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Status of Recent Practical Applications of PFM to the Assessment of Structural Systems in Nuclear Plants in the United States

Mark Kirk*

Senior Materials Engineer
United States Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Division of Engineering, Component Integrity Branch
mark.kirk@nrc.gov

*** The views expressed herein are those of the author. They do not constitute an official position of the USNRC.**

International Symposium on Improvement of Nuclear Safety Using Probabilistic Fracture Mechanics
Organized by the PFM Subcommittee, Atomic Energy Research Committee of the Japan Welding Engineering Society

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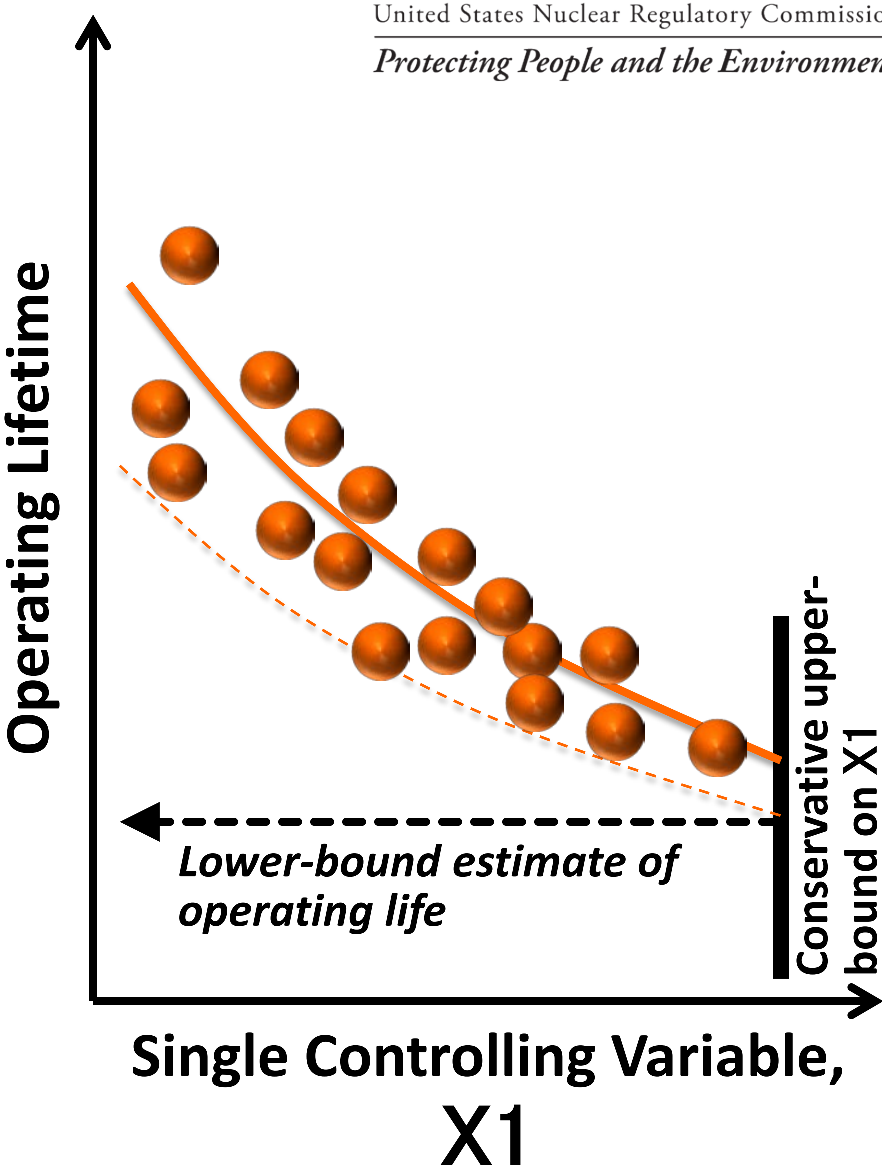
Outline

- **Comparison of deterministic & probabilistic approaches to structural integrity assessment**
- **Example Application 1: pressurized thermal shock (PTS) of the reactor pressure vessel (RPV)**
- **Example Application 2: leak before break (LBB) of primary system piping**
- **Concluding remarks**

Deterministic Analyses

Why do we use them?

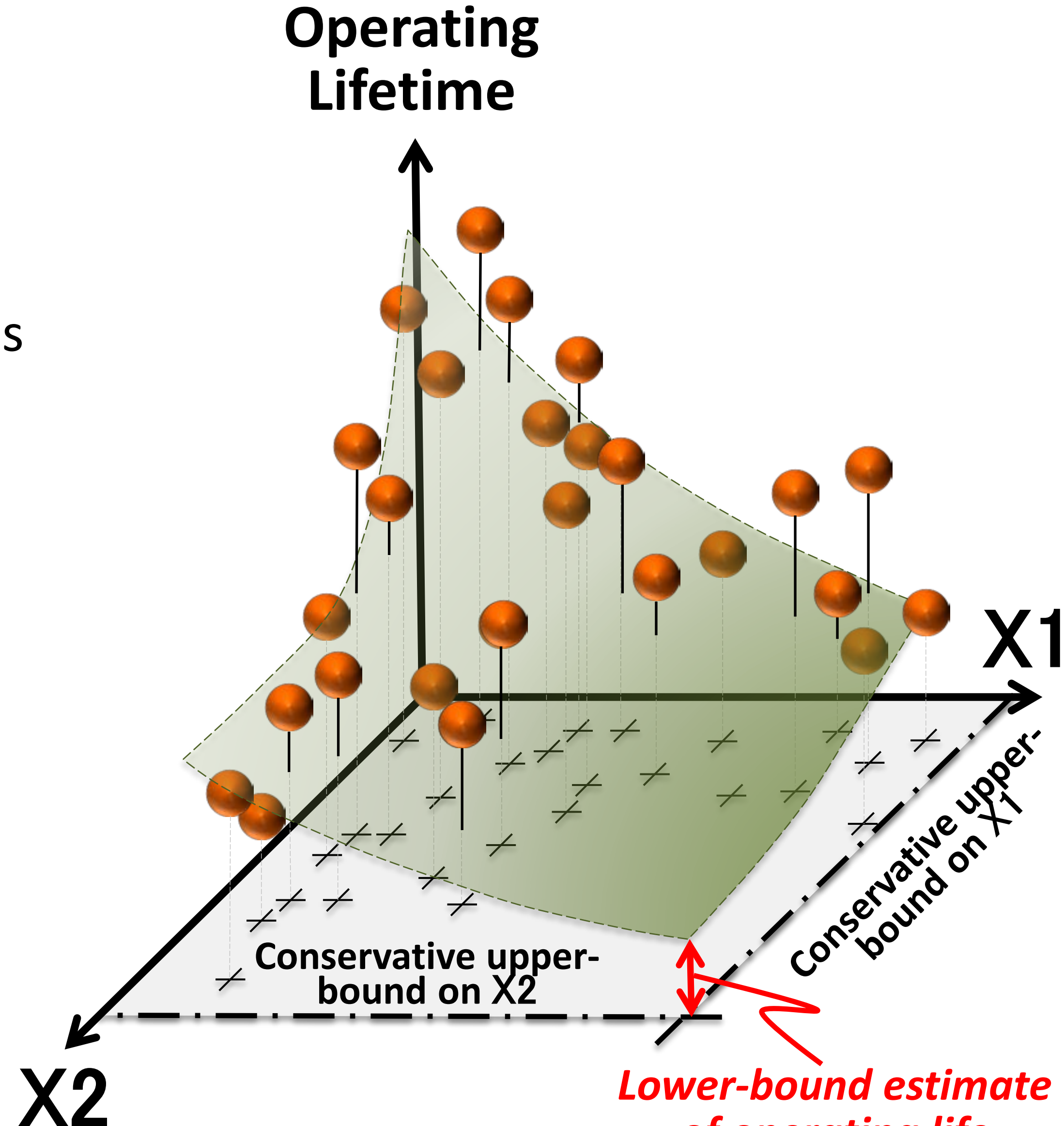
- **Easier …**
  - than probabilistic analyses
  - to demonstrate their conservatism than for a probabilistic analysis
- **A simplified example**
  - One variable (X1) controls operating lifetime
  - A conservative upper bound on X1 produces a safe (***& reasonable***) lower-bound estimate of operating life



Deterministic Analyses

When do they break down?

- **A slightly less simplified example**
  - Two variables (X1 & X2) control operating lifetime
  - Conservative upper bounds on X1 & X2 can produce a safe (***but unreasonable***) lower-bound estimate of operating life
- **The unreasonableness becomes more extreme as the number of controlling variables increases (X1, X2, X3, ⋯ Xn)**



Probabilistic Analyses

Why might they be used?

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- **To address deficiencies of the deterministic approach:**
  - Conservatism quickly multiplies
    - When every variable is bounded
    - When inherently conservative models are used
  - Does not scale well to multi-variate problems
    - Quantifying the conservatism of the answer becomes impossible

- **Probabilistic approach**
  - Conservatism & safety ensured by controlling to the end result (failure probability)

An Incomplete List of Variables in a PTS Analysis

temperature

cladding

event type

(R,T)

Mn

load

Φ

(a,2c)

Ni

Cu

P

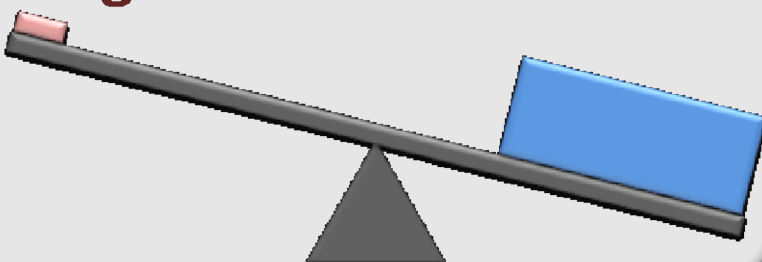
$= f\,(x, y, z, t)$

Deterministic *vs.* Probabilistic

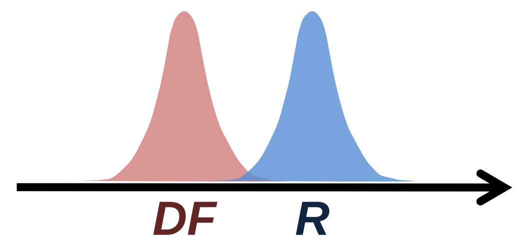
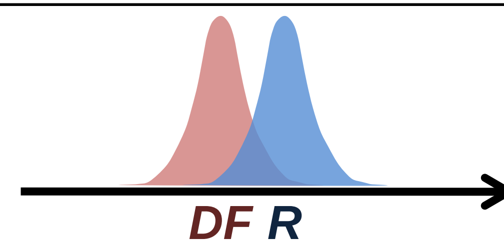
Reality

The requirement imposed in a <u>deterministic framework …</u>

Fracture Driving Force < Fracture Resistance



… is a comforting abstraction, but it obscures the fact that in the reality we seek to represent driving force and resistance are inherently distributed quantities.

