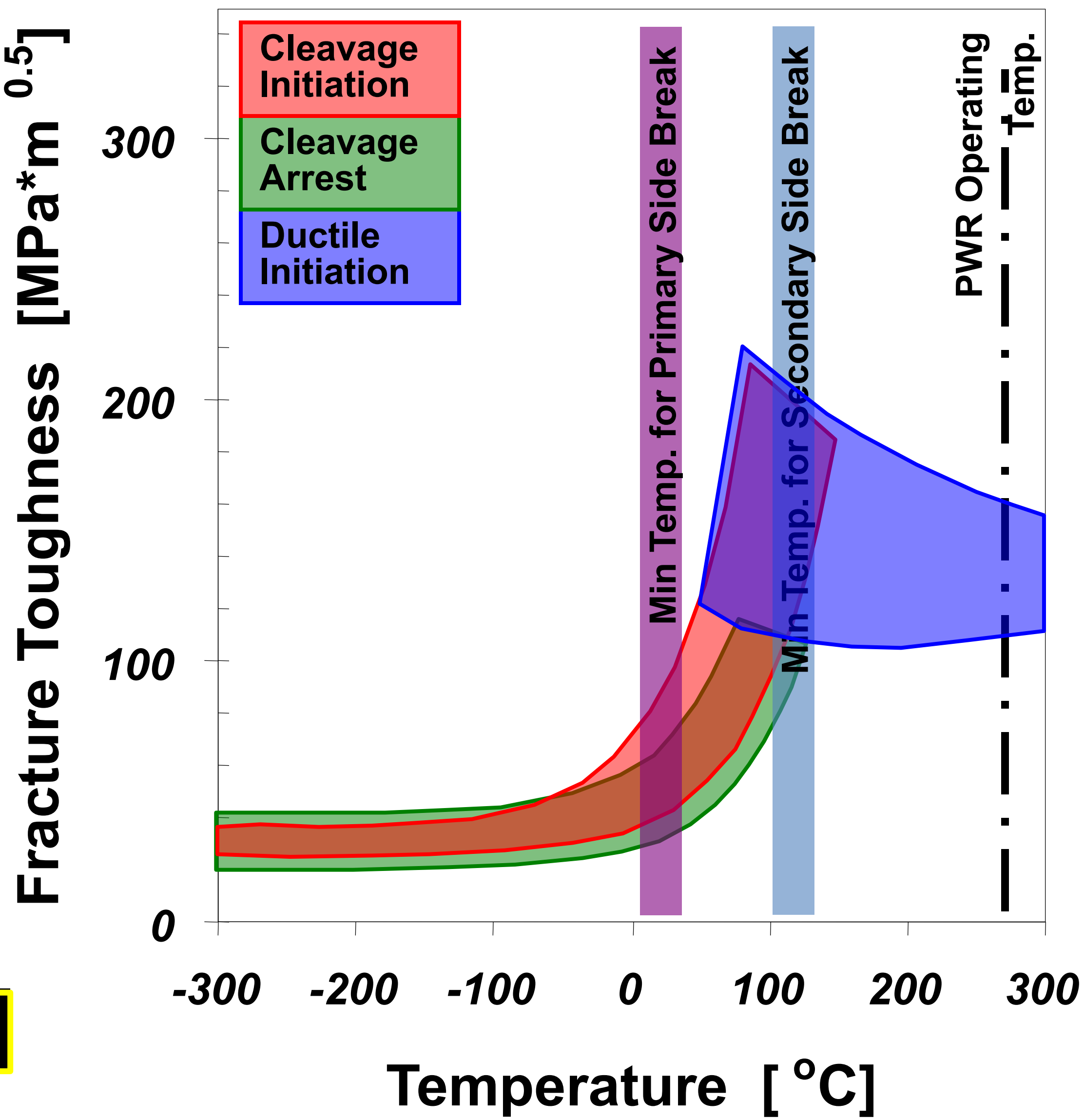

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- Example: Toughness curves for the most embrittled axial weld in a highly embrittlement plant
  - → At beginning of life
  - → At 40 years
  - → At 60 years

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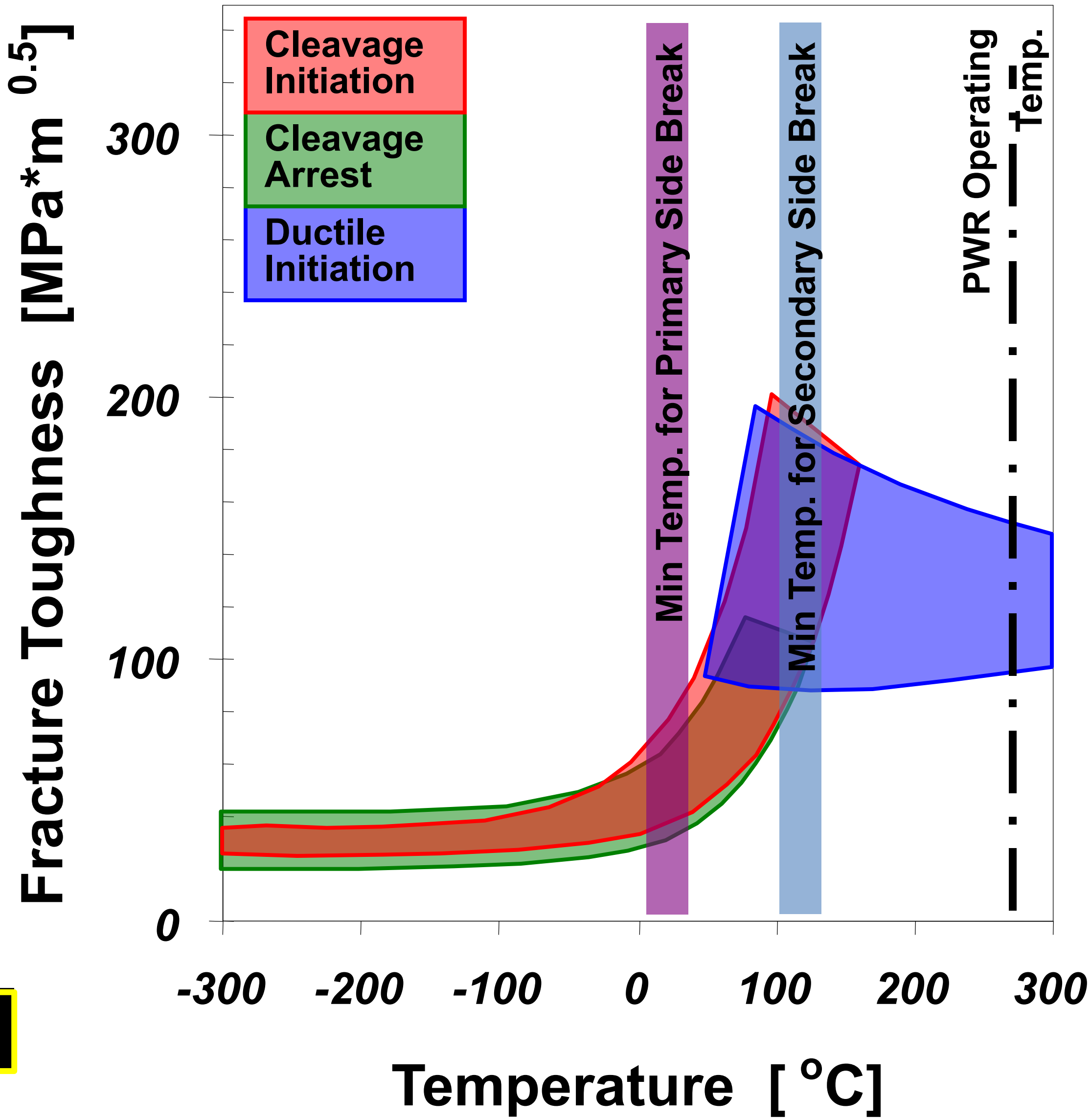

