ASME PVP Workshop

PWR Nuclear Plant Reactor Pressure Vessels: Recent evolutions on integrity assessment. New tools and methodology in progress, and future perspectives

PTS Analysis of NPPs in the USA

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American Society of Mechanical Engineers

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U.S.NRC

United States Nuclear Regulatory Commission

Protecting People and the Environment

Presentation Outline

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

- Current (circa-1984) PTS regulations
- PTS re-evaluation project
  - Overview & motivation
  - Approach
  - Major technical outcomes
  - Voluntary alternative PTS rule: 10 CFR 50.61a
- Lessons learned & efforts moving forward

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10CFR50.61 Provisions

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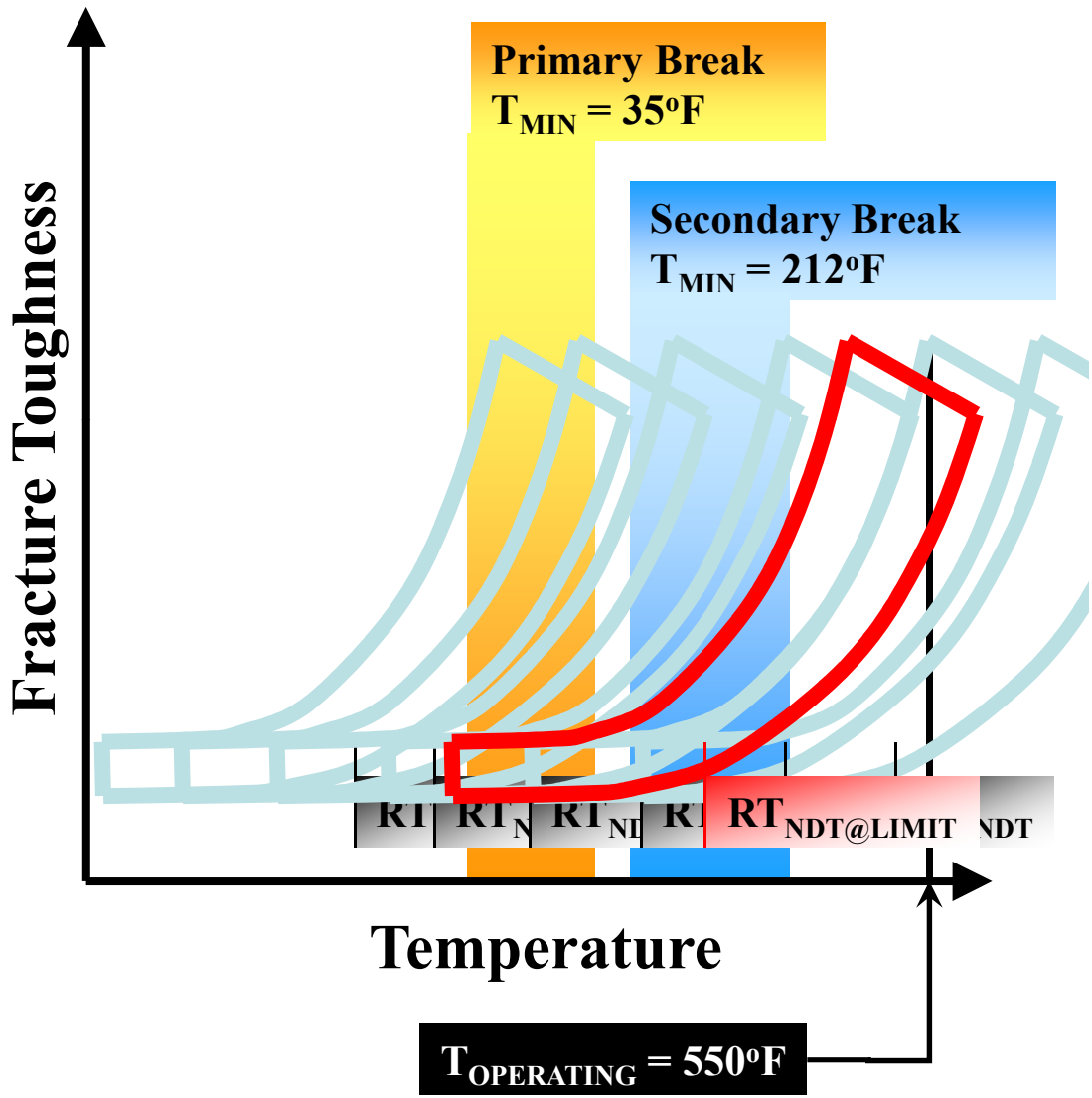
- Vessel condition monitored using an estimate of the steel's fracture toughness transition temperature after irradiation (RT_{NDT}) obtained through a 10CFR50 App. H surveillance program.

- If RT_{NDT} exceeds 300ºF (for circ. welds) or 270ºF (for all other materials) before end of license (EOL), the licensee must
  - Do something to keep RT_{NDT} below 300ºF or 270ºF
    - Reduce Flux: Reduce embrittlement rate
    - Anneal: De-embrittle the material (see RG 1.162)
  - Show that RT_{NDT} above 300ºF or 270ºF is safe
    - Analyze: Plant specific analysis per RG 1.154



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PTS Project
Participants

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UNITED STATES NUCLEAR REGULATORY COMMISSION

EPRI

UT-BATTELLE
ornl

UNIVERSITY OF MARYLAND 1856

Duke Energy

PEAI

PNL

BROOKHAVEN NATIONAL LABORATORY

Consumers Energy
Count on Us

SAIC
An Employee-Owned Company

Sandia National Laboratories

FirstEnergy

FRAMATOME

LSL

INEEL

Constellation Energy Group

SARTREX

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Technical Motivations

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Developments since the 1980s suggested the overall conservatism of the rule.

- **PRA**
  - Use of latest PRA/HRA data
  - More refined binning
  - Operator action credited
  - Acts of commission considered
  - External events considered
  - Medium and large-break LOCAs considered
- **TH**
  - Many more TH sequences modeled
  - TH code improved
- **PFM**
  - Significant conservative bias in toughness model removed
  - Spatial variation in fluence recognized
  - Most flaws now embedded rather than on the surface, also smaller
  - Material region dependent embrittlement props.
  - Non-conservatisms in arrest and embrittlement models removed

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Regulatory Motivations

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- Produces unnecessary burden

  Technical improvements suggest strongly that current RT_{NDT} limits of 300ºF and 270ºF are more conservative than needed to maintain safety.

- Does not necessarily increase overall plant safety

  Focus on unnecessarily conservative RT_{NDT} limits can divert resources from other more risk-significant matters.

- Creates an artificial impediment to license renewal

  Unnecessarily conservative RT_{NDT} limits alter perception of the safe operational life of a nuclear power plant.

- ***Causes work that produces no real benefit***

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PTS Project

Uncertainty Modeling a Central Feature

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Our approach features

- **Explicit treatment of uncertainties**
- **Uncertainty classification & separation**
  - ✓ **Aleatory**
  - ✓ **Epistemic**
- **Uncertainty quantification**

Good engineering practice

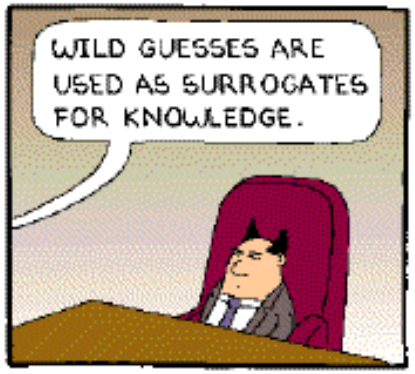
Ensures that the mathematical model represents uncertainties as they are physically understood (or believed) to exist.