Actual Situation (Reality)	
$P_{FAILURE}$	Distributions
Zero	
Small	
Large	

Deterministic *vs.* Probabilistic

Mathematical Models of Reality

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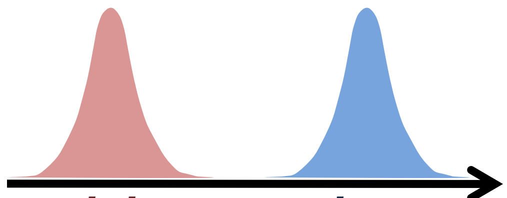
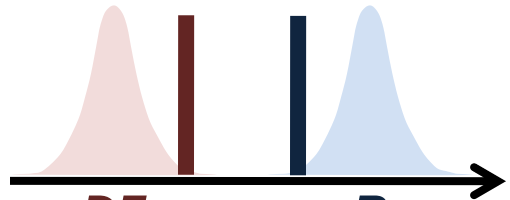
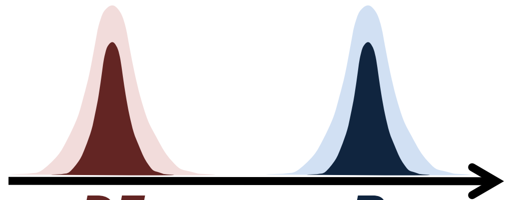
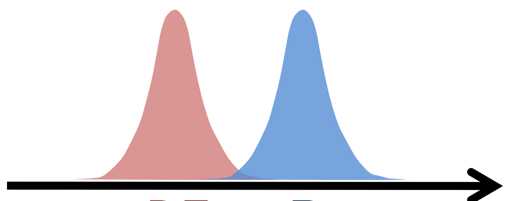
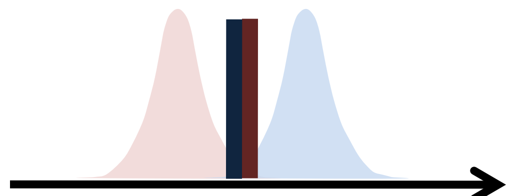
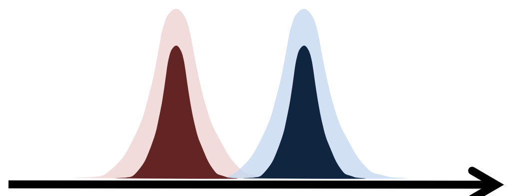
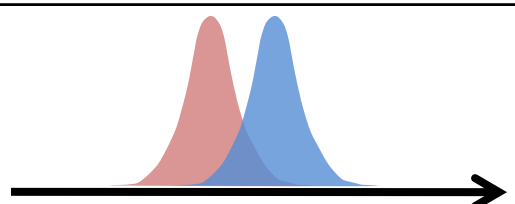
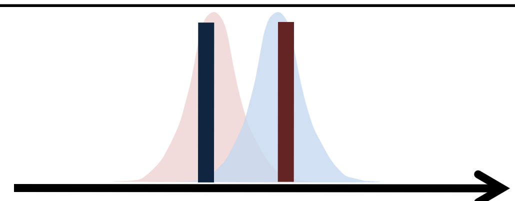
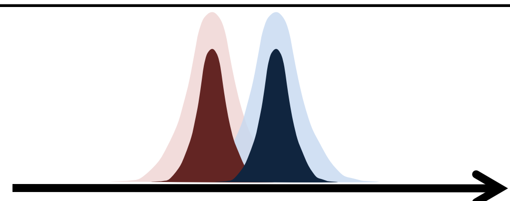
Actual Situation (Reality)		Models of Reality	
$P_{FAILURE}$	Distributions	Deterministic	Probabilistic
Zero		 ***Estimate: No "Failure"***	 ***Estimate: P_{FAIL}=0***
Small		 ***Estimate: "Failure"***	 ***Estimate: P_{FAIL}= Very Small***
Large		 ***Estimate: "Failure"***	 ***Estimate: P_{FAIL}= Large***

Future events are correctly represented as probabilities, not absolutes.

Deterministic *vs.* Probabilistic

Similarities and Differences

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Similarities

- Both treat uncertainty
  - Deterministic models ***bound*** uncertainty
  - Probabilistic models ***quantify*** uncertainty
- Probabilistic models may contain deterministic aspects where full information is lacking, e.g.:
  - Conservative models
  - Bounding inputs
  - And so on …

Differences

- How result is expressed
  - **Deterministic**: “Failed” or “Not Failed”
  - **Probabilistic**: A failure probability
- Who the decisionmaker is
  - **Deterministic**: Only the engineering analyst (because “failure” is unacceptable)
  - **Probabilistic**: Many people (because some failure probability can be accepted)

Nothing changes by adopting a probabilistic analysis, other than acknowledging that which already exists.

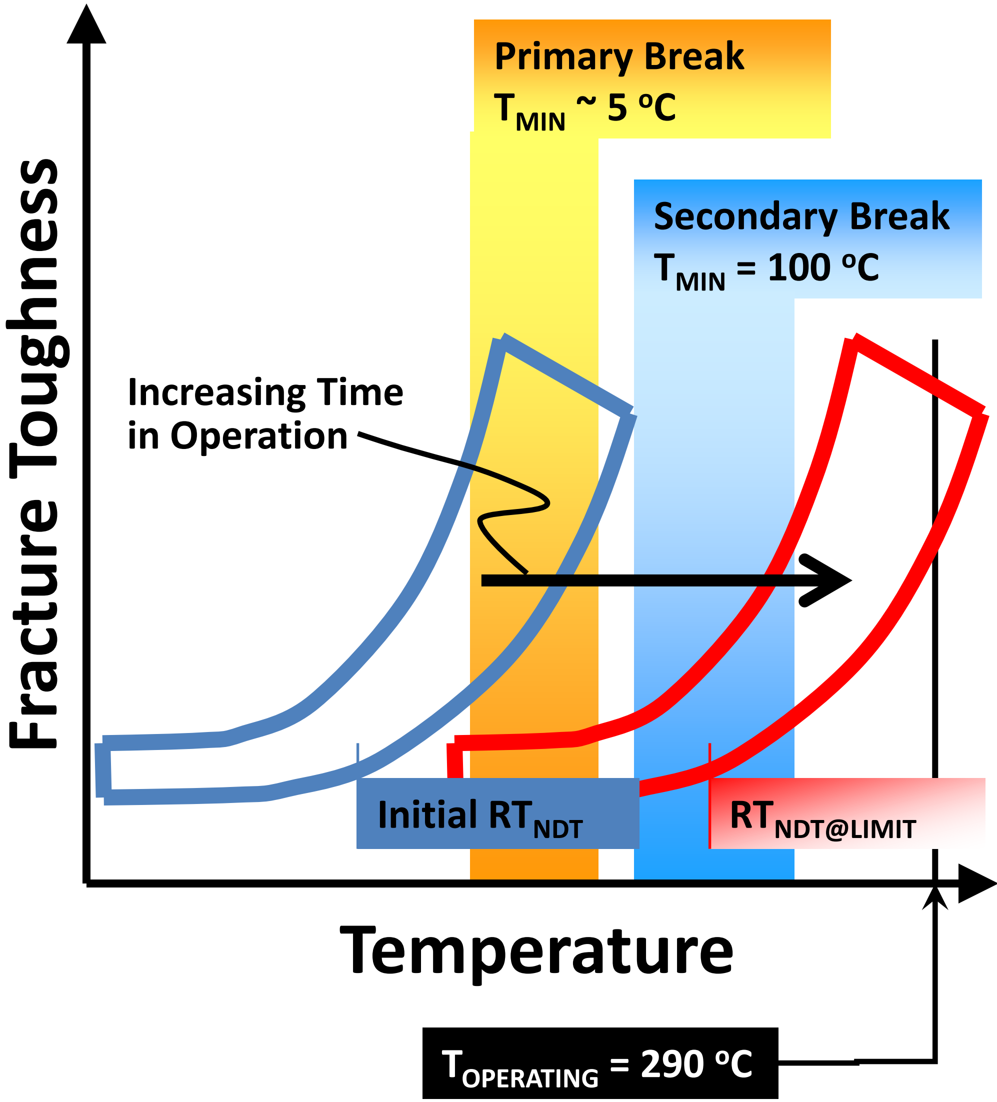
First Example Application of PFM

PRESSURIZED THERMAL SHOCK

Pressurized Thermal Shock

- **10 CFR 50.61 (PTS Rule)**
  – Established 1985
  – Conservatisms inherent to basis for RT_{PTS} can limit operable lifetime
- **Considerations in development of 10 CFR 50.61a (Alternate Rule)**
  – 10 CFR 50.61 conservatisms will cause plant-specific submittals, all addressing the same issues
  – Alternative approaches considered
    - Individual review of plant-specific assessments
    - Comprehensive re-assessment of PTS performed proactively & with thorough review by technical experts

selected



Key Aspects of 10 CFR 50.61a Development

- **Policy**

  Establishing a risk-informed limit consistent with Commission policy guidance

- **Technical**

  Translating this limit into screening tool expressed in terms of measurable variables (e.g., embrittlement, flaws)

- **Communication and Education**

  Obtaining input from and addressing the concerns of a diverse array of constituencies

10 CFR 50.61a Limits Follow from Policy Decisions

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51 FR 28044, Safety Goal Policy Statement (1986)