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- Example: Toughness curves for the most embrittled axial weld in a highly embrittlement plant
  - → At beginning of life
  - → At 40 years
  - → At 60 years
  - → At TWCF ≈ 10^{-6} / year

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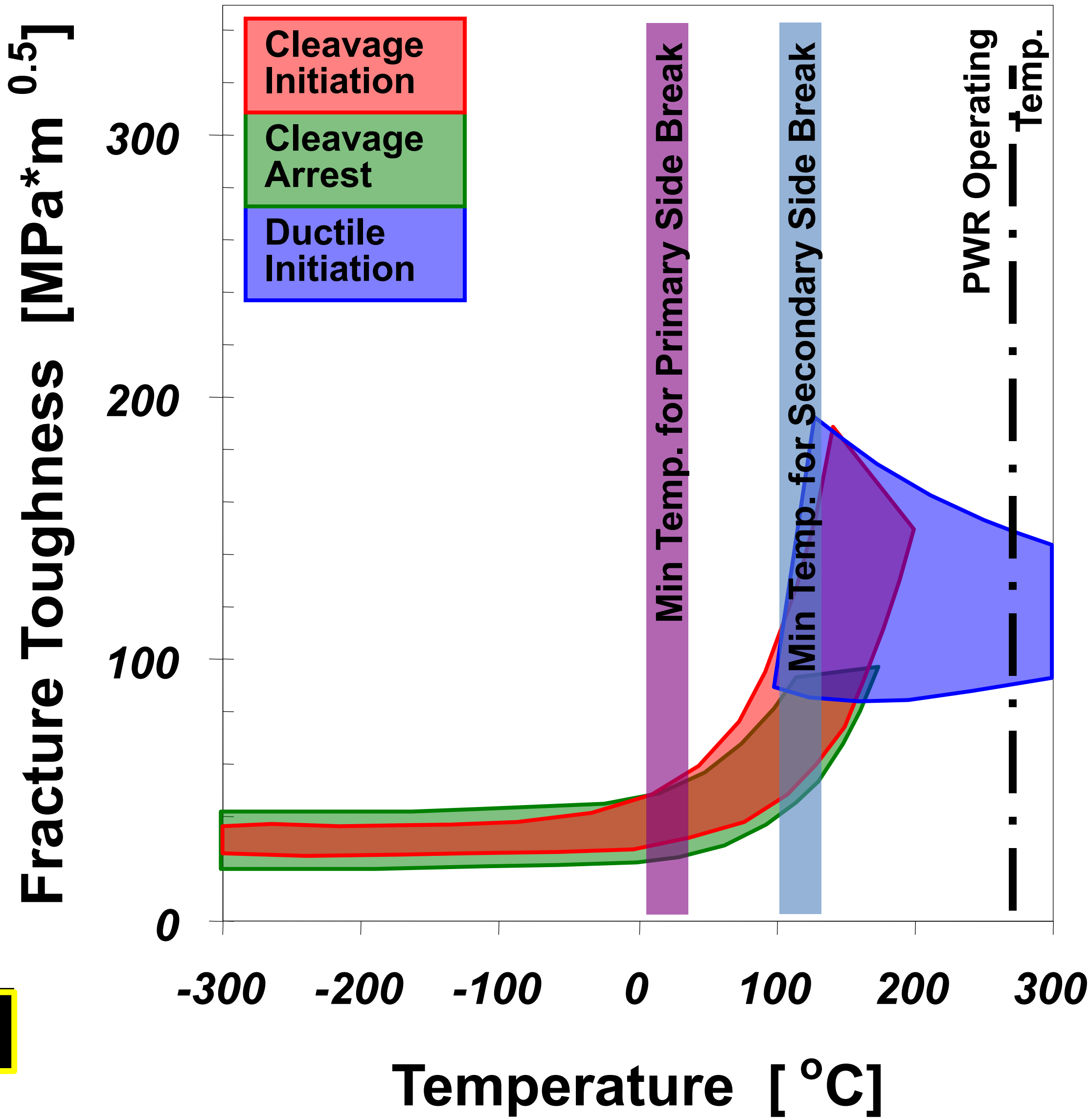
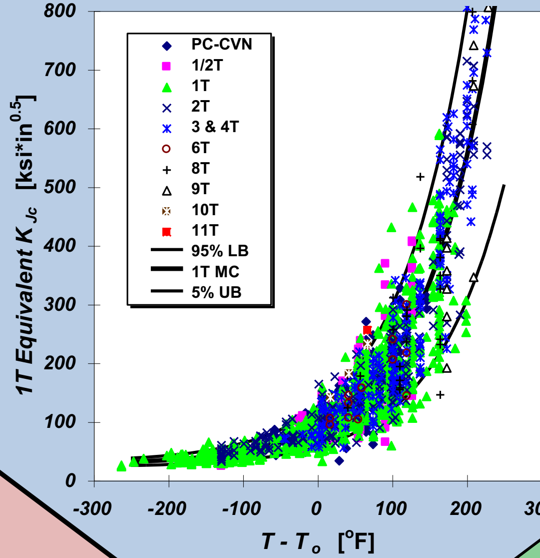