Irreducible

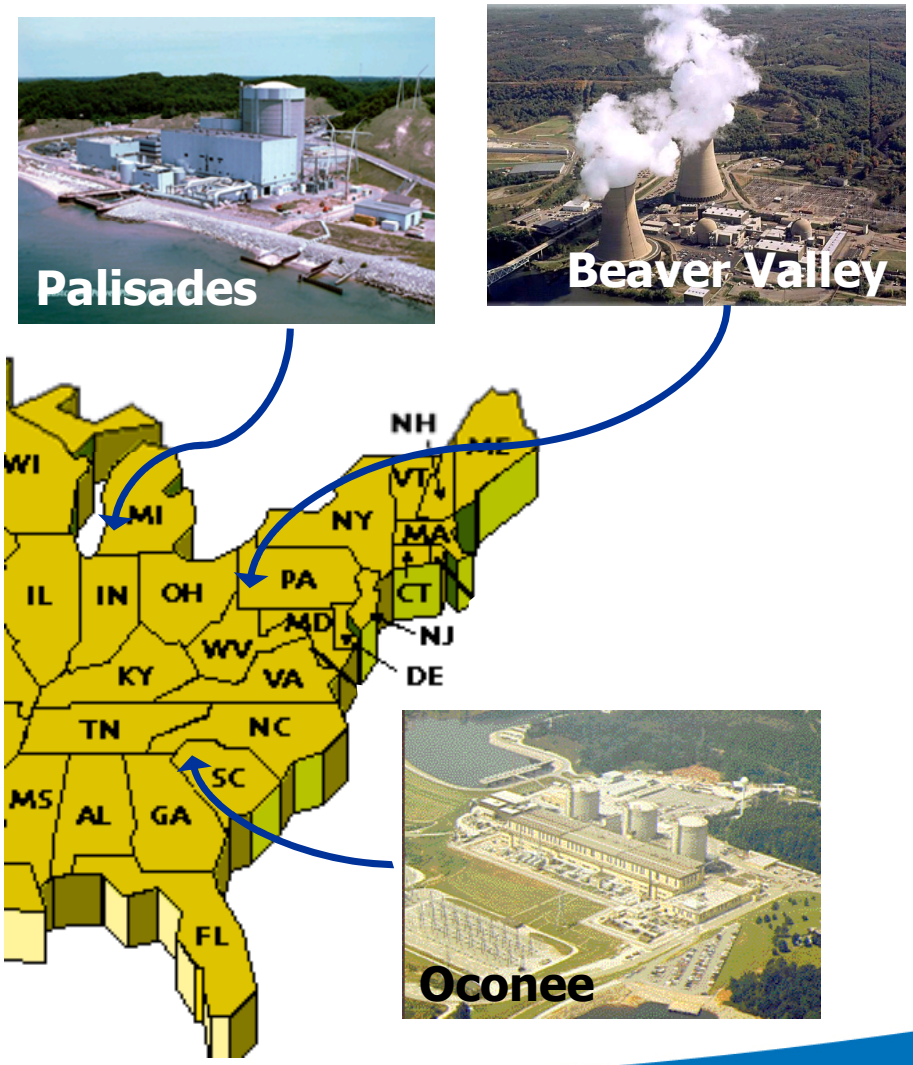
Knowable *(in principal)*

Following a systematic process makes uncertainties "visible" and, thereby, improves comprehensiveness

Epistemic Uncertainty
(per Scott Adams)

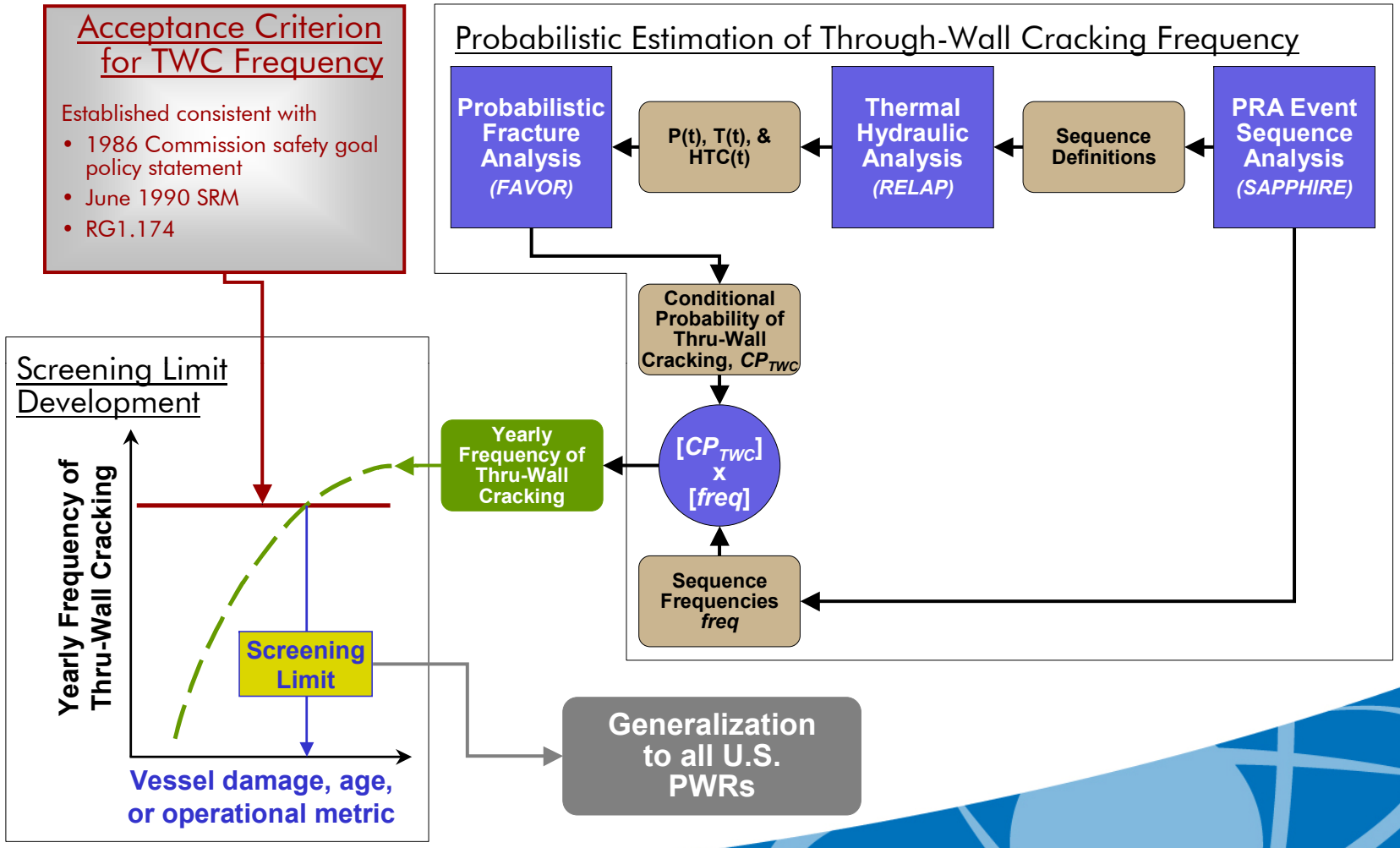


Scope of Analysis



- Detailed analysis of 3 PWRs
  - All PWR manufacturers
    - 1 Westinghouse (W)
    - 1 Combustion Engineering (CE)
    - 1 Babcock & Wilcox (B&W)
  - 1 plant from original (1980s) PTS study
  - 2 plants very close to the current PTS screening criteria
- Generality to all PWRs assessed
  - Characteristics of dominant transients
  - Examination of 5 more high embrittlement plants

Overall Model



Risk-Informed PTS Limits Follow from Policy Decisions

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51 FR 28044, *Safety Goal Policy Statement (1986)*

SECY-00-0077, *Modifications to Safety Goal Policy Statement*

Regulatory Guide 1.174

10 CFR 50.61a
Voluntary Alternative Pressurized Thermal Shock Rule

QHOs < 0.1% of the total public risk (prompt & latent)

CDF < 1×10^{-4}/ry

CDF & QHO limits for generic decisions

	Mean	Δ-Mean
CDF	10^{-4}/ry	10^{-5}/ry
LERF	10^{-5}/ry	10^{-6}/ry

- Accident sequence progression study shows that through-wall cracking rarely leads to LERF
- Conservatively assumes equivalence of LERF and the yearly through-wall cracking frequency (TWCF) of the reactor pressure vessel
- **Tolerable limit on TWCF established as 10^{-6}/ry**

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Major Technical Outcomes

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- Operational transients that most influence PTS risk
- Material features that most influence PTS risk
- Some highlighted features of PFM model
  - Adjustment for RT_{NDT} model uncertainty
  - Warm pre-stress
  - Difference between crack initiation and through-wall cracking as a "failure" criteria