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

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

CDF < 1×10^{-4}/ry CDF & QHO limits for generic decisions

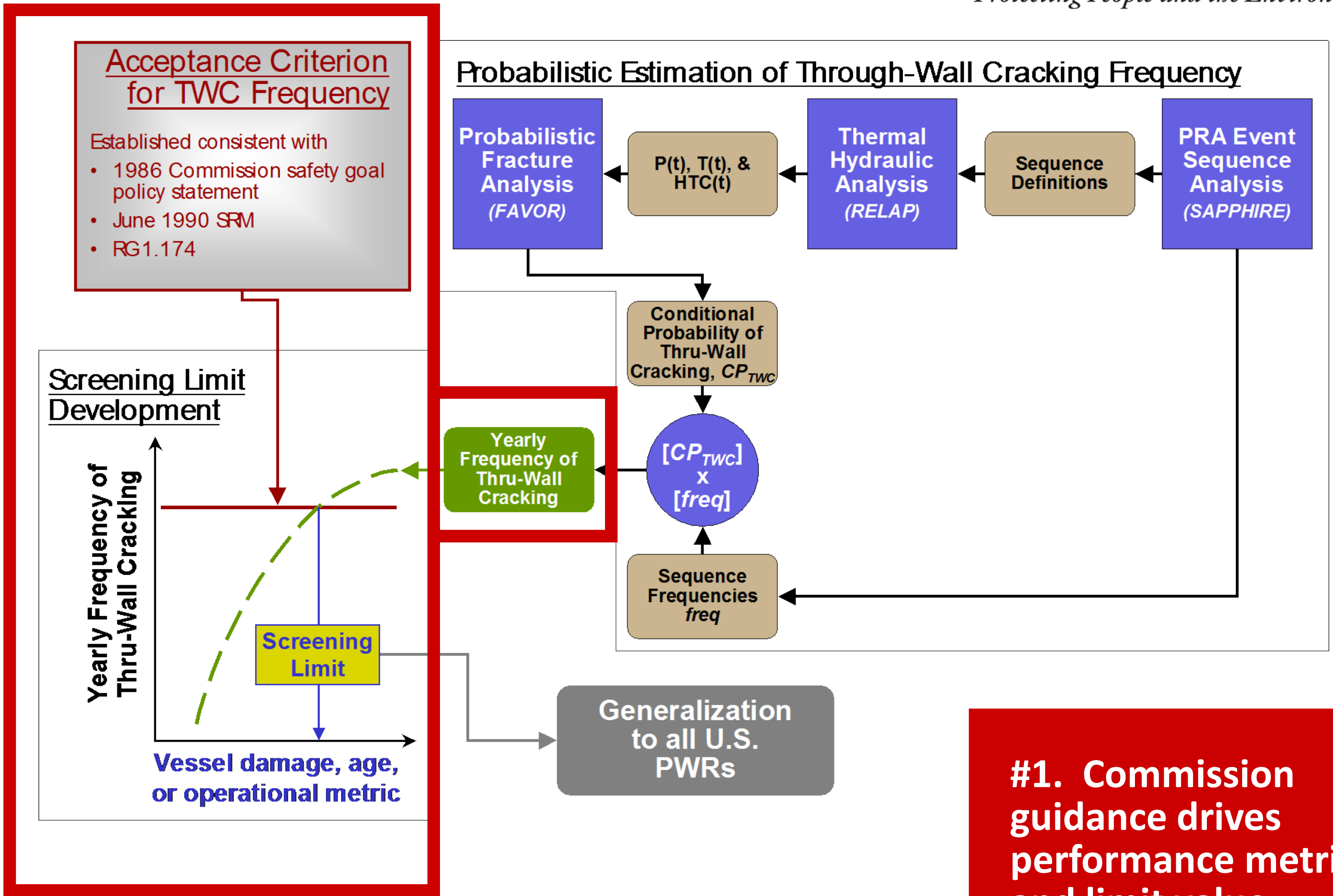
Regulatory Guide 1.174

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

10 CFR 50.61a
Voluntary Alternative Pressurized Thermal Shock Rule

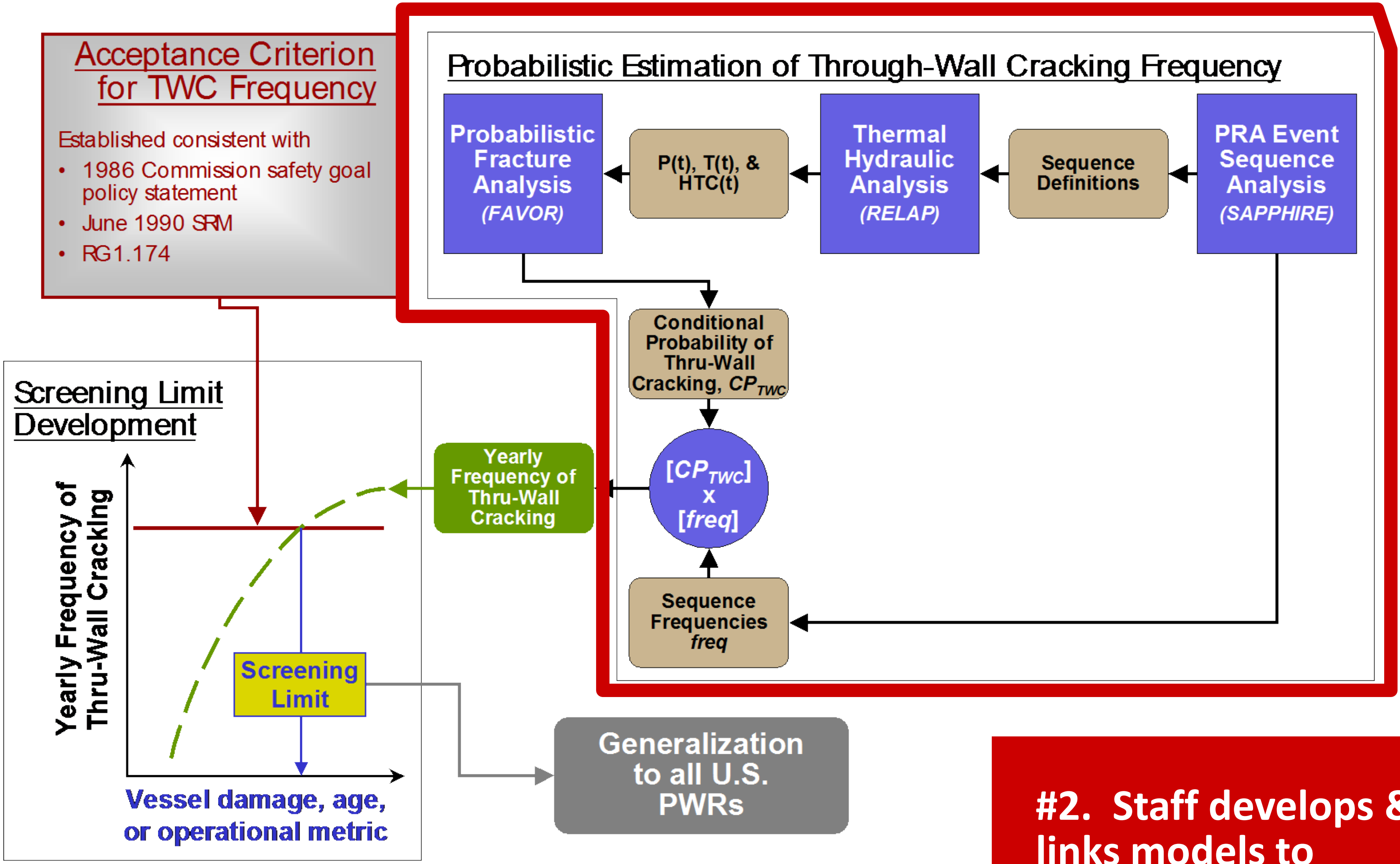
- **Accident sequence progression study shows that through-wall cracking rarely leads to LERF**
- **Conservatively assumes equivalence of LERF and the yearly through-wall cracking frequency (TWCF) of the reactor pressure vessel**
- ***Along with defense-in-depth considerations, a tolerable limit on TWCF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

Technical Approach



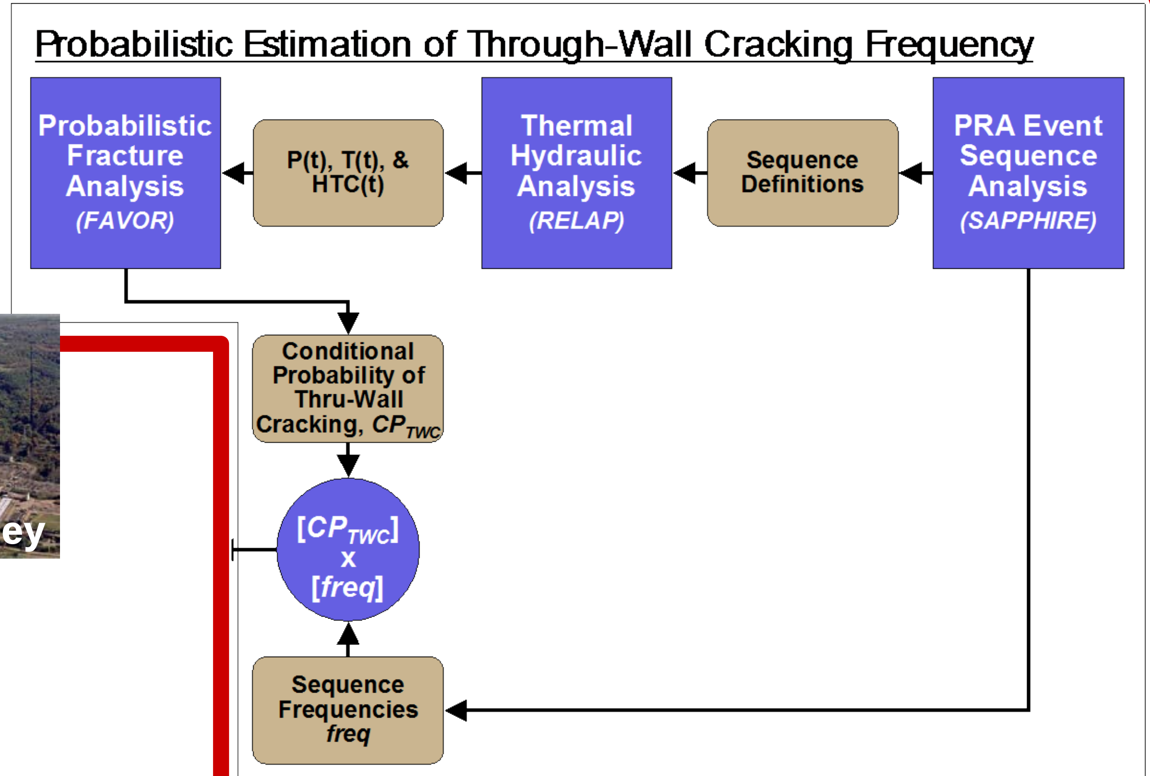
#1. Commission guidance drives performance metric, and limit value.

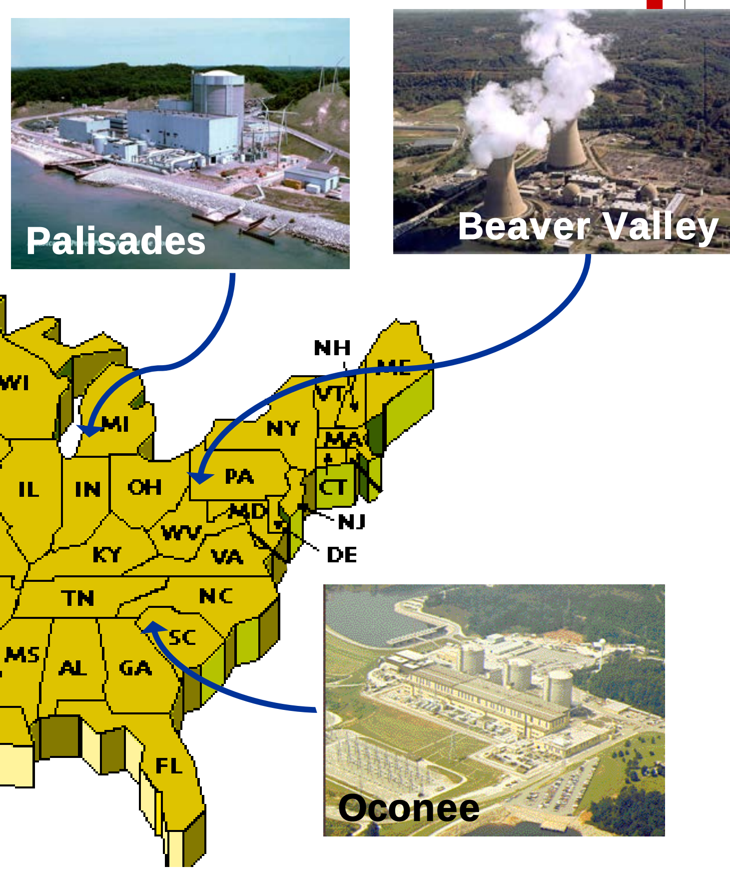
Technical Approach



#2. Staff develops & links models to estimate this performance metric.