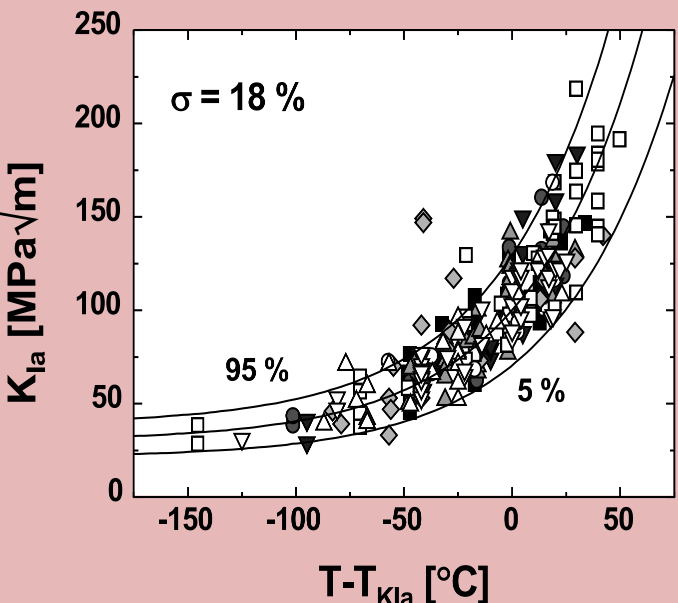
MC-based Fracture Toughness Models

Crack Initiation Toughness: K_{Jc} Master Curve

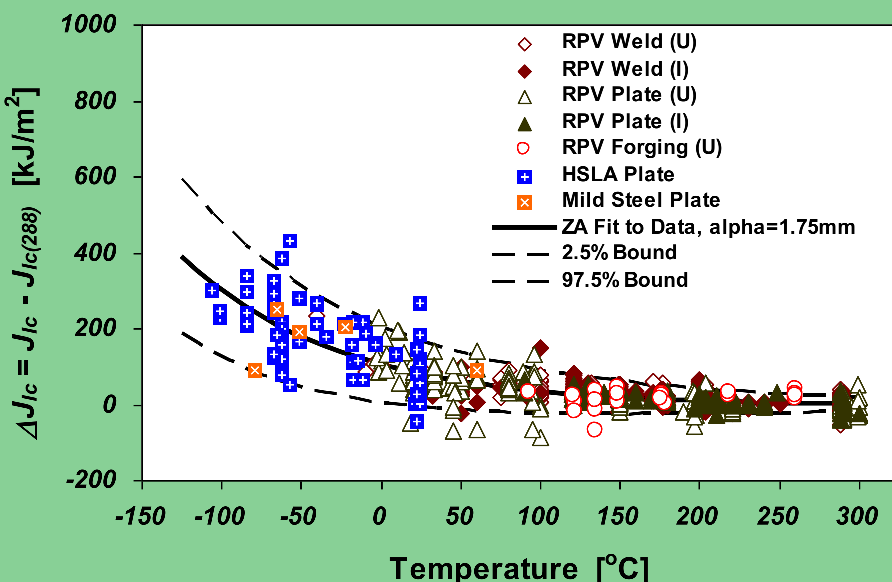


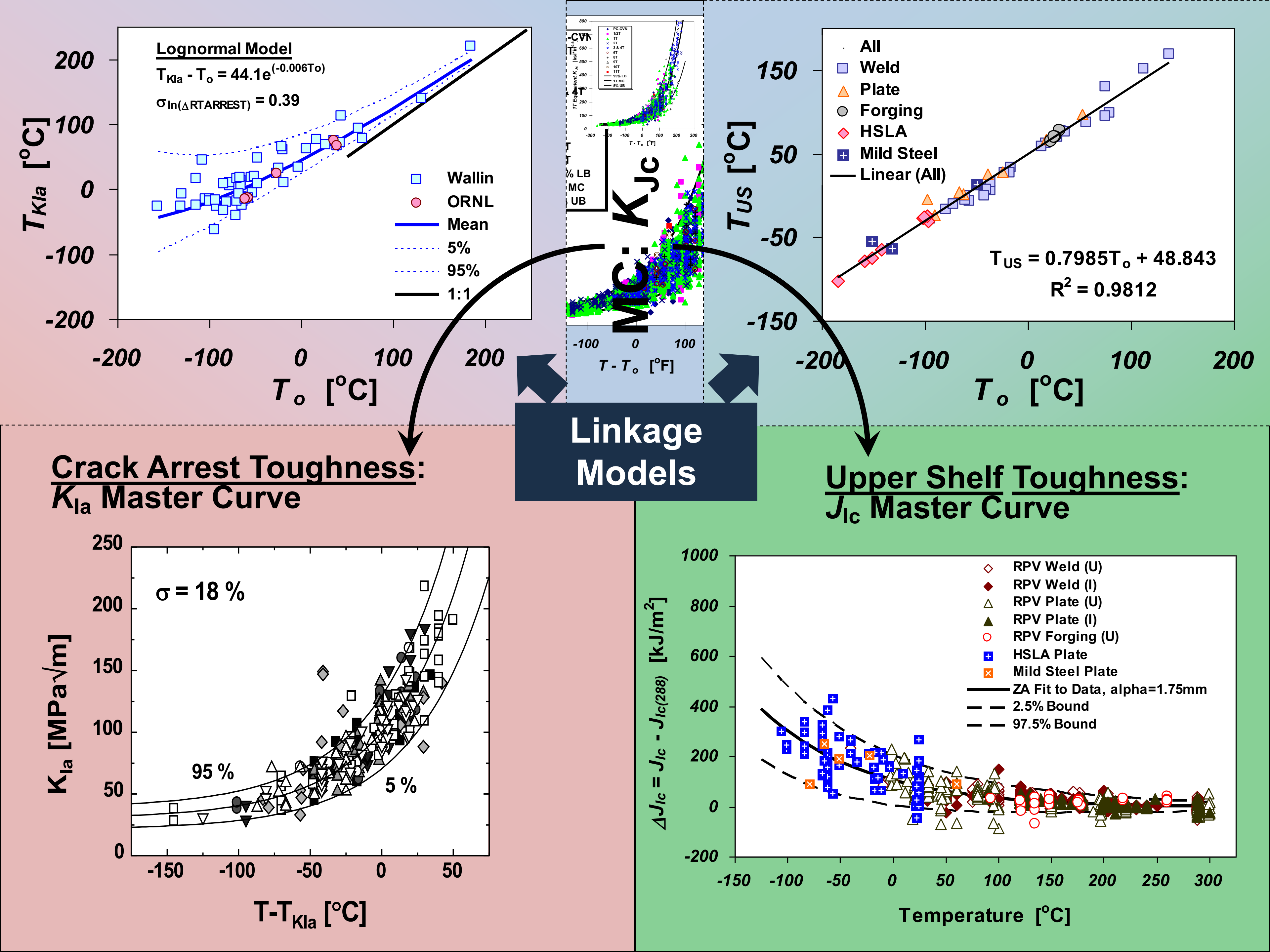
Primary Toughness Models

Crack Arrest Toughness: K_{Ia} Master Curve



Upper Shelf Toughness: J_{Ic} Master Curve



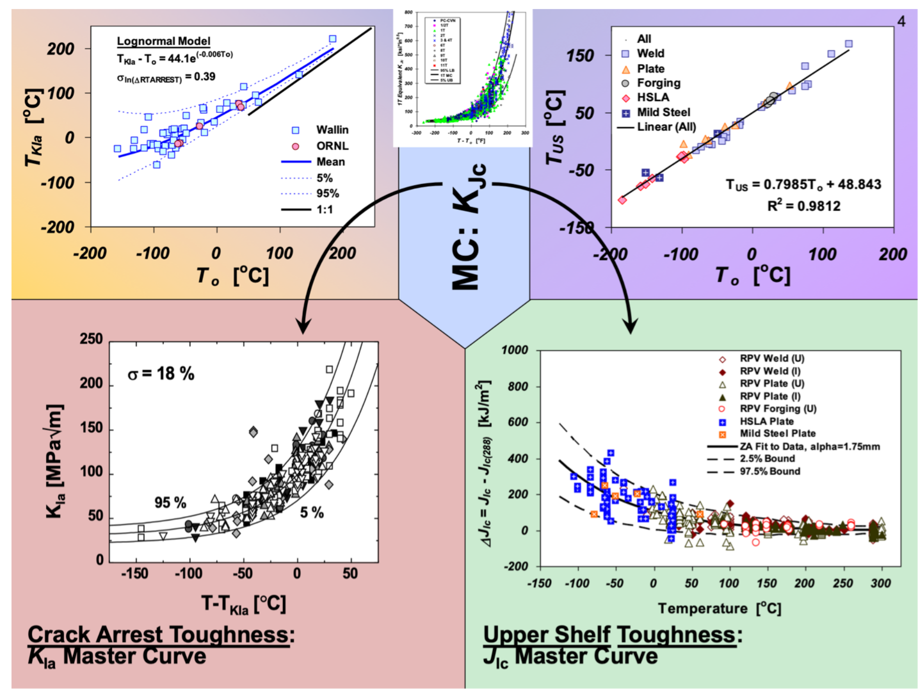


Lognormal Model
$T_{KIa} - T_o = 44.1e^{(-0.006To)}$
$\sigma_{ln(\Delta RTARREST)} = 0.39$
Wallin
ORNL
Mean
5%
95%
1:1
T_{KIa} [°C]
T_o [°C]
MC: K_{Jc}
T - To [°F]
All
Weld
Plate
Forging
HSLA
Mild Steel
Linear (All)
$T_{US} = 0.7985T_o + 48.843$
$R^2 = 0.9812$
T_{US} [°C]
T_o [°C]
Linkage Models
Crack Arrest Toughness: K_{Ia} Master Curve
σ = 18 %
95 %
5 %
K_{Ia} [MPa√m]
$T-T_{KIa}$ [°C]
Upper Shelf Toughness: J_{Ic} Master Curve
RPV Weld (U)
RPV Weld (I)
RPV Plate (U)
RPV Plate (I)
RPV Forging (U)
HSLA Plate
Mild Steel Plate
ZA Fit to Data, alpha=1.75mm
2.5% Bound
97.5% Bound
$\Delta J_{Ic} = J_{Ic} - J_{Ic(288)}$ [kJ/m²]
Temperature [°C]