Technical Basis
Transient Classes Modeled

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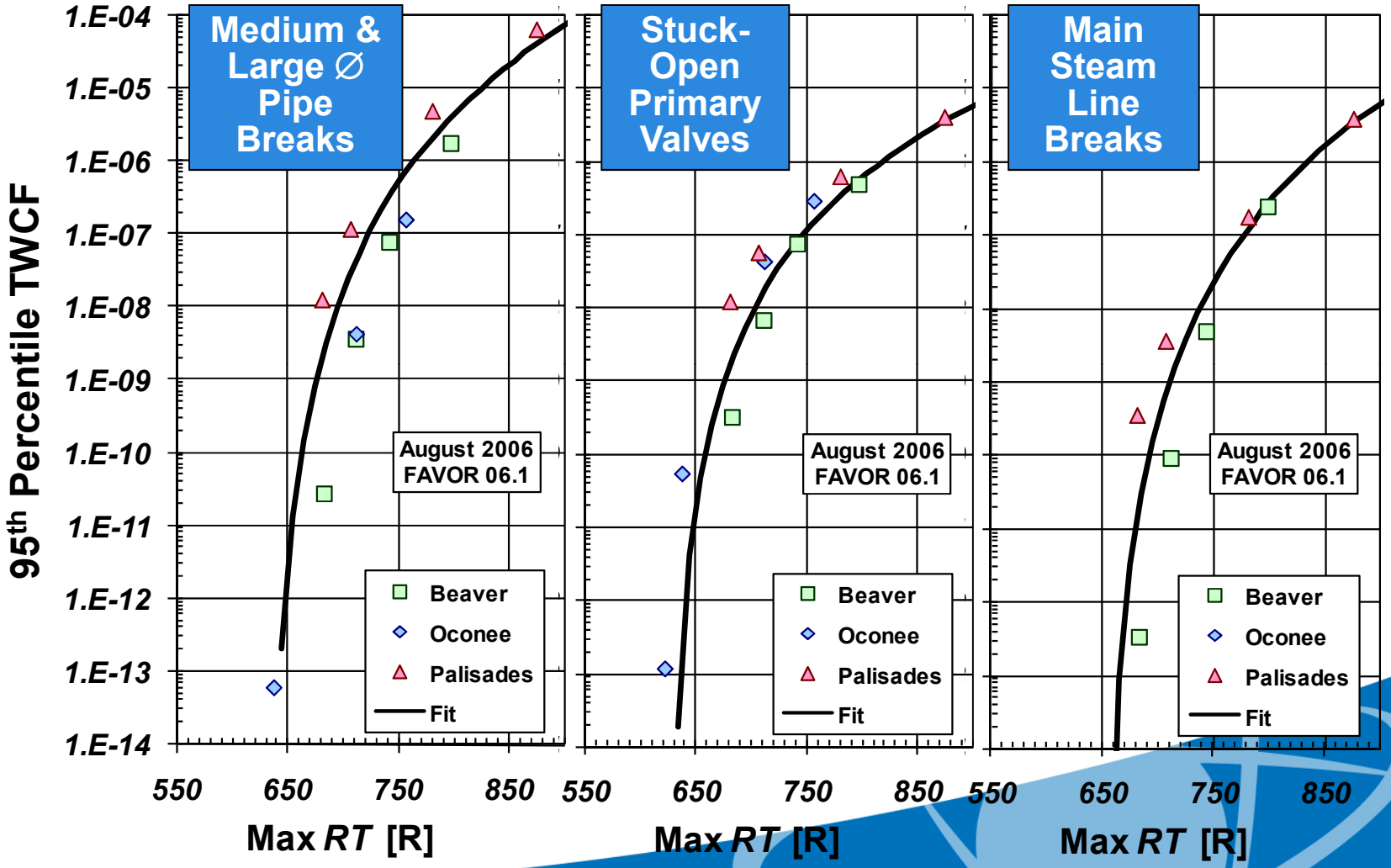
Primary System Faults

- Pipe breaks
  - Large
  - Medium
  - Small
- Stuck open valves that later re-close
- Feed and bleed

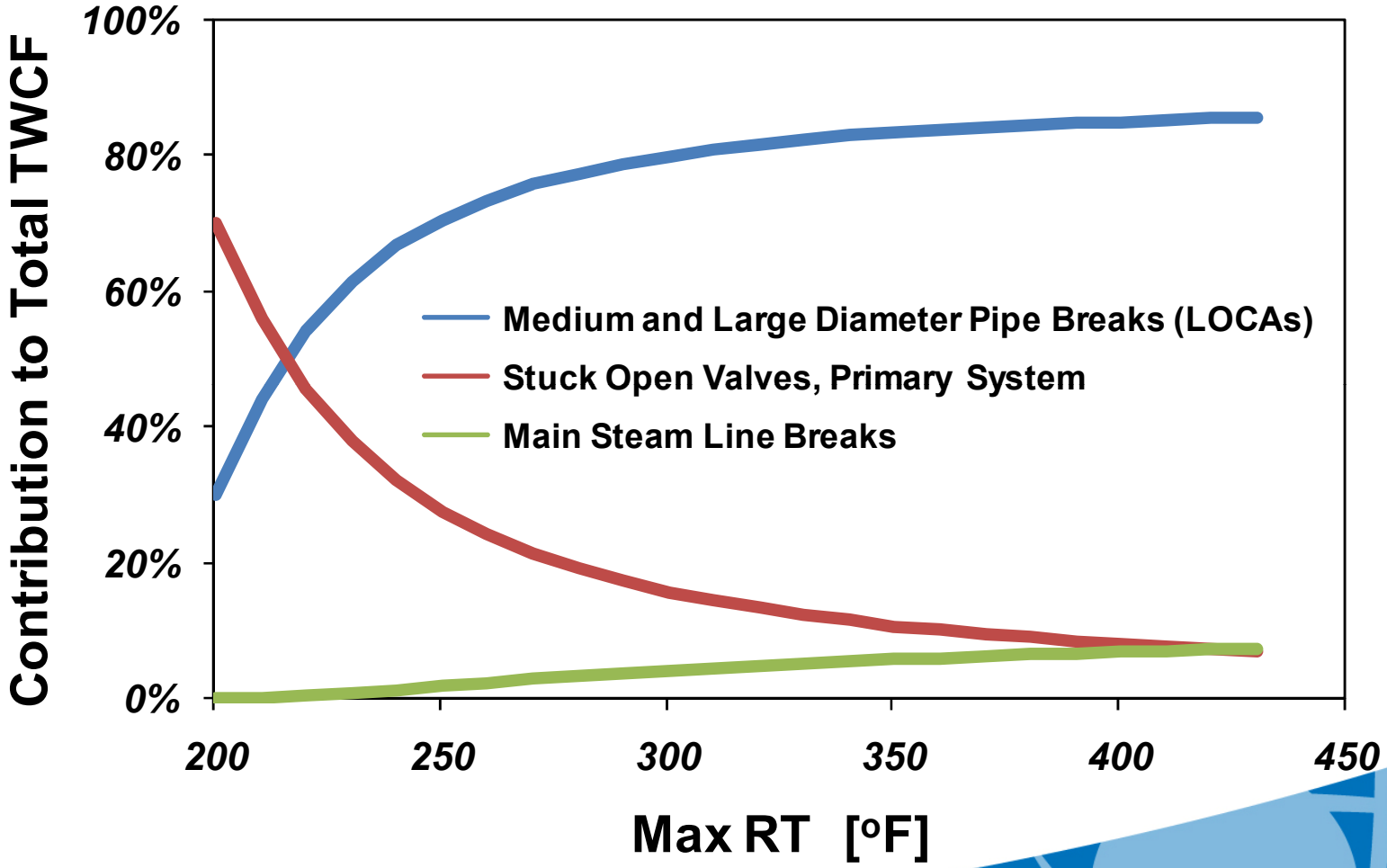
Secondary System Faults

- Main steam line break
- Stuck open valves
- Steam generator tube rupture
- Pure overfeed

Important Transient Classes



Important Transient Classes



Summary of Findings
Important Transient Classes

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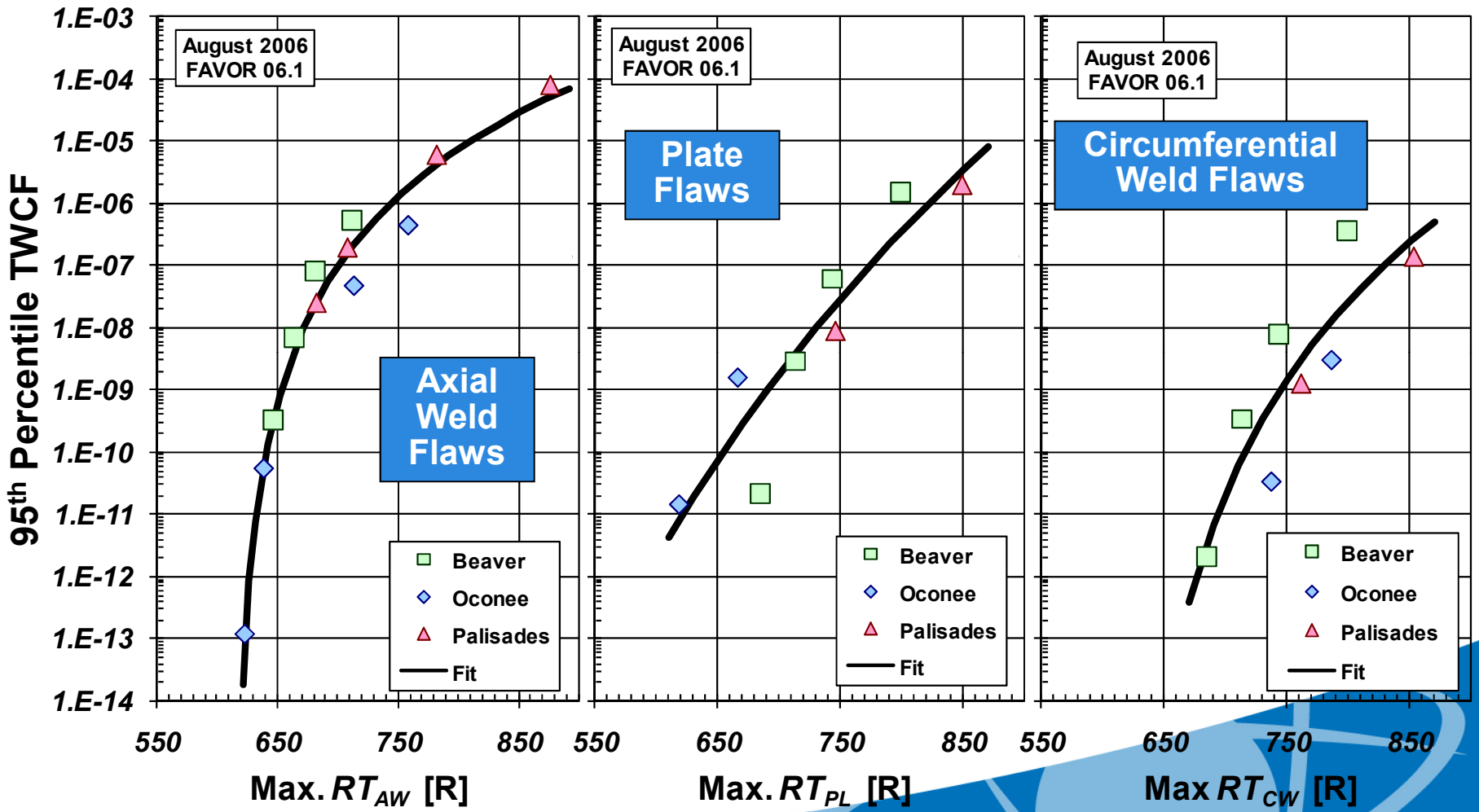
- Primary side faults dominate risk
  - Due to low temperature on primary side (35°F)
- Very severe secondary faults (MSLB) make a minor contribution
  - Primary side temperature cannot fall below 212°F, so material still tough even at high embrittlement
- All other transient classes produce no significant risk
  - Challenge is low even if transient occurs