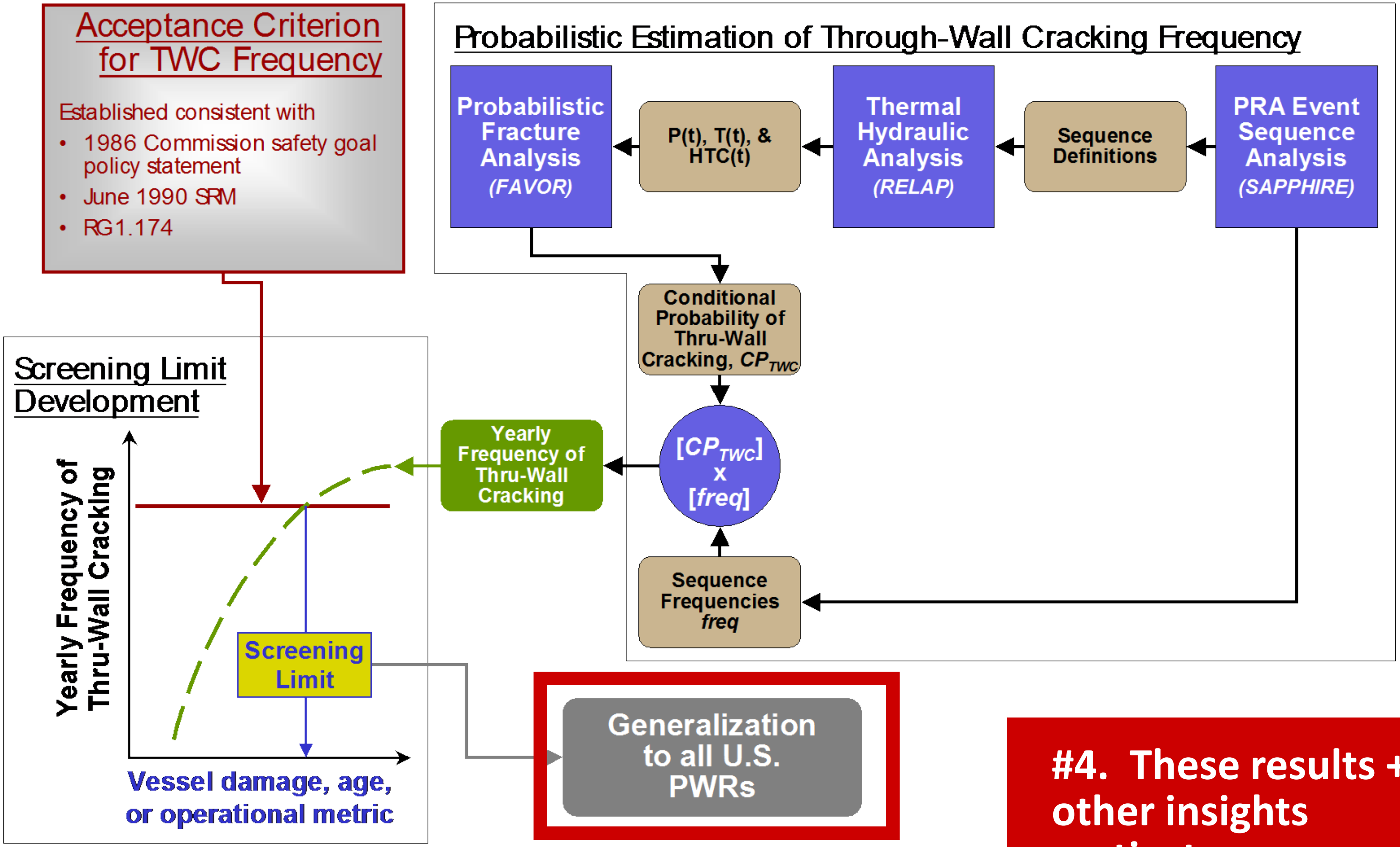
Technical Approach





#3. Metric estimated based on detailed analysis of 3 plants.

Technical Approach



#4. These results + other insights motivate generalization to all plants.

Probabilistic Fracture Model

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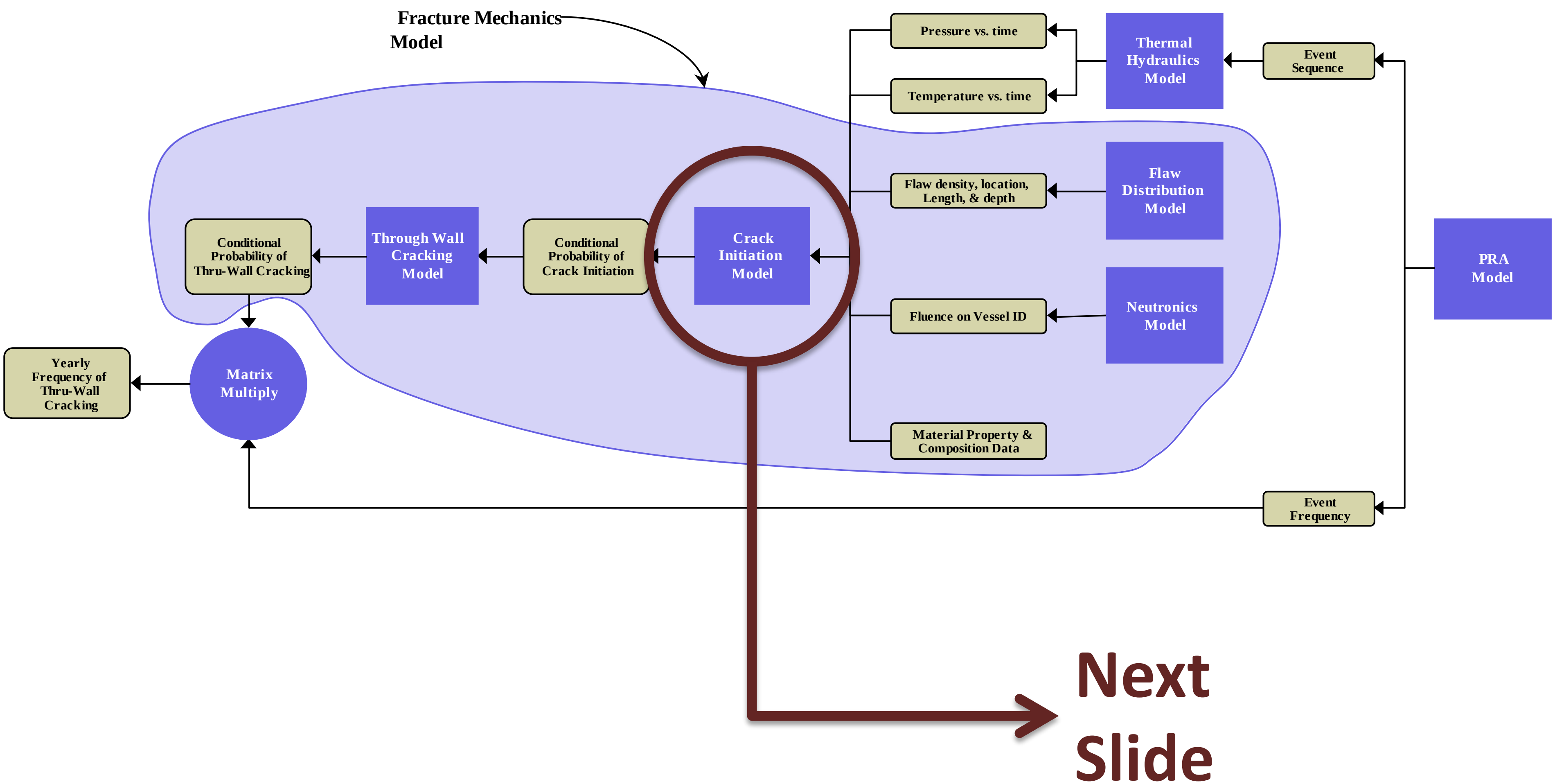

Details of the Crack Initiation Model

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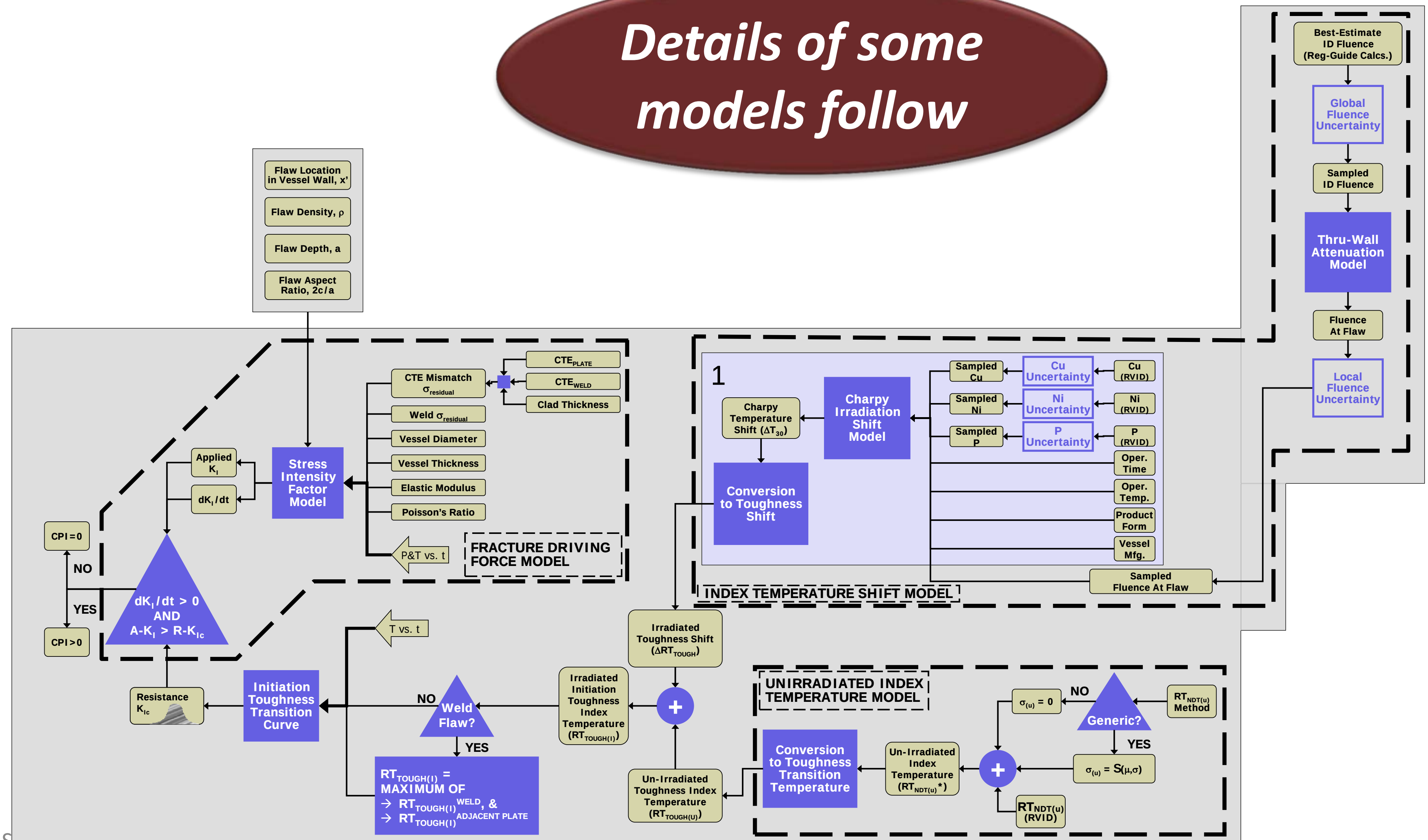
Details of some models follow