Proposed ASME CC N-830-1

- **Recent advancements provide opportunities to adopt best estimate toughness models in the ASME Code**
  - Models for toughness vs temperature (K_{Jc}, K_{Ia}, J_{Ic}/ $J_{0.1}$/ J-R)
  - Models to account for systematic linkage between these quantities (T_{US} and T_{KIa})
  - Models provide full statistical distributions, permitting estimation of mean and bounding curves.

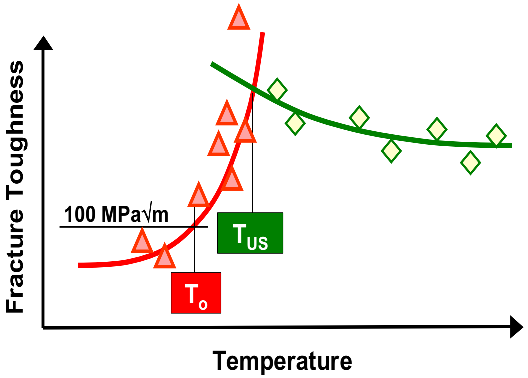
- **CC N-830-1 proposes a direct-toughness approach**
  - Proposes use of MC-based suite of best estimate toughness models as alternative to current Appendix A & K methodology
  - **Proposed treatment of uncertainties is consistent with the data used in model development**



Uncertainty in N-830-1 Toughness Models

- **The toughness metrics (K_{Jc}, K_{Ia}, and J_{Ic}/*J-R*) and the index temperatures (T_0, T_{KIa}, T_{US}) were derived from the same data and thus *reflect the same uncertainties***
  - associated with experimental error (**epistemic**), and
  - material variability (**aleatory**)
- **Care was taken to avoid the possibility of '*double counting*,' in the treatment of uncertainties when the models are used together**
  - Avoid producing *unrealistic* or overly conservative estimates of fracture toughness.
- **The approach adopted in proposed CC N-830-1 is to:**
  - **Account** for the experimental error and material variability in the **primary** toughness vs. temperature models
  - **Do not account** for experimental error and material variability in the **linkage models** (T_{KIa}, T_{US}), which themselves are determined from the K_{Jc}, K_{Ia}, and J_{Ic}, toughness vs. temperature data.

Uncertainty Treatment in CC N-830-1



Primary Model Uncertainty

- **Epistemic Uncertainty Treatment**
  - **The value of T_0 is adjusted by adding the 2σ, where the uncertainty, σ, on T_0 is given in ASTM E1921:**

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

- **Aleatory Uncertainty Treatment**
  - **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. ."
  - **Sampling on the distributions for each model simulates the uncertainty inherent in the property for use in probabilistic codes**

Mean values of linkage models (T_{US} and $T_{K_{Ia}}$) are used

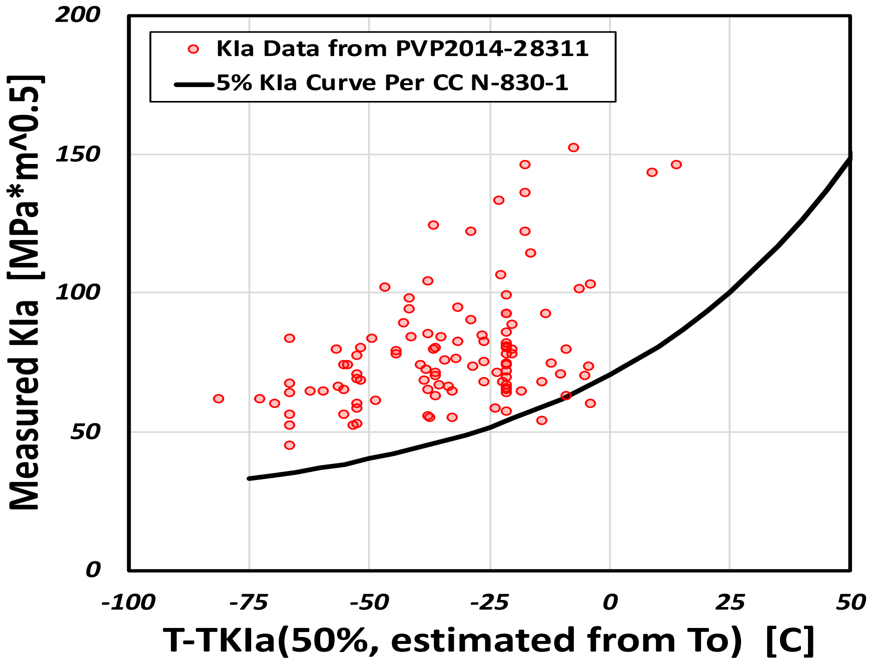
PEAI

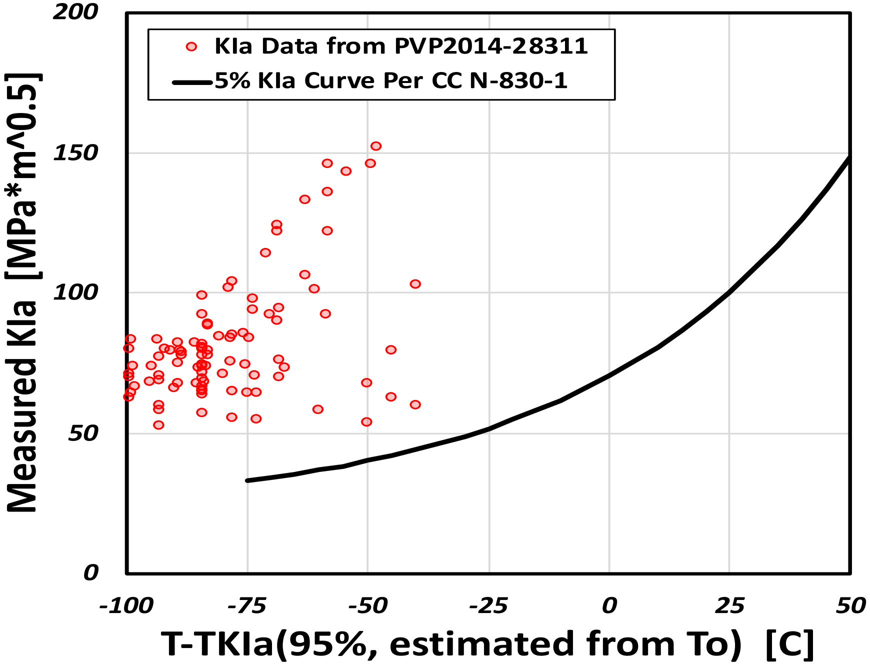
Validation of Uncertainty Treatment: T_0-K_{Ia}