Important Material Features



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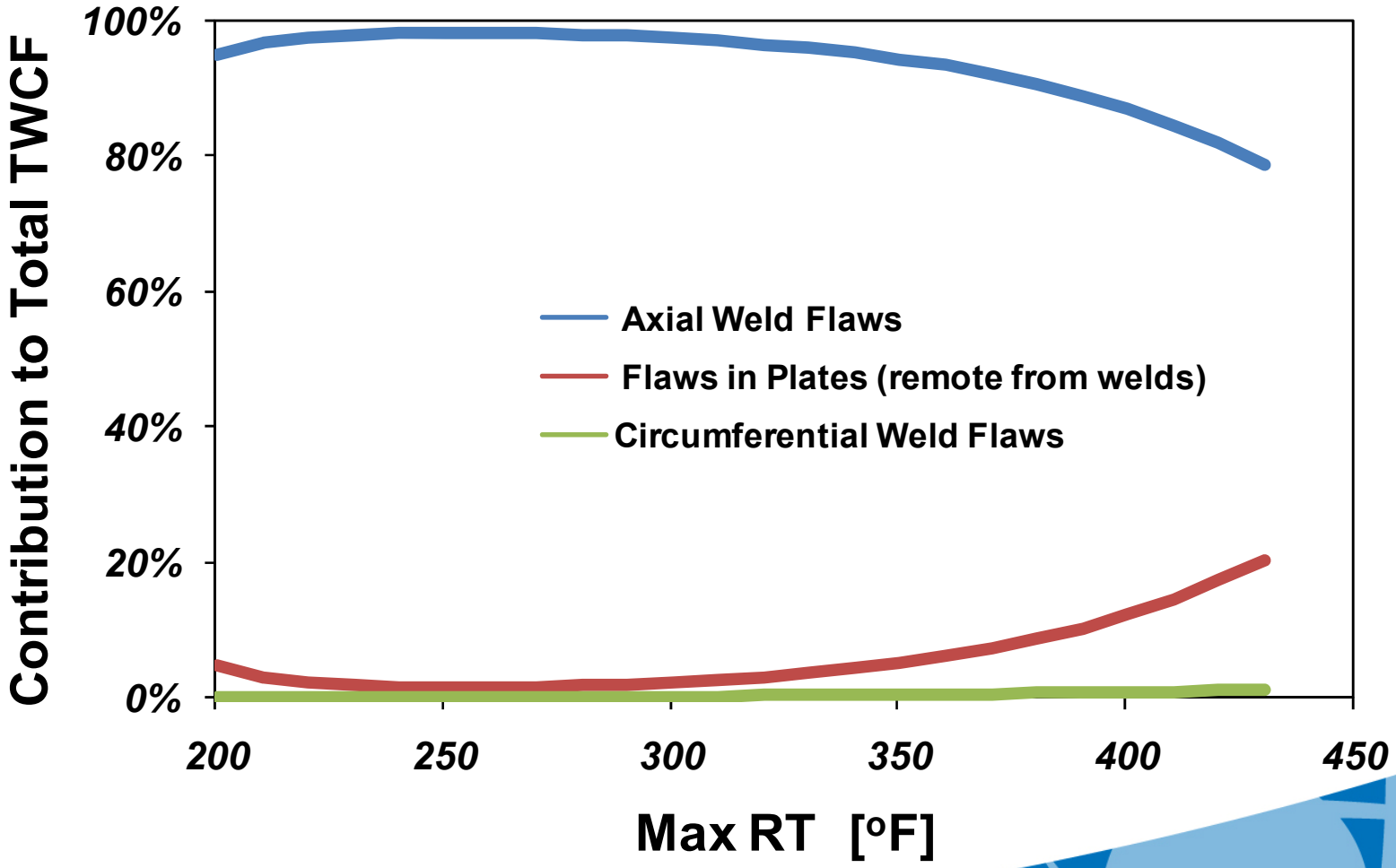

Summary of Findings

Important Material Features

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- Axial cracks dominate risk, circumferential cracks do not
  - Circ cracks arrest due to vessel geometry
  - Axial cracks are much less likely to arrest
- Thus, the properties of materials associable with axial flaws dominate
  - Axial weld properties
  - Plate properties
- 3-parameter characterization of RPV embrittlement unifies results across all study plants
  - Failures are blamed on the responsible material/flaw features

Initiation Toughness Model Indexed to RT_{NDT}

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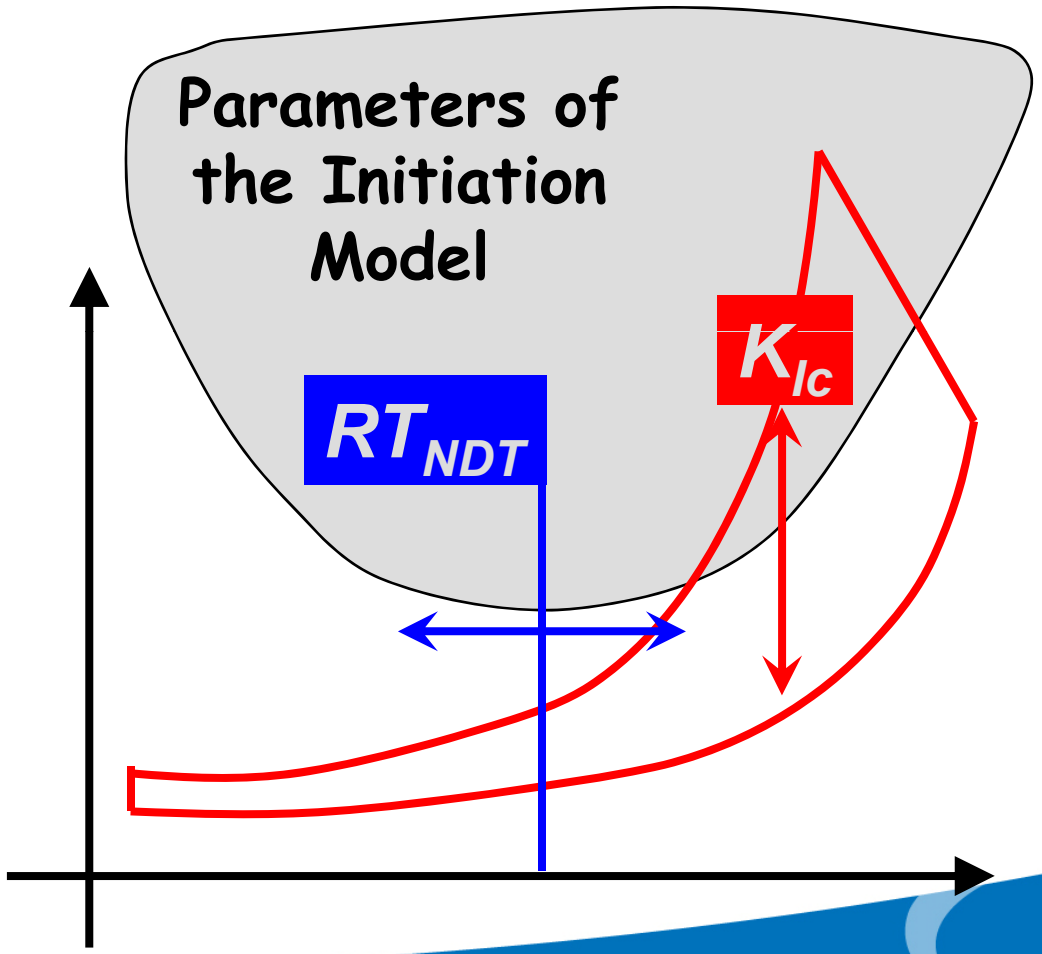