Parameters of Crack Initiation Model

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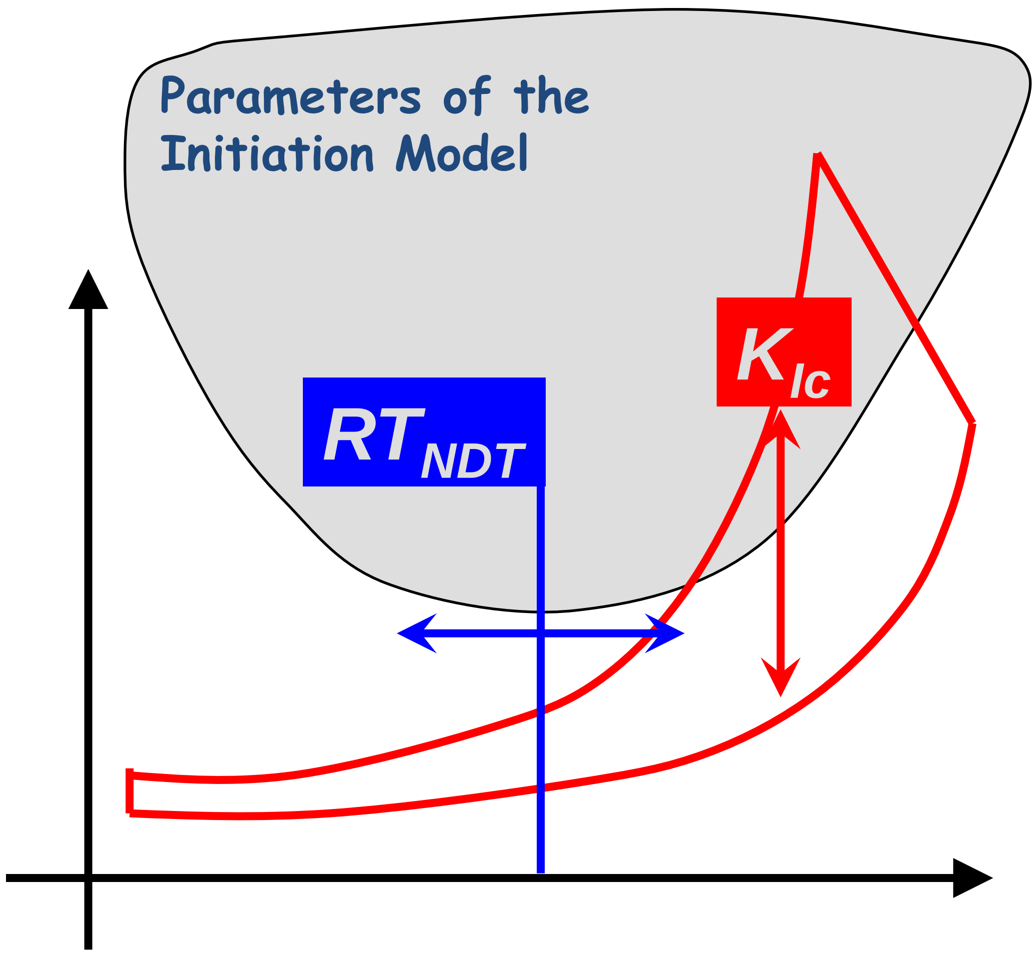
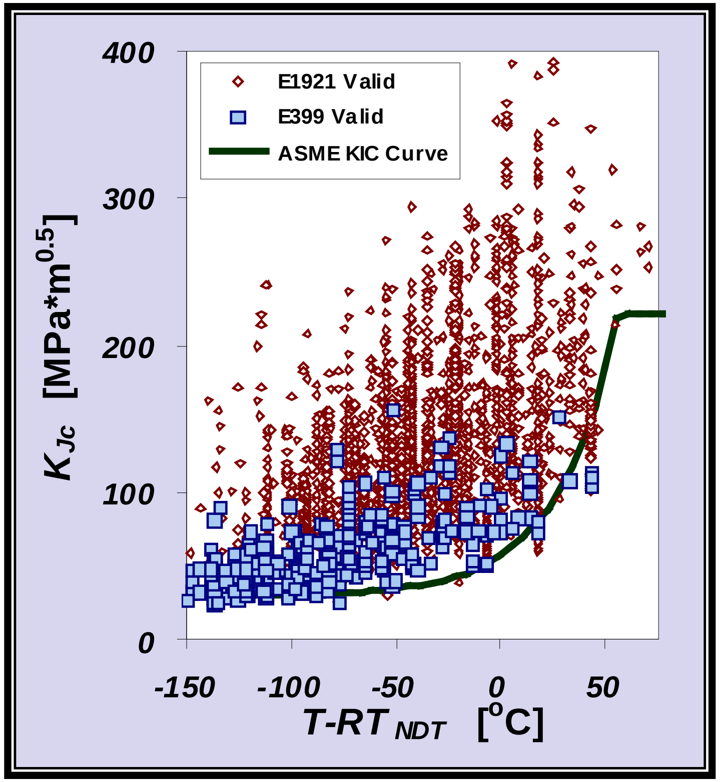
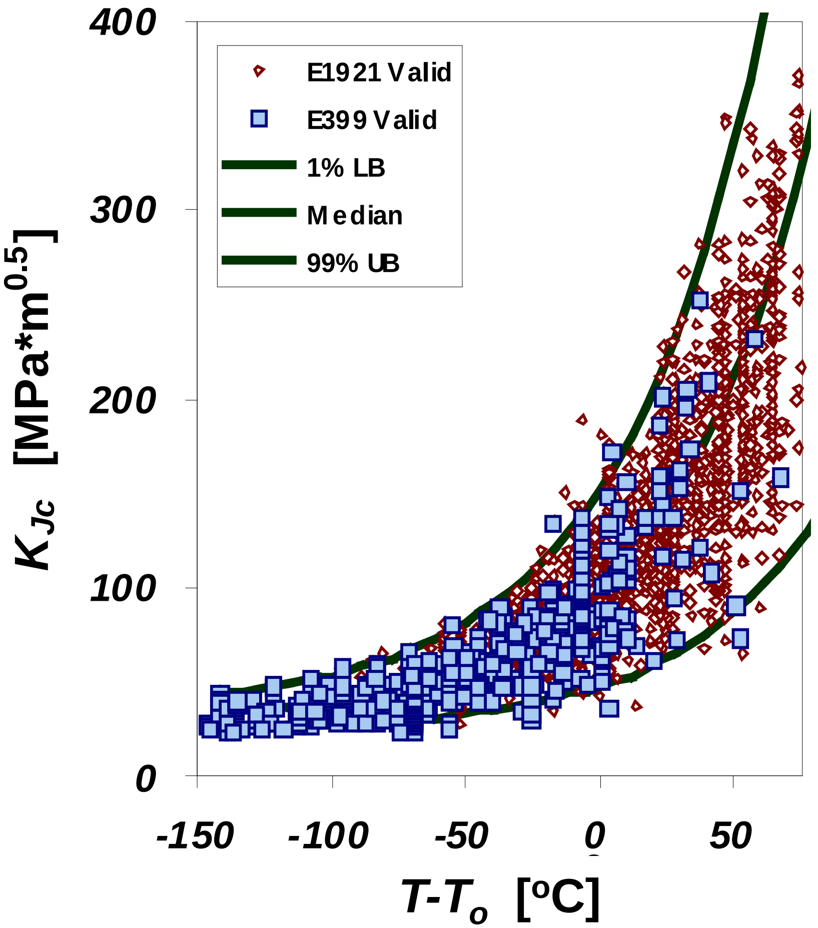




Uncertainty Treatment in the Crack Initiation Model

- Because of implicit conservative bias, fracture toughness models based on the RT_{NDT} index temperature contain a mix of
  - Epistemic uncertainty in RT_{NDT}, and
  - Aleatory uncertainty in K_{Ic}
- Use of the best-estimate Master Curve index temperature (T_o) effectively removes epistemic uncertainty, leaving only the aleatory uncertainties produced by material variability



Crack Initiation Toughness

K_{Jc}

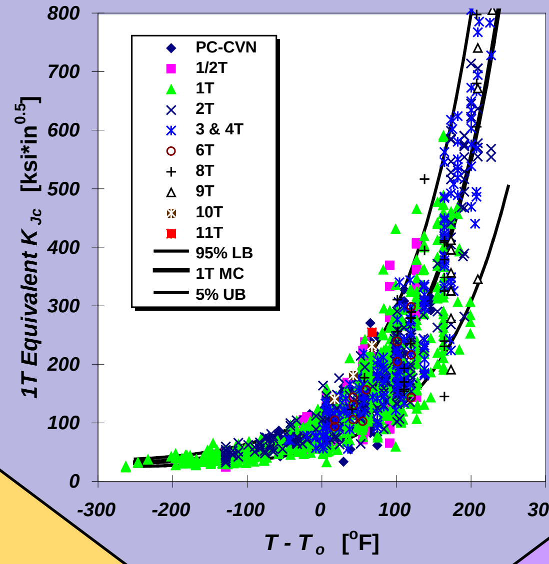
The Probabilistic FAVOR Model uses Linked Toughness Distributions