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 model: T_{0ADJ} - K_{Ia}

Using the T_{0adj} AND the 2σ lower bound linkage model is WAY over conservative

PEAI

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:

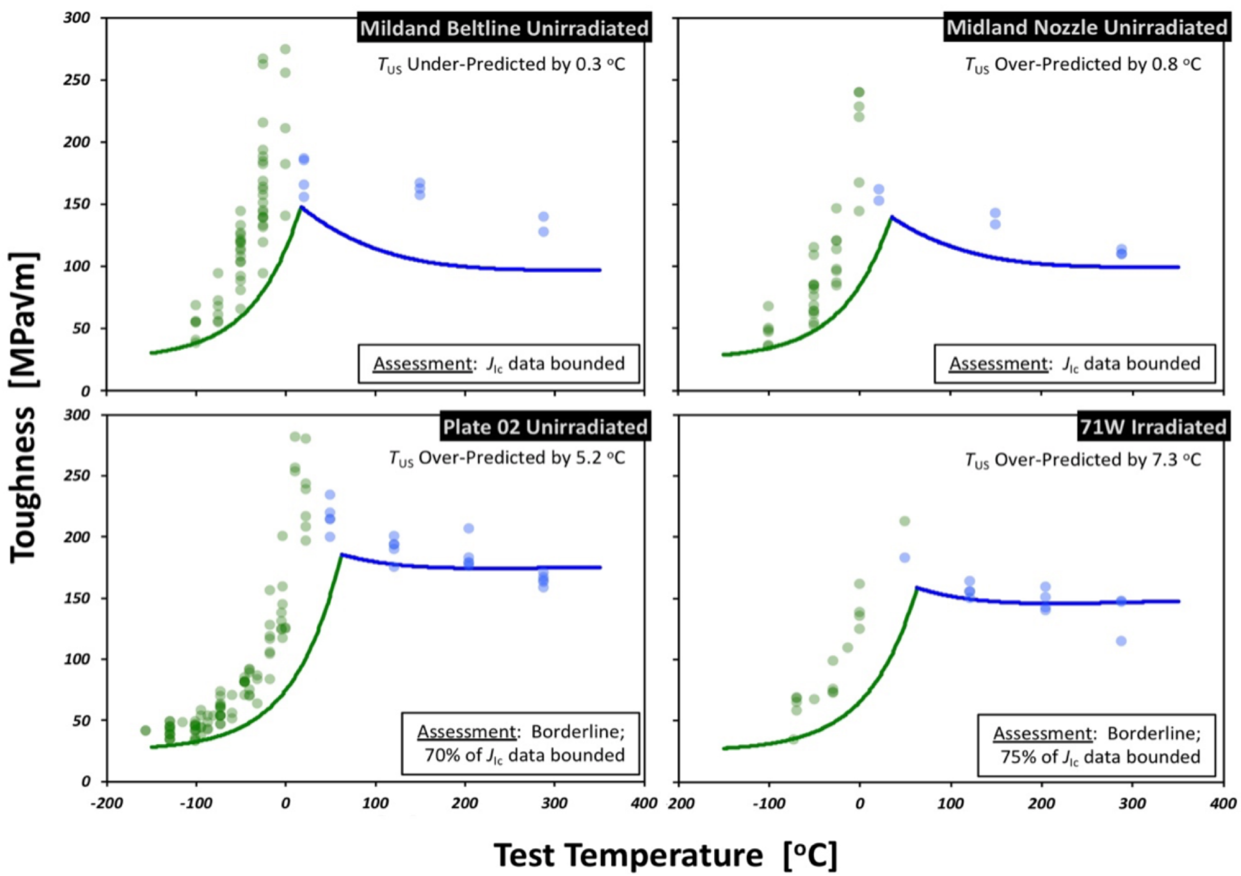
- Midland Beltline (Unirradiated). T_{US} under-predicted by 0.3 °C.
- Midland Nozzle (Unirradiated). T_{US} over-predicted by 0.8 °C.
- Plate 02 (Unirradiated). T_{US} over-predicted by 5.2 °C.
- Weld 71W (Unirradiated). T_{US} over-predicted by 7.3 °C.

The position of K_{Jc} and the J_{Ic} models were determined for each material using:

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

$$T_{US} = b_{PF} + 0.84T_{0(ADJ)}$$

Approximately 95% bounding is achieved using the mean linkage models: $T_0 - J_{Ic}$

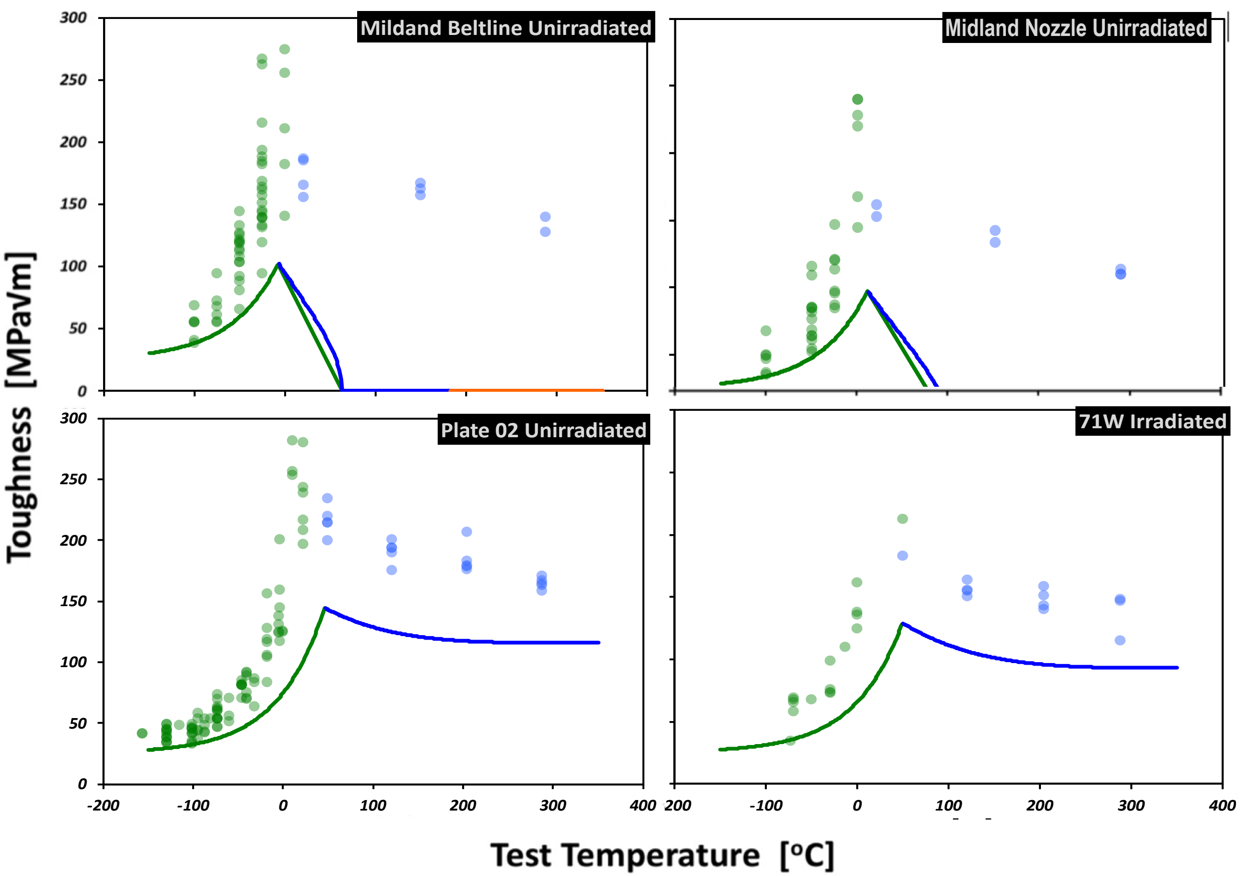


Validation of Uncertainty Treatment: T_0-J_{Ic}

Using the same four datasets, the position of T_{US} and the J_{Ic} model were determined for each material using both $T_{0(adj)}$ and the 2σ LB