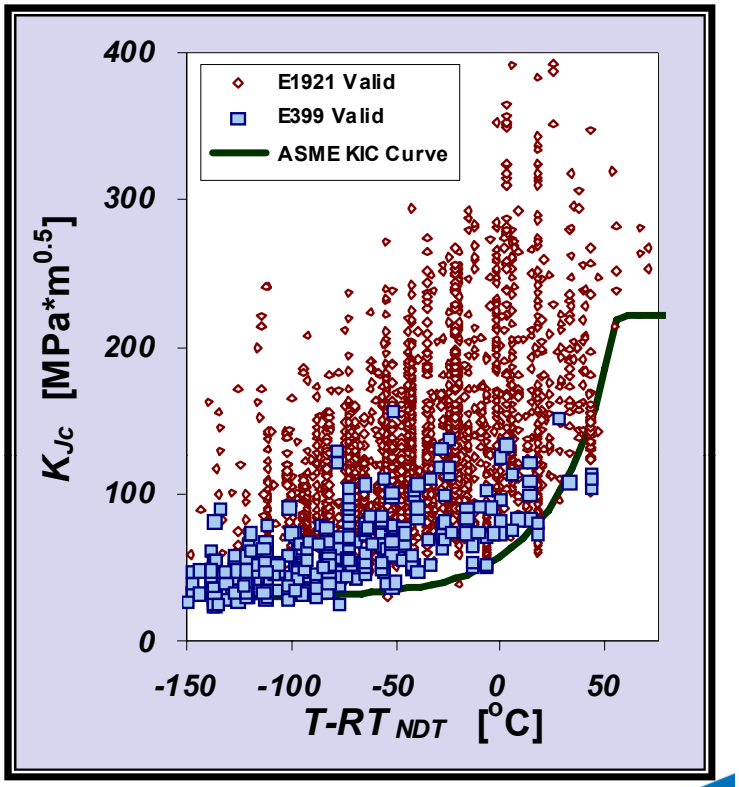

Mixed Epistemic (RT_{NDT}) & Aleatory (K_{Ic}) Uncertainties

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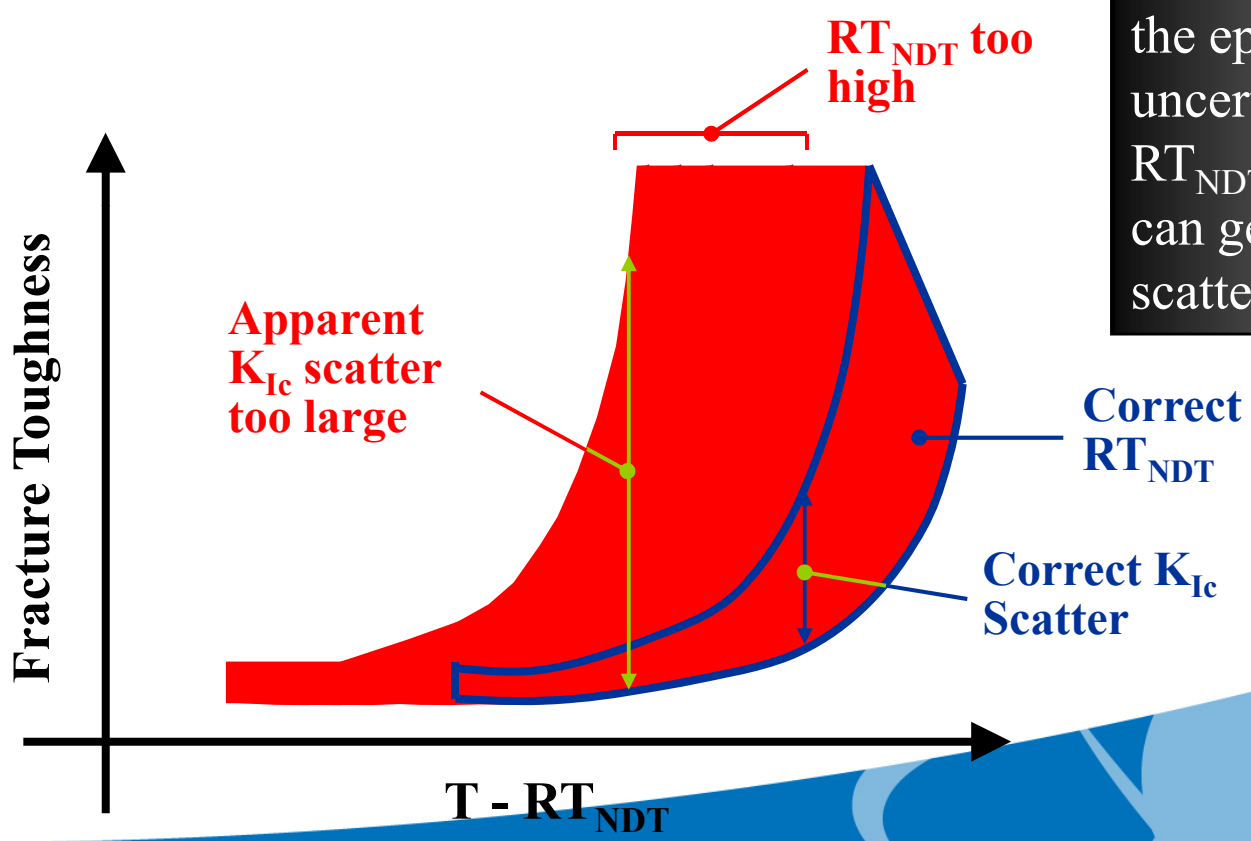
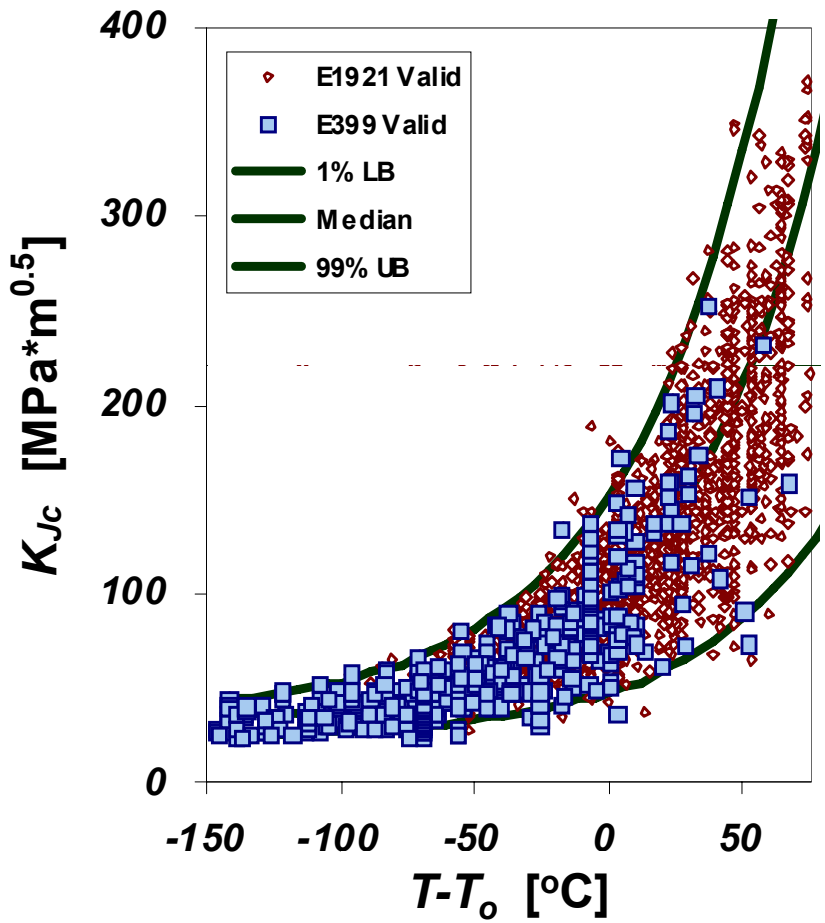
- Need to be separated for accuracy
- Increase the apparent K_{Ic} scatter

Need to quantify the epistemic uncertainty in RT_{NDT} so that we can get the K_{Ic} scatter correct



Separation of Uncertainties Using T_o

- Fracture toughness models based on the RT_{NDT} index temperature contain both epistemic & aleatory uncertainties
- Use of the best-estimate Master Curve index temperature (T_o) effectively removes epistemic uncertainty, leaving only the aleatory uncertainties produced by material variability