Crack Arrest Toughness

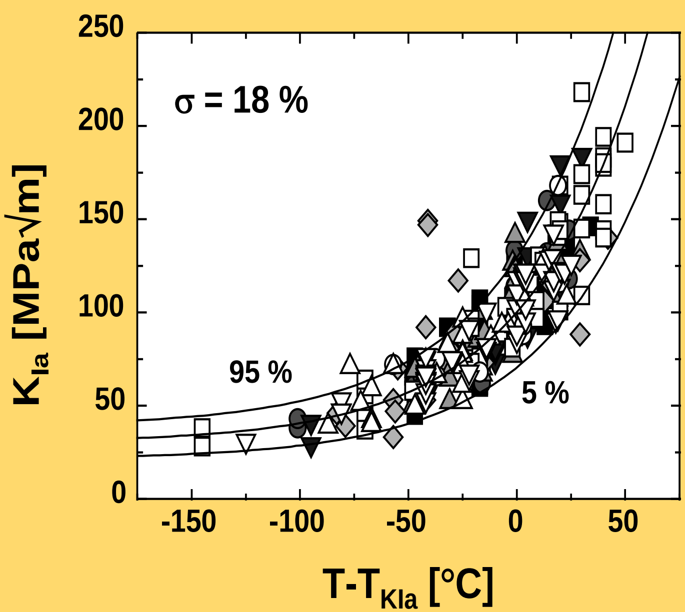
K_{Ia}

Upper Shelf Toughness

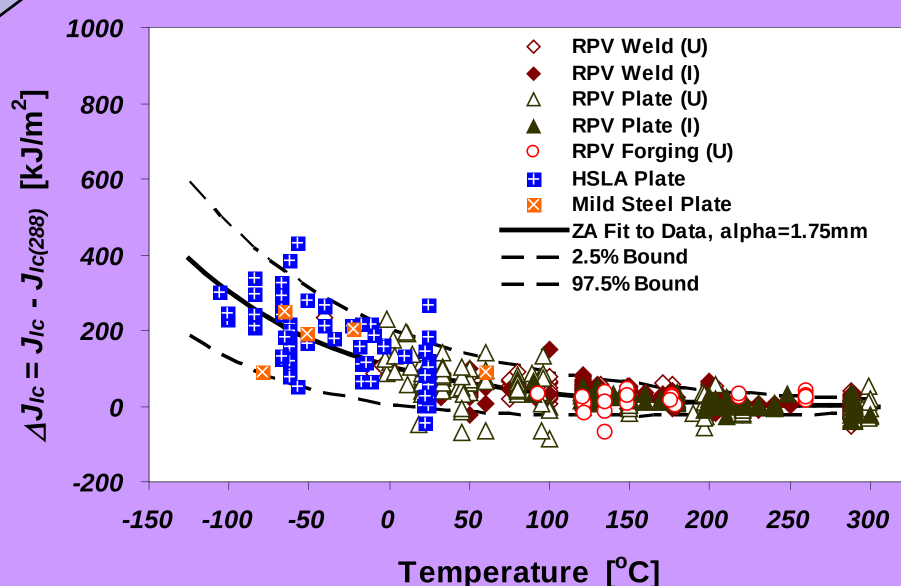
J_{Ic}



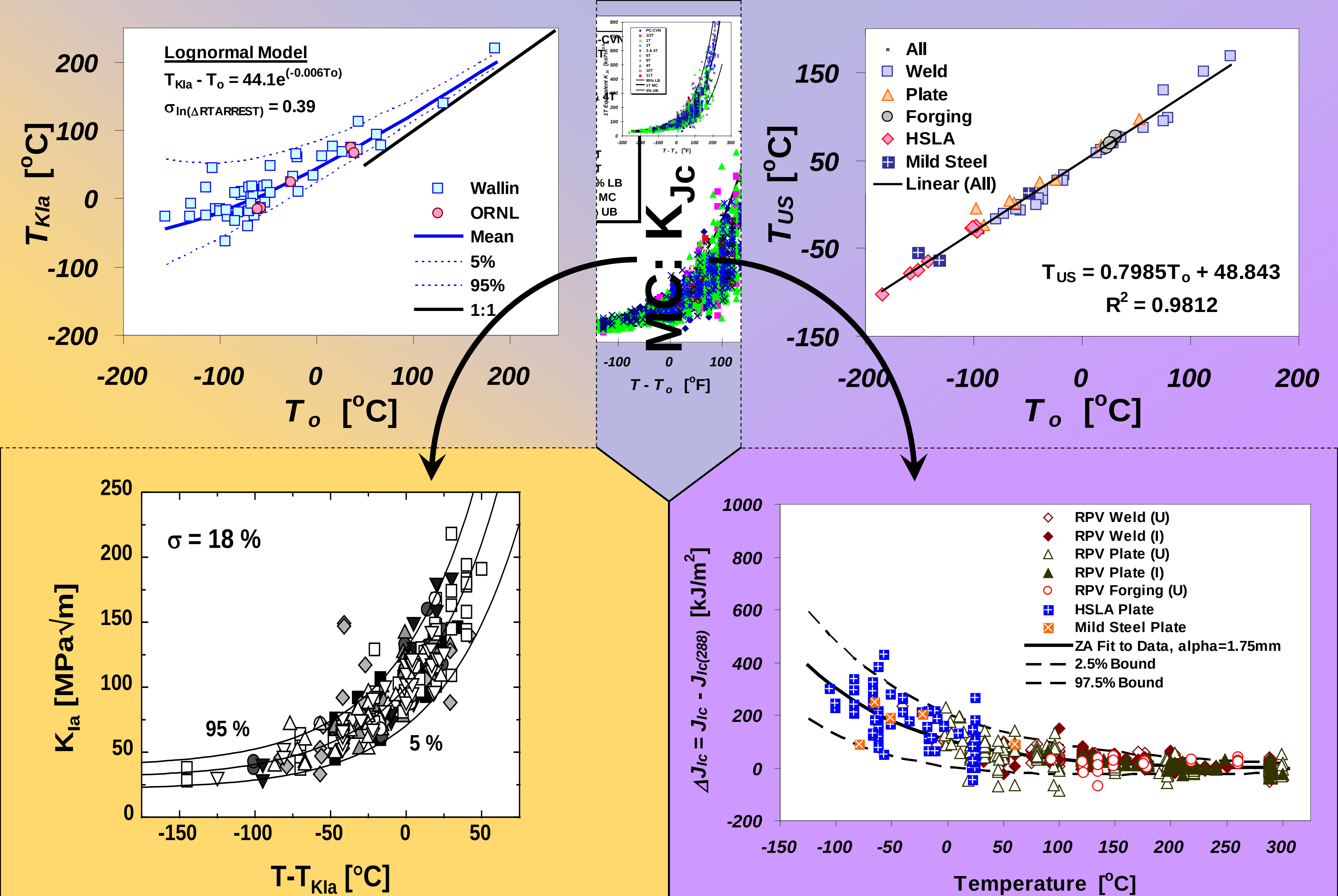
Crack Initiation Toughness:
K_{Jc} Master Curve [Wallin]



Crack Arrest Toughness:
K_{Ia} Master Curve [Wallin, Kirk]



Upper Shelf Toughness:
J_{Ic} Master Curve [EricksonKirk]



Crack Arrest Toughness:
K_{Ia} Master Curve [Wallin, Kirk]

Upper Shelf Toughness:
J_{Ic} Master Curve [EricksonKirk]

Major Outcomes of PTS Re-Evaluation Analyses

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- What operational transients most influence PTS risk?
- What material features most influence PTS risk?
- Are these dominant material features / transients common across the fleet?
- New limits on embrittlement based on RI calculations

Important Transient Classes

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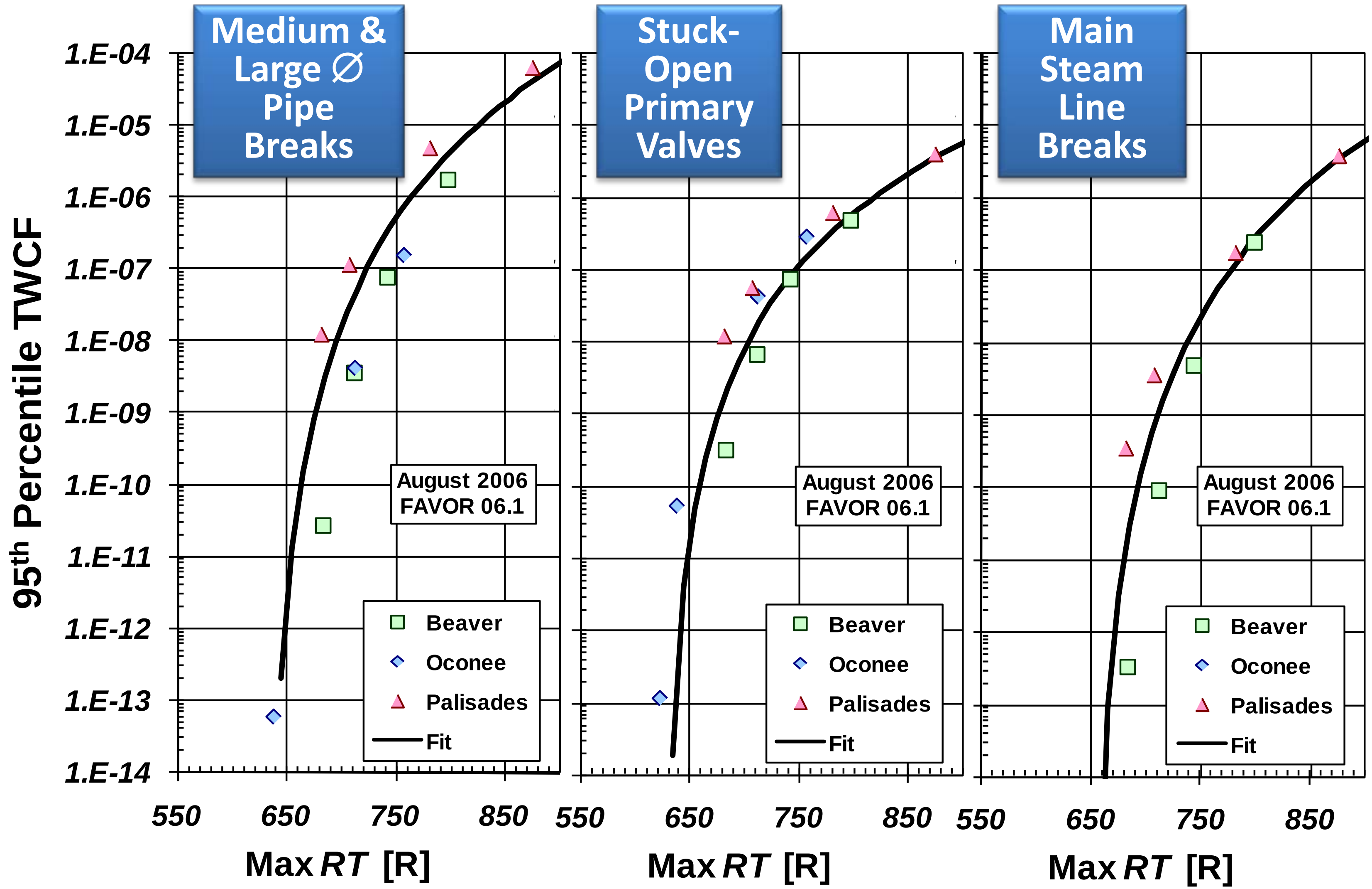

Important Transient Classes

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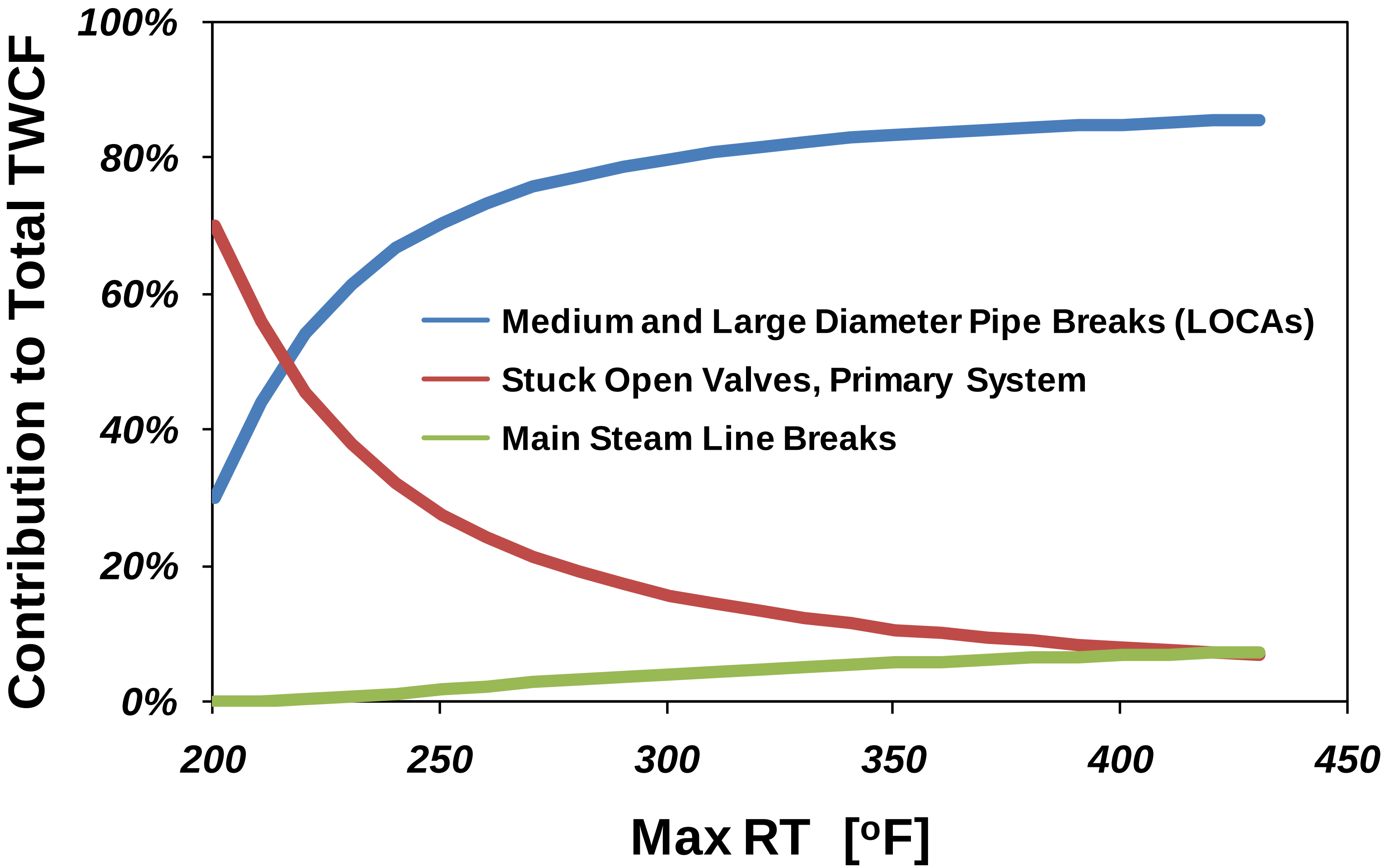