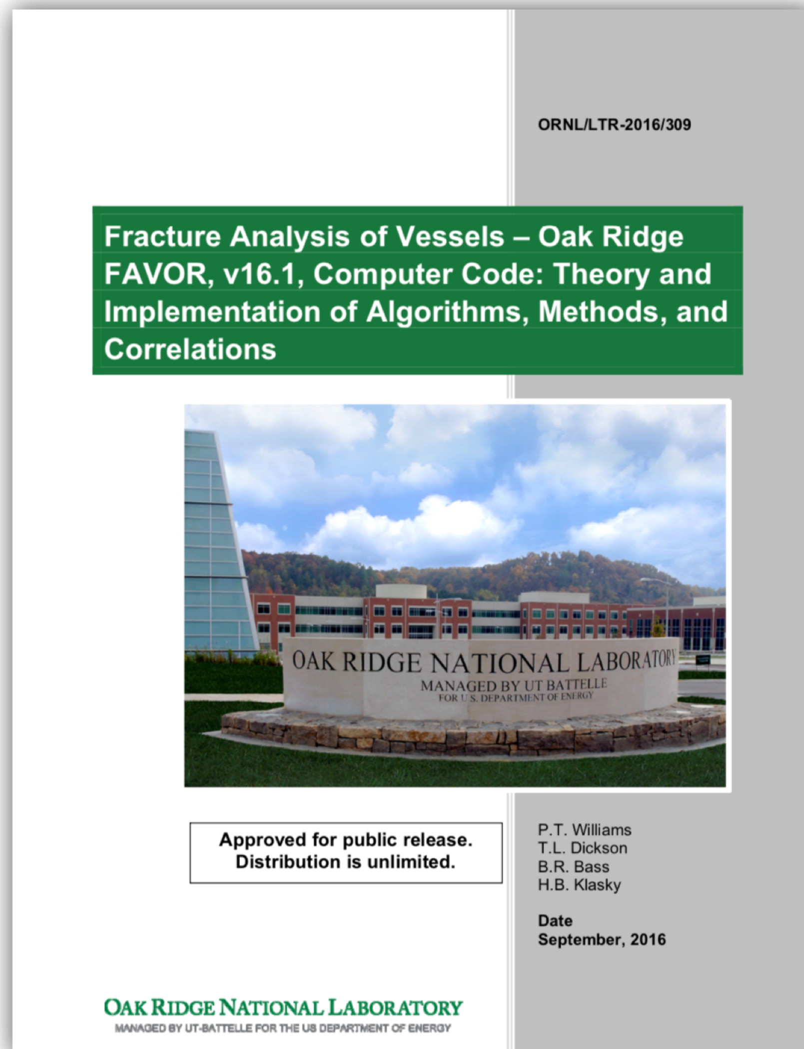
$$T_{0(ADJ)} = T_0 + 2\sigma \qquad T_{US} = b_{PF} + 0.84T_{0(ADJ)} + 2\sigma$$

Bounding is now overly conservative, and in some cases does not make physical sense (predictions of $-J_{Ic}$)



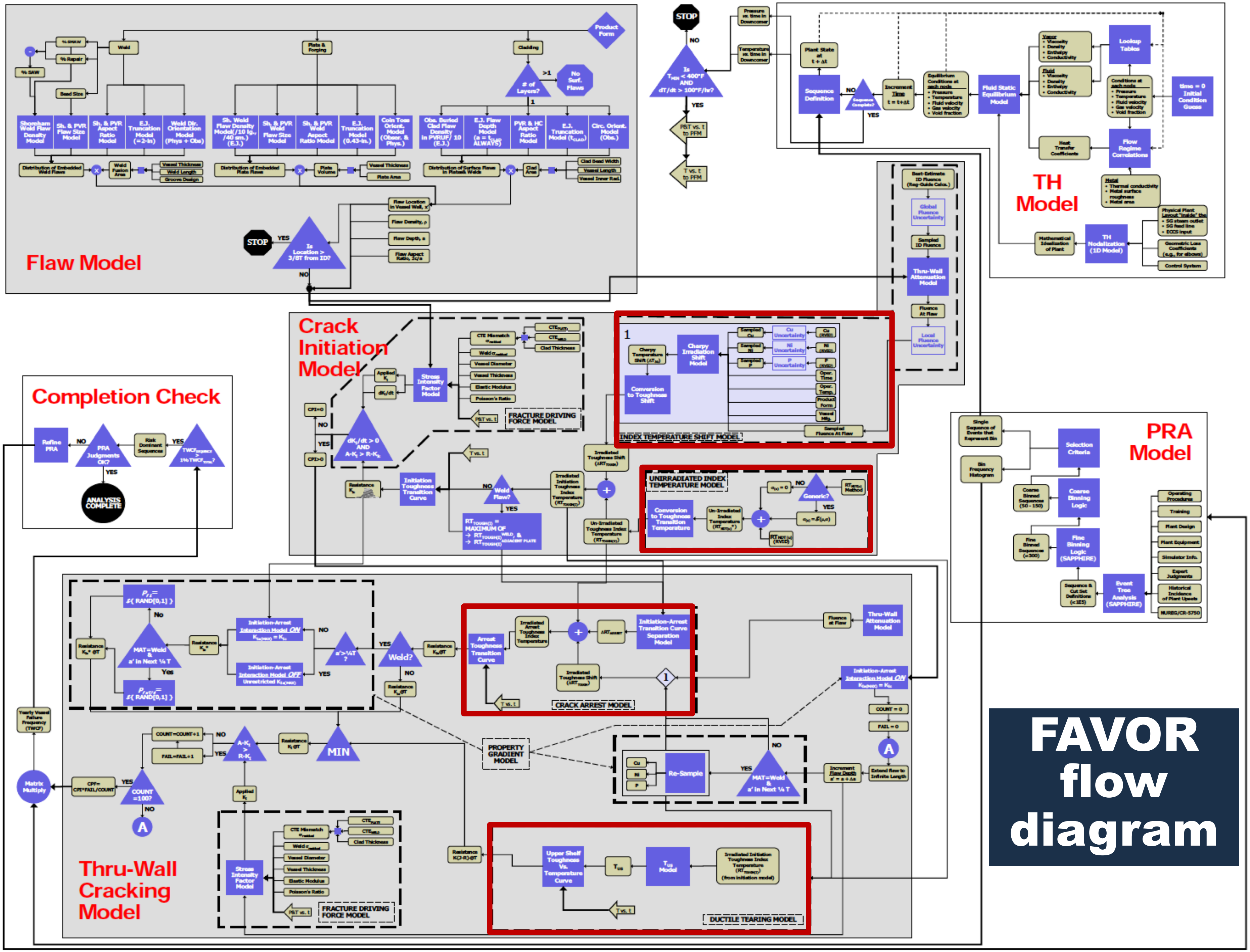
FAVOR

- Probabilistic code used to assess probability of crack initiation and through-wall cracking probability for RPV steels
- Used by NRC in the development of the alternative PTS rule (10 CFR 50.61a)
  - Extensive internal and external reviews
- Used subsequently by industry and NRC to assess emergent issues
  - BTP 5-3
  - Quasi-laminar flaws
- Used internationally
  - Taiwan
  - Japan
  - Belgium