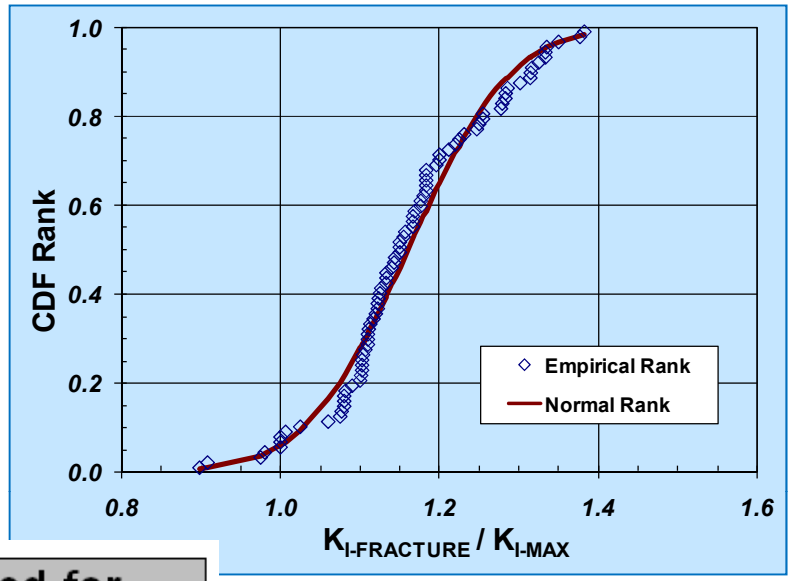
Warm Pre-Stress

Definition of Different Models

Condition 1: $K_{applied} \geq K_{Jc(min)}$

Condition 2: $\frac{dK_{applied}}{dt} > 0$

Condition 3: $K_{applied}(t) \geq \alpha \cdot K_{applied(max \forall t>0)}$

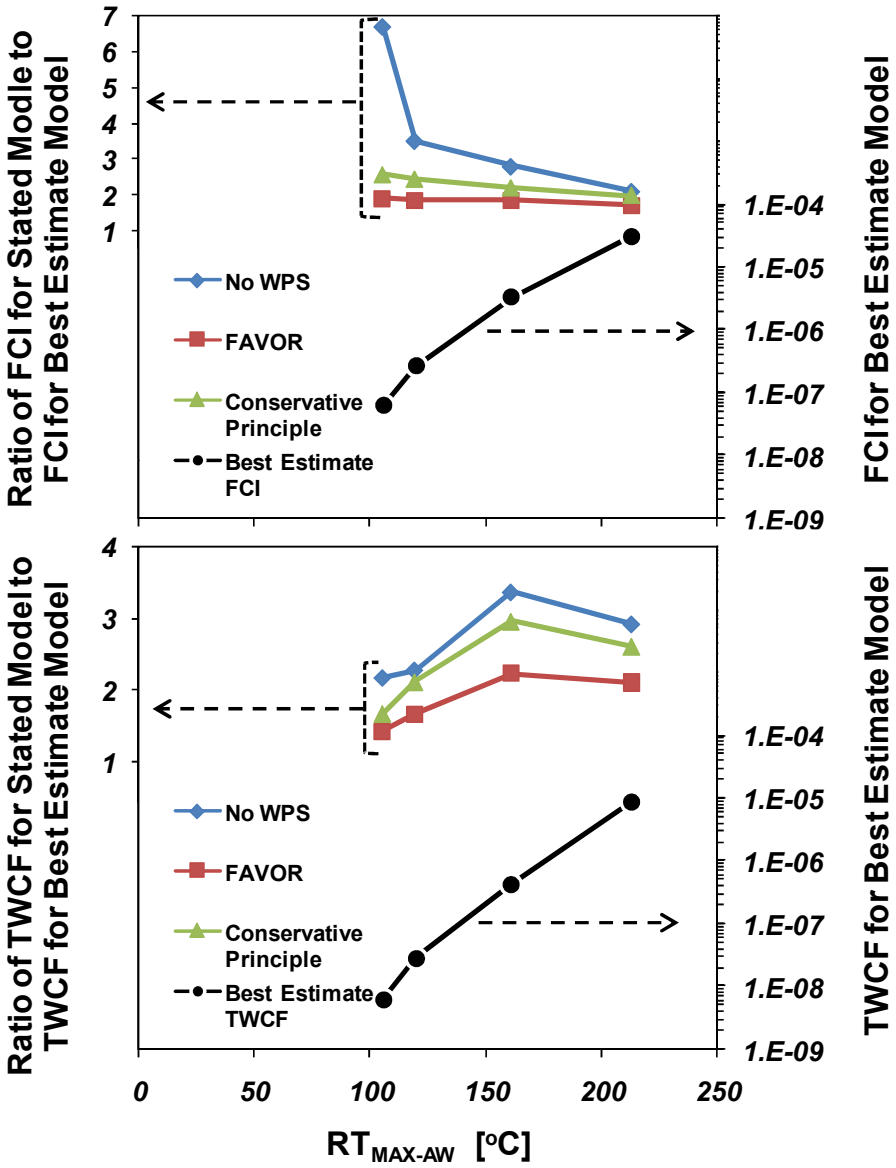


[Moinerau 2007]

WPS?	Model ID	Conditions required for CPI>0
No	Conventional LEFM	Only condition 1.
Yes	Conservative Principle WPS	Condition 1 and 2.
	FAVOR WPS	Condition 1, 2, and 3, $\alpha = 1$.
	Best Estimate WPS	Condition 1, 2, and 3 α is sampled from the distribution shown in Figure 2.

Warm Pre-Stress

Effect of Different Models on Risk Metrics

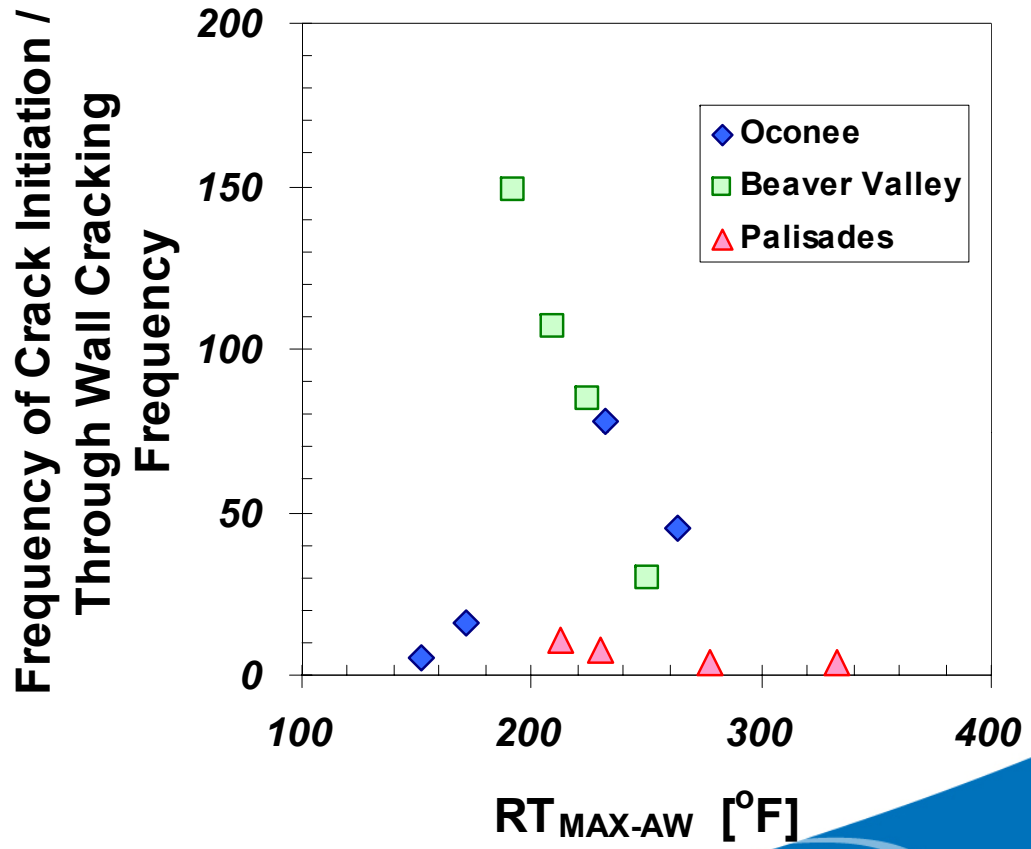


- FAVOR estimates of
  - FCI (frequency of crack initiation)
  - TWCF (through wall cracking frequency)
- FAVOR estimates are conservative relative to "best estimate" (based on experimental data) by about a factor of 2

"Failure" Criteria

Crack Initiation *vs* Thru-Wall Cracking

- At both high & low embrittlement, $P_{INIT} \approx P_{FAIL}$
  - At low RT, stuck open valves dominate. Over-pressurization always fails vessel
  - At high RT, failure follows initiation closely
- At intermediate embrittlement
  - For axial weld limited plans: $P_{INIT} \approx P_{FAIL}$
  - For plate & circ weld limited plants: $P_{INIT} >> P_{FAIL}$