Primary side faults dominate risk: *lower temperature*

Important Material Features

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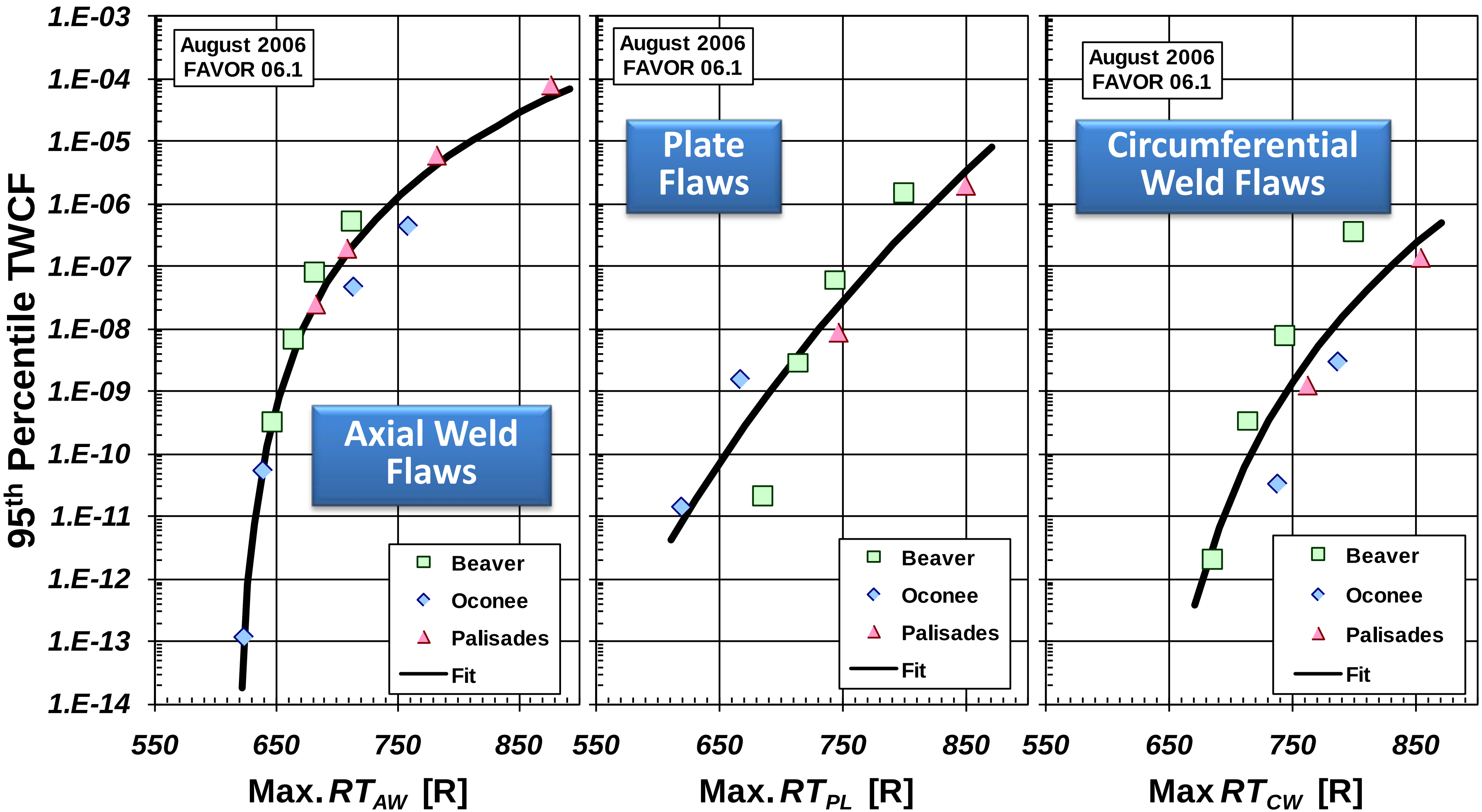
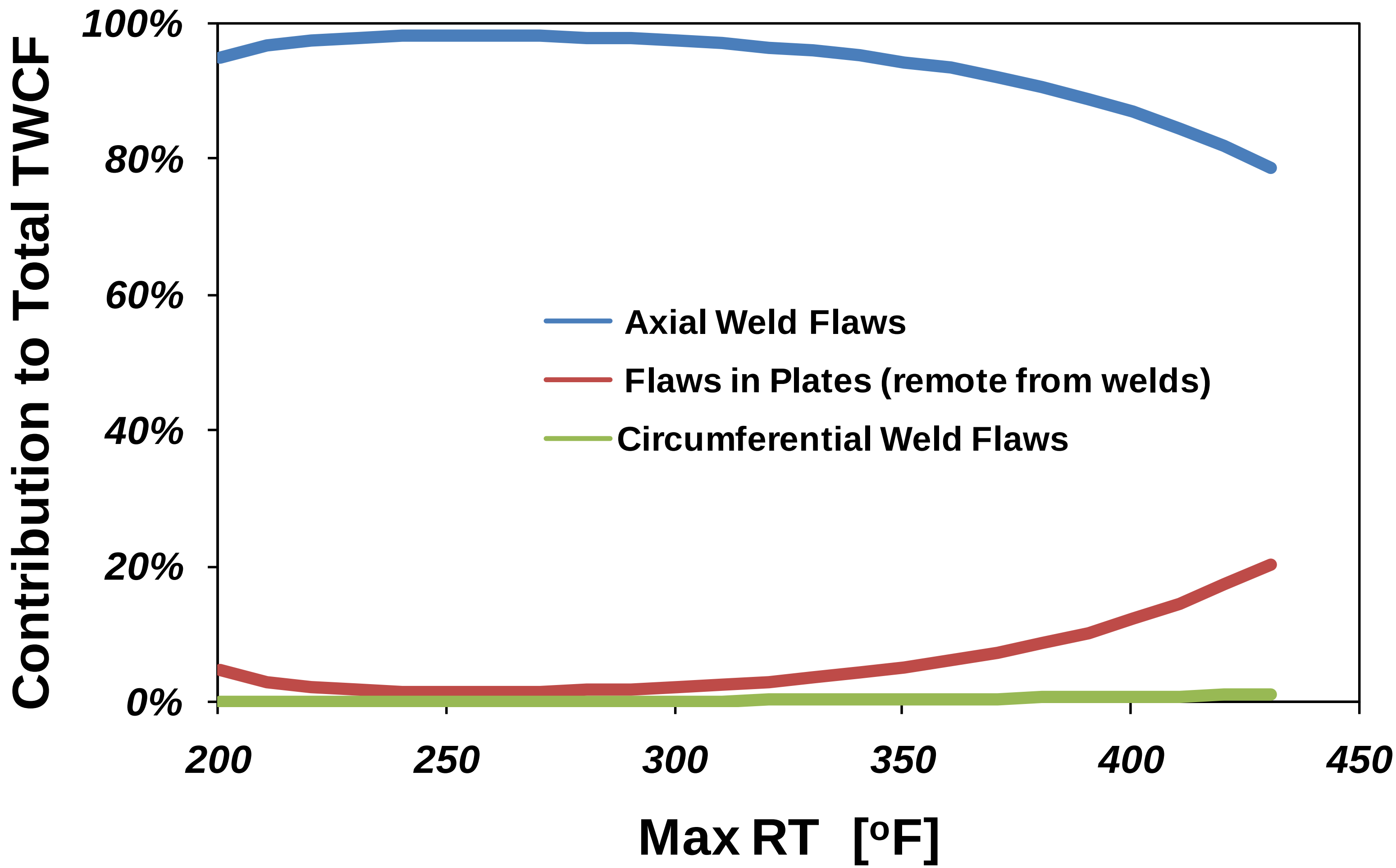


Important Material Features



Axial weld flaws dominate risk: *size & orientation*

Outcome

50.61 *vs.* 50.61a Comparison

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Less restrictive embrittlement limits are justified by new calculations, & enable longer operations, but gating criteria must be satisfied to use 10 CFR 50.61a.

	10 CFR 50.61 *REQUIRED*	10 CFR 50.61a *VOLUNTARY*
Reference Temperature Limits	More restrictive	Less restrictive
Plant-specific surveillance data check	Required – 1 test	Required – 3 tests
Plant specific inspection for flaws	Not required	Required

10 CFR 50.61a Limits for Plate Plants

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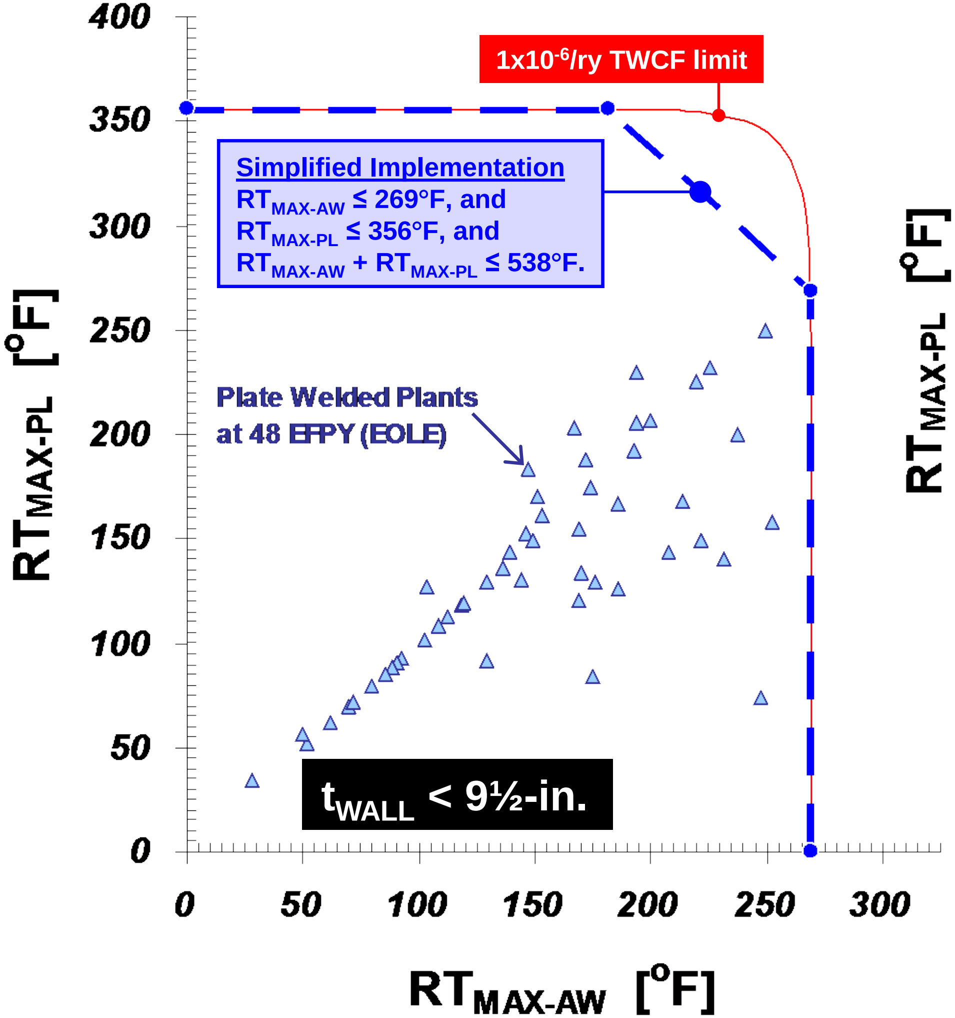