[ML16273A032, …A033, … A034]

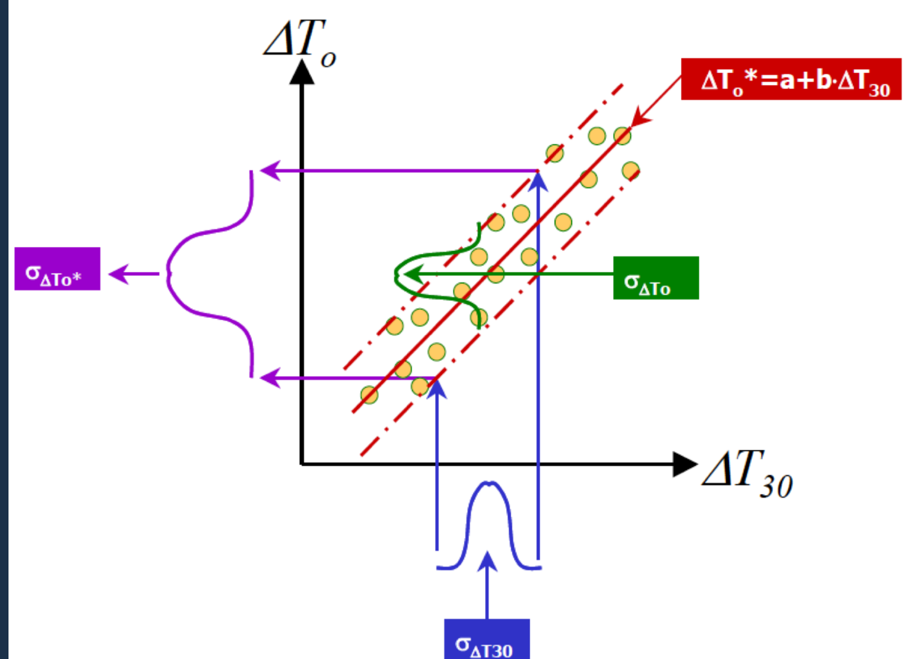
FAVOR flow diagram



Uncertainty Treatment in FAVOR

Uncertainties are defined as aleatory or epistemic

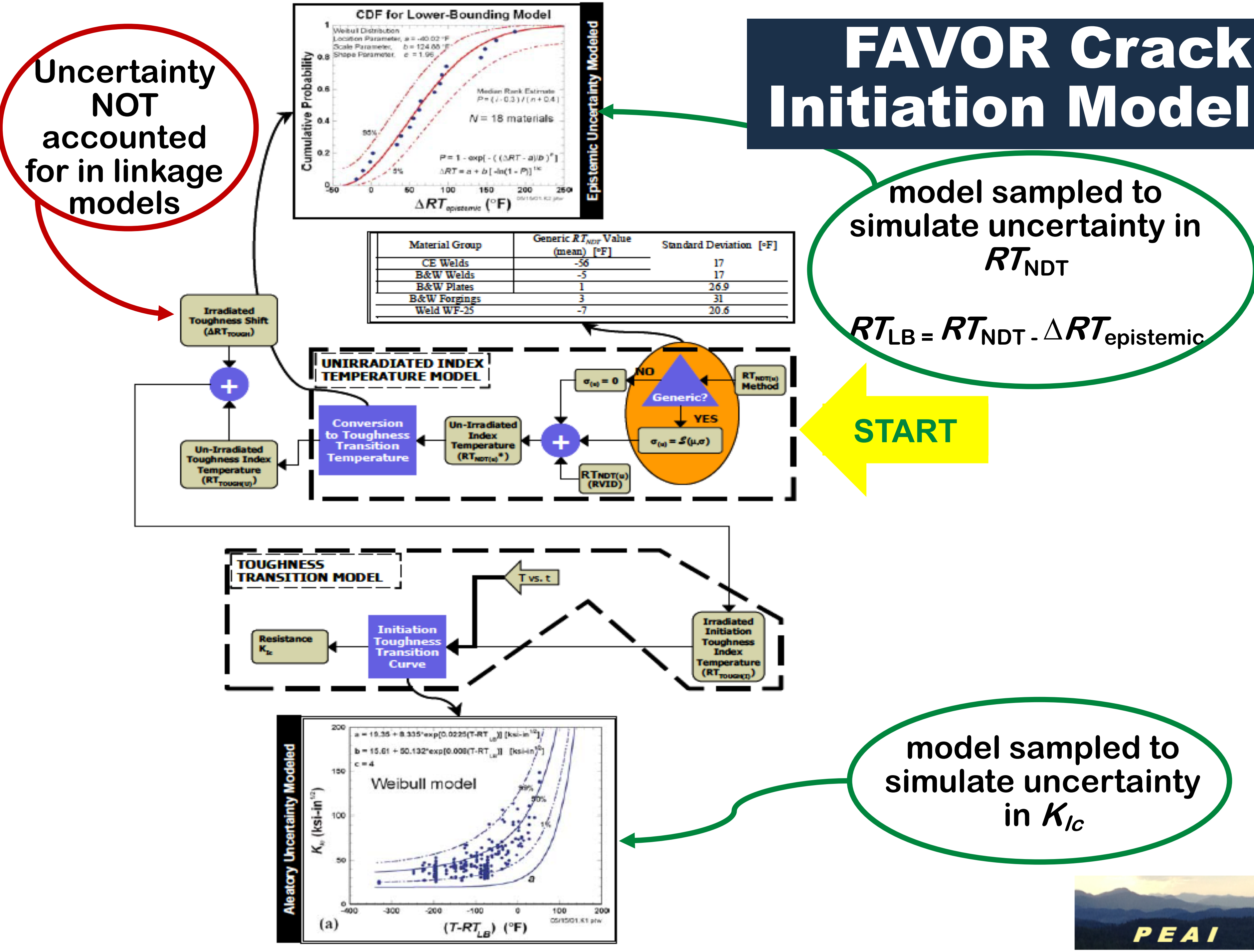
- **Epistemic variables** are sampled once for each simulated RPV run and thereafter held fixed. Resampled for next RPV.
- **Aleatory variables** (e.g. K_{Ic}) provide the basis for estimating the probability of crack initiation/arrest for each time during a transient



Models are defined as primary or linkage

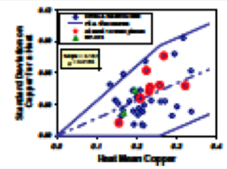
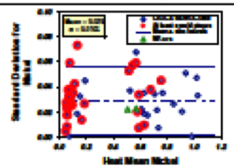
- Uncertainty is simulated by sampling from values within the defined distribution of each primary model
- Uncertainty simulation in the linkage models is mixed
  - Mean values are used for T_{US}, ΔT_{30}
  - Uncertainty accounted for in T_{KIa} (ΔRT_{arrest})