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10 CFR 50.61a RT Limits

Implementation for Plate Plants

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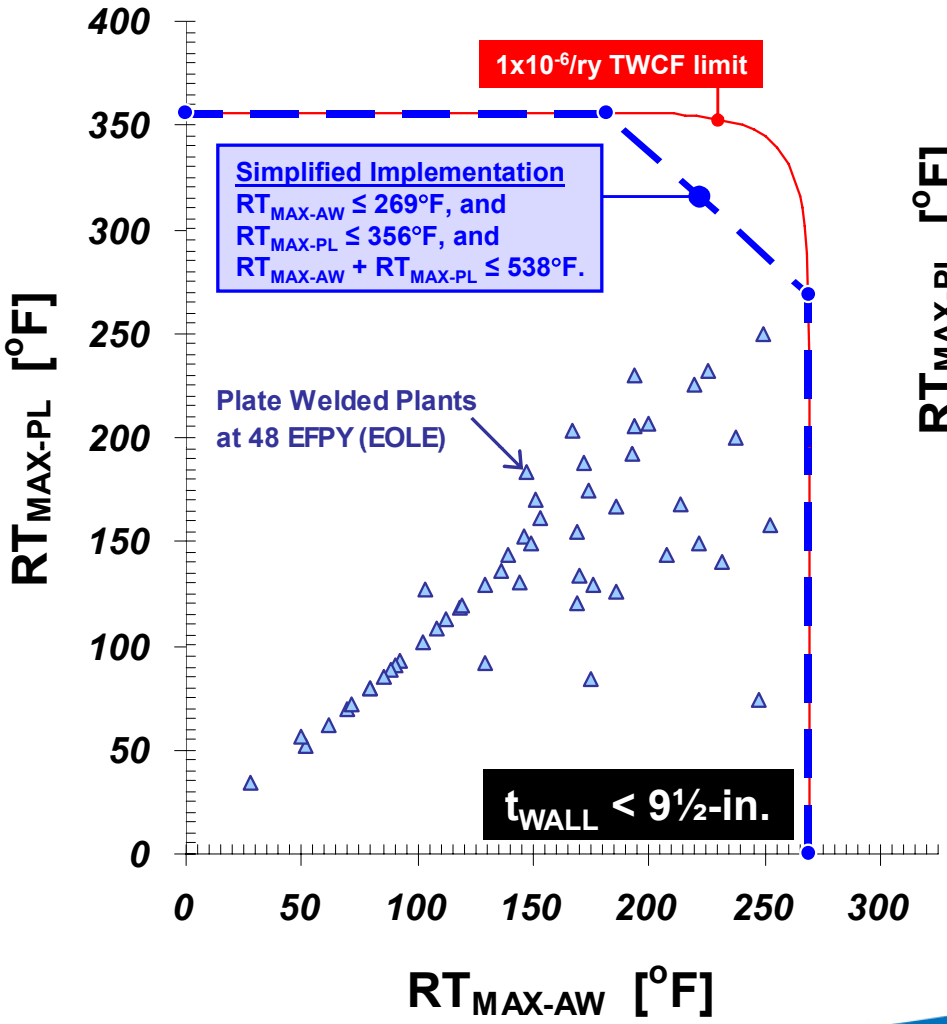

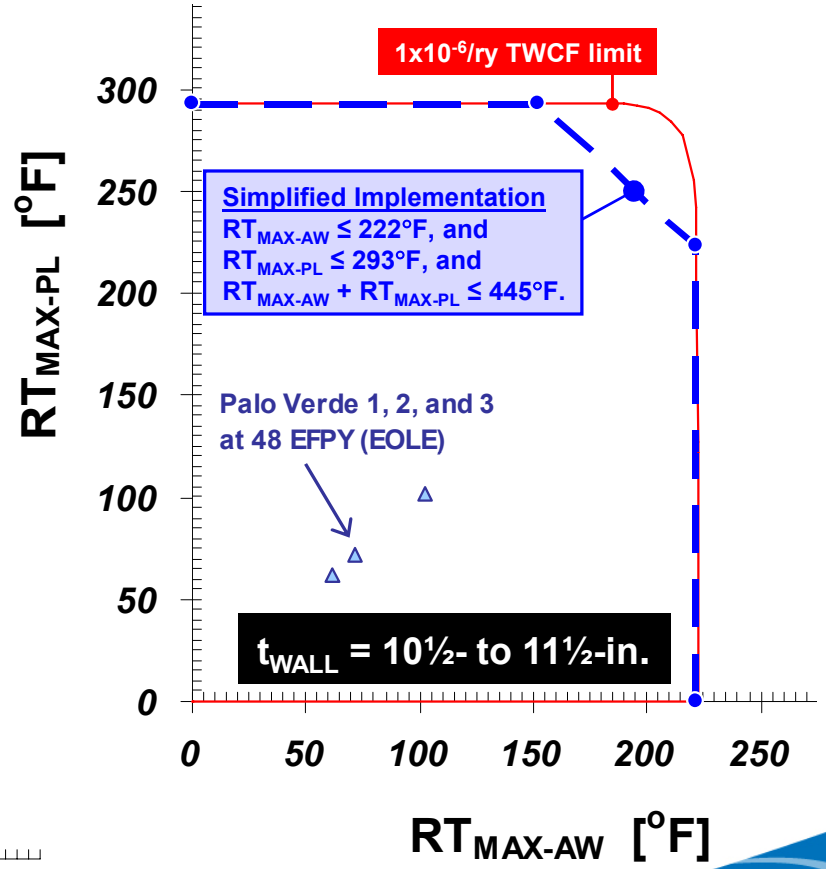

Surveillance Check

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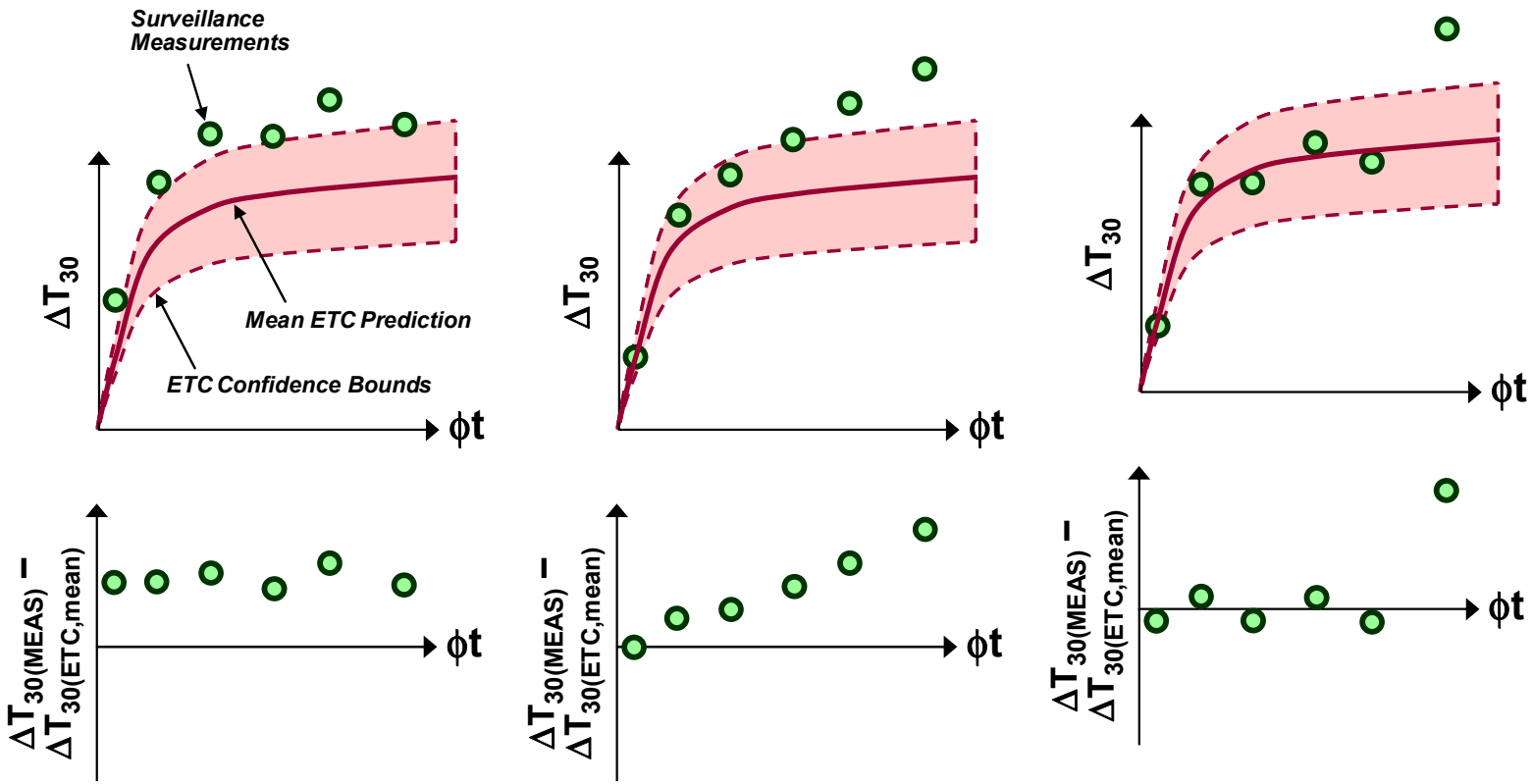