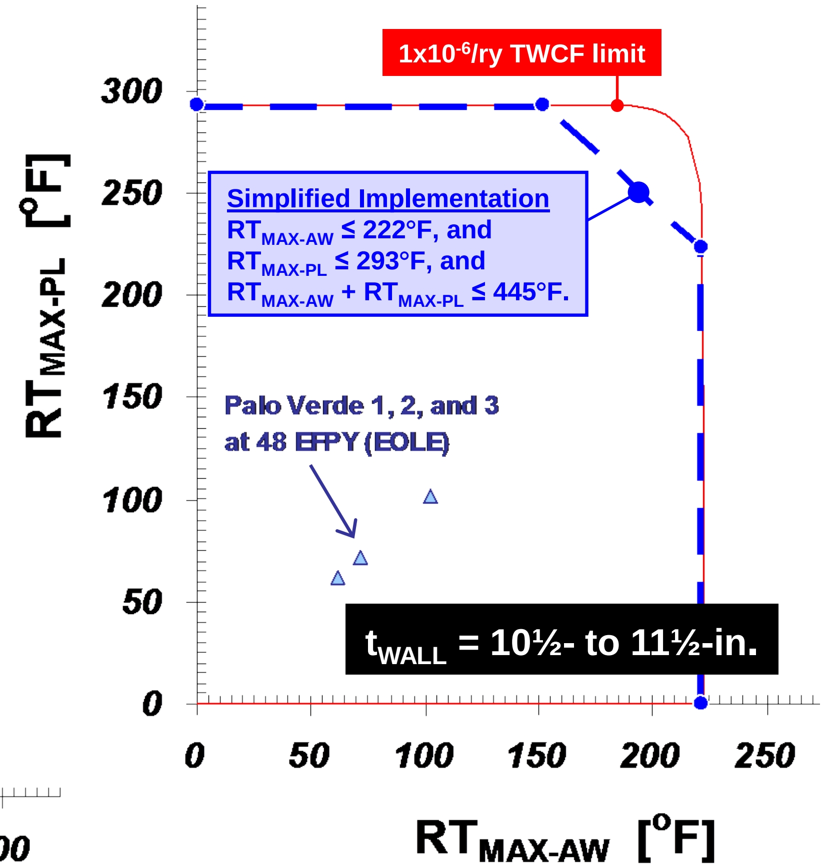

If plants can satisfy the gating criteria, most should be compliant with 10 CFR 50.61a.

10 CFR 50.61a Summary

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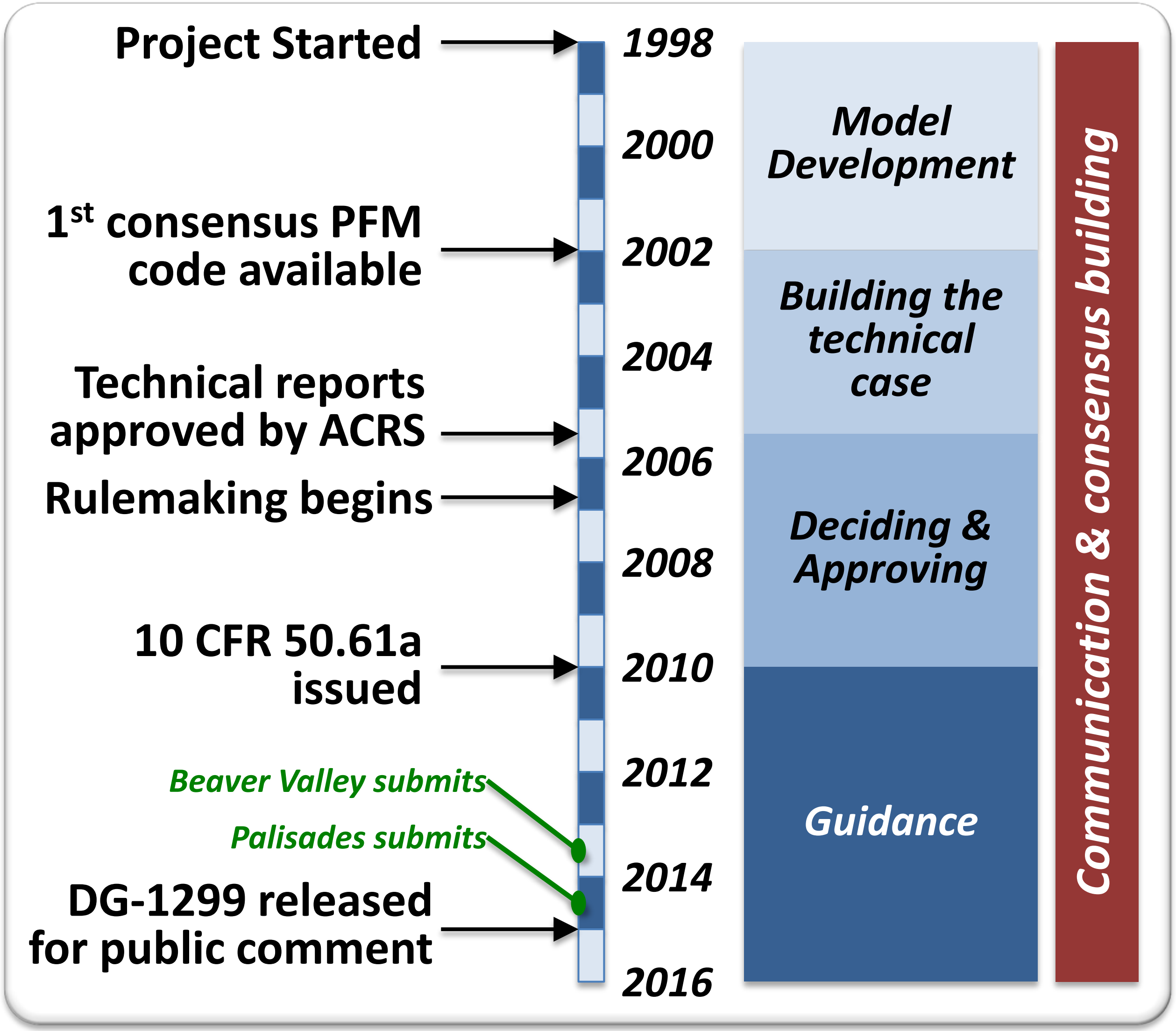
- **50.61a opens the possibility for increased operational lifetime with no compromise to safety**
  - New embrittlement limits justified by more realistic analysis
- **Making this change took considerable time & resources:**
  - Complexity of the topic
  - "New" approach ("probabilistic" instead of "deterministic")
  - Variety of stakeholders involved
- **Unanticipated benefits**
  - Comprehensive review of all model components
  - Updated state of knowledge influences regulations



Second Example Application of PFM

LEAK BEFORE BREAK

LBB Background

Problem Being Addressed

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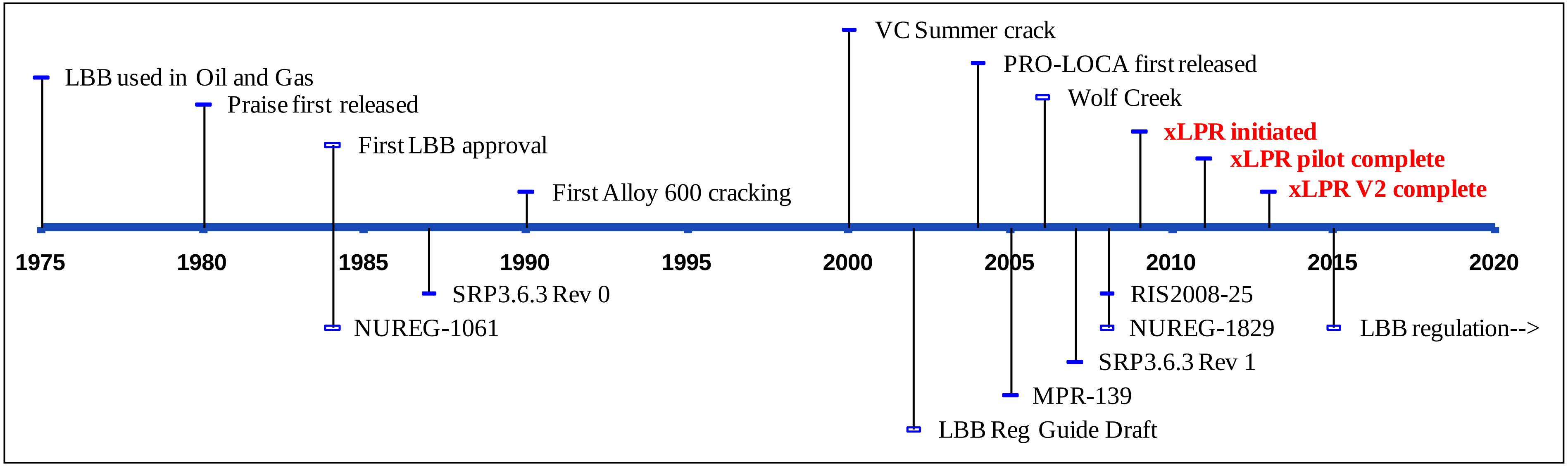
- **10 CFR 50 Appendix A General Design Criteria 4: permits exclusion of local dynamic effects of pipe ruptures from design basis**
- **LBB-justified modifications to plant design (e.g. elimination of pipe whip restraints, jet impingement shields) have been approved …**
  - Assuming that no active degradation mechanisms exist
  - But active degradation mechanisms (PWSCC) do exist
- **Solutions**
  - Short term: mitigations and inspections
  - Long term: probabilistic evaluation

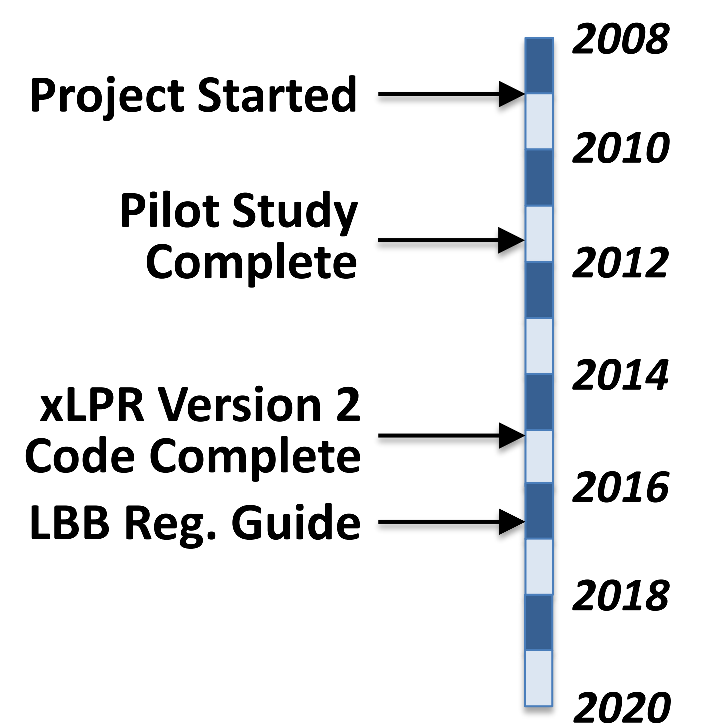


xLPR Overview

Goals & Timeline

- Develop a ***probabilistic*** assessment tool that can be used to directly assess compliance with 10 CFR 50 App-A GDC-4
- Tool will be
  - **Comprehensive** with respect to known challenges and loadings
  - **Vetted** with respect to scientific adequacy of models and inputs
  - **Flexible** to permit analysis of a variety of in service situations
  - **Adaptable**: able to accommodate
    - evolving / improving knowledge
    - new damage mechanisms