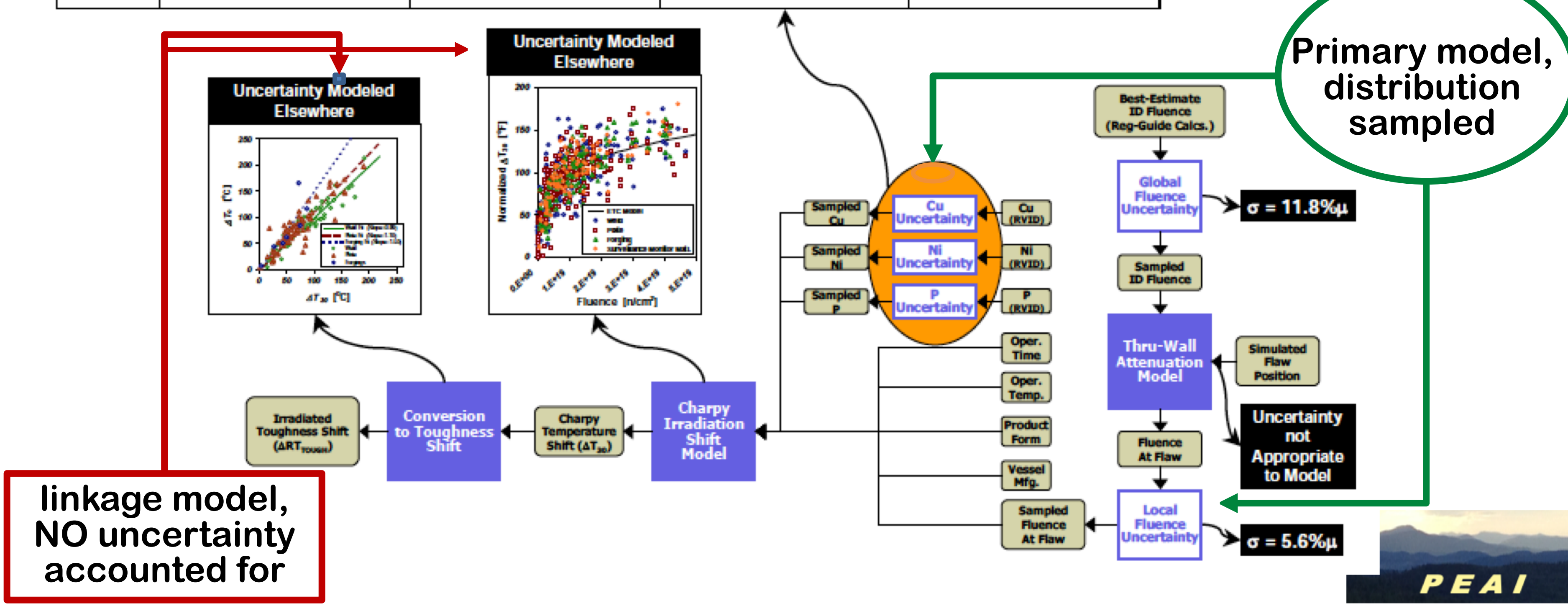
FAVOR Crack Initiation Model



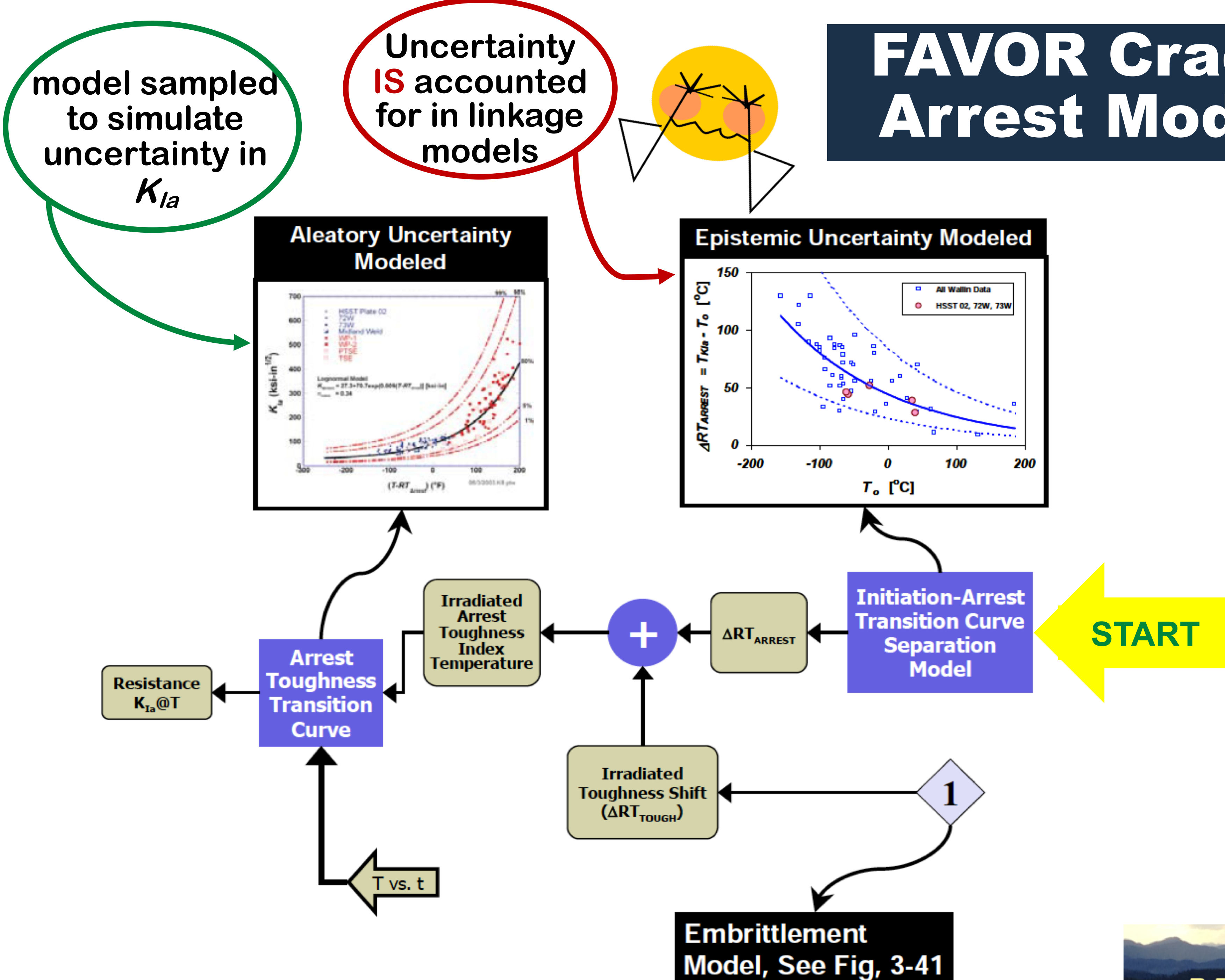
Material Group	Generic RT_{NDT} Value (mean) [°F]	Standard Deviation [°F]
CE Welds	-56	17
B&W Welds	-5	17
B&W Plates	1	26.9
B&W Forgings	3	31
Weld WF-25	-7	20.6

FAVOR Embrittlement Model

	Weld σ		Plate & Forging σ	
	Sub-Region	Local	Sub-Region	Local
Cu		0.0131	0.0073	0.0035
NI		0.0119	0.0244	0.0124
P	0.0013	0.0008	0.0013	0.0008



FAVOR Crack Arrest Model



Summary and Conclusions

- Information flow through a code controls the cumulative impact of various sources of uncertainty on failure probabilities.
- Sub-models must be linked together appropriately to ensure that there is no distortion of the flow of information
- To avoid double counting of uncertainty contribution from various sources
  - Account for uncertainty in primary models (derived directly from data), but
  - Do NOT account for uncertainties in linkage models derived from primary models
    - Can result in excessive conservatism, or
    - Can result in non-physically realistic predictions of model outcomes
- Perhaps there is an analogy to complex human relationships?