Mean Test

Slope Test

Outlier Test

Surveillance Check

10 CFR 50.61a

- Mean, slope, and outlier tests are required for all surveillance data sets with 3 or more ΔT_{30} values
  - Check only for non-conservative predictions
  - All tests passed: Use generic ΔT_{30} values
  - 1 test failed: Material specific analysis required

Flaw Distribution Check

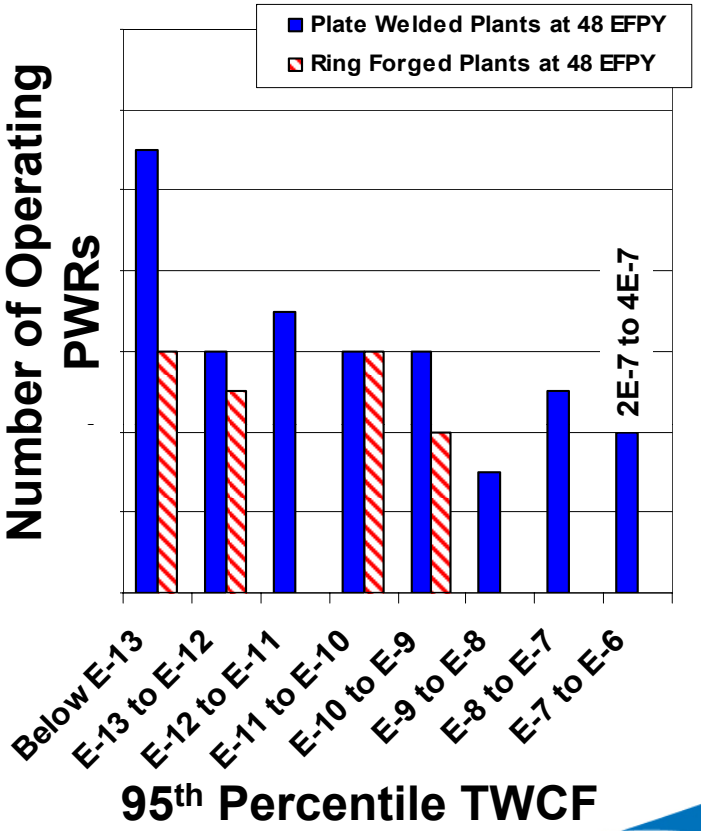
10 CFR 50.61a

- Licensees required to demonstrate, based on ISI data, that flaw distribution in RPV is bounded by that assumed in FAVOR calculations

10 CFR 50.61a

Summary

- Limits for forged plants, and for sub-clad flaws, also included
- Limits apply to all currently operating U.S. PWRs
- All plants assessable based only on available materials and fluence information
- All PWRs conform to limits, even through 60 years of operation
- To use less restrictive limits of 10CFR50.61a, plant specific aspects must be checked (defense in depth)
  - Flaw distribution
  - Embrittlement



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Regulatory Resolution of a Complex Issue Takes a LONG Time

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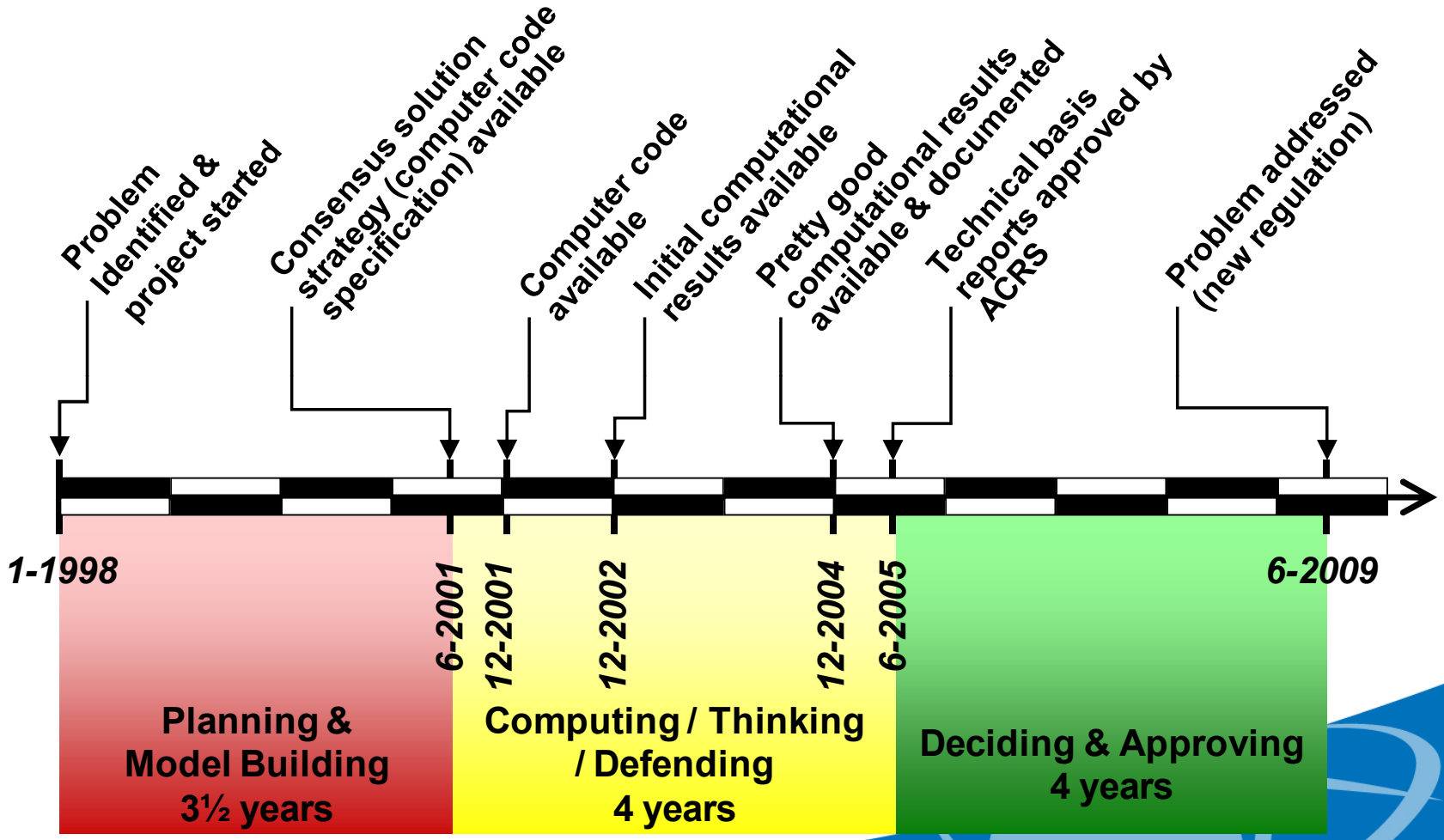

Observation

The Same Features Define Every Structural Integrity Problem

- Feature Summary
  - Environment, Loading, Geometry, and Material,
- The temporal variation (or not) of these
- A definition of the end state, or states, we care about

Proposed 4 Components of
A Generic Approach to Probabilistic Assessment of Structural Integrity

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- A ***general template*** onto which any structural integrity problem can be mapped
- A ***questionnaire*** designed to comprehensively identify and define the models and parameters that populate the template
  - This becomes the programming specification
- A ***modular computer code*** that mirrors the structure of the template
- A standard ***documentation and review process*** that mirrors the structure of the template

General Template for …

A Generic Approach to Probabilistic Assessment of Structural Integrity

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Define Initial Conditions (t=0)

- Geometry
- Material
- Loading
- Environment

In each case:
- Define models and parameters (M&P)
- Define relationships between M&P
- Decide if each M&P is modeled as
  - Certain or uncertain
  - If uncertain, epistemic or aleatory
- Characterize M&P quality
  - Pretty good
  - Conservative

Define Temporal Variations (t>0)

- # of timescales that define problem?
- What (of geometry, material, loading, & environment) change in each timescale?
- Can progress along the timescale be altered?

- For each M&P, answer the same questions as for the initial condition
- Define interdependencies between models and parameters

Define End State

- What does end state (or states) matter?
- Max tolerable failure frequency for regulatory review?
- Max tolerable failure frequency for mitigation?

Application of Lessons Learned

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- We are trying the general template and questionnaire out in a new project
  - Risk-informed revision of LBB guidance
    - Accounting for PWSCC
    - Accounting for repairs
- Effort is just starting
  - Now a collaborative NRC / EPRI effort
  - ***International partners / collaborators welcomed***

Thank You for Your Attention

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- Questions / comments ?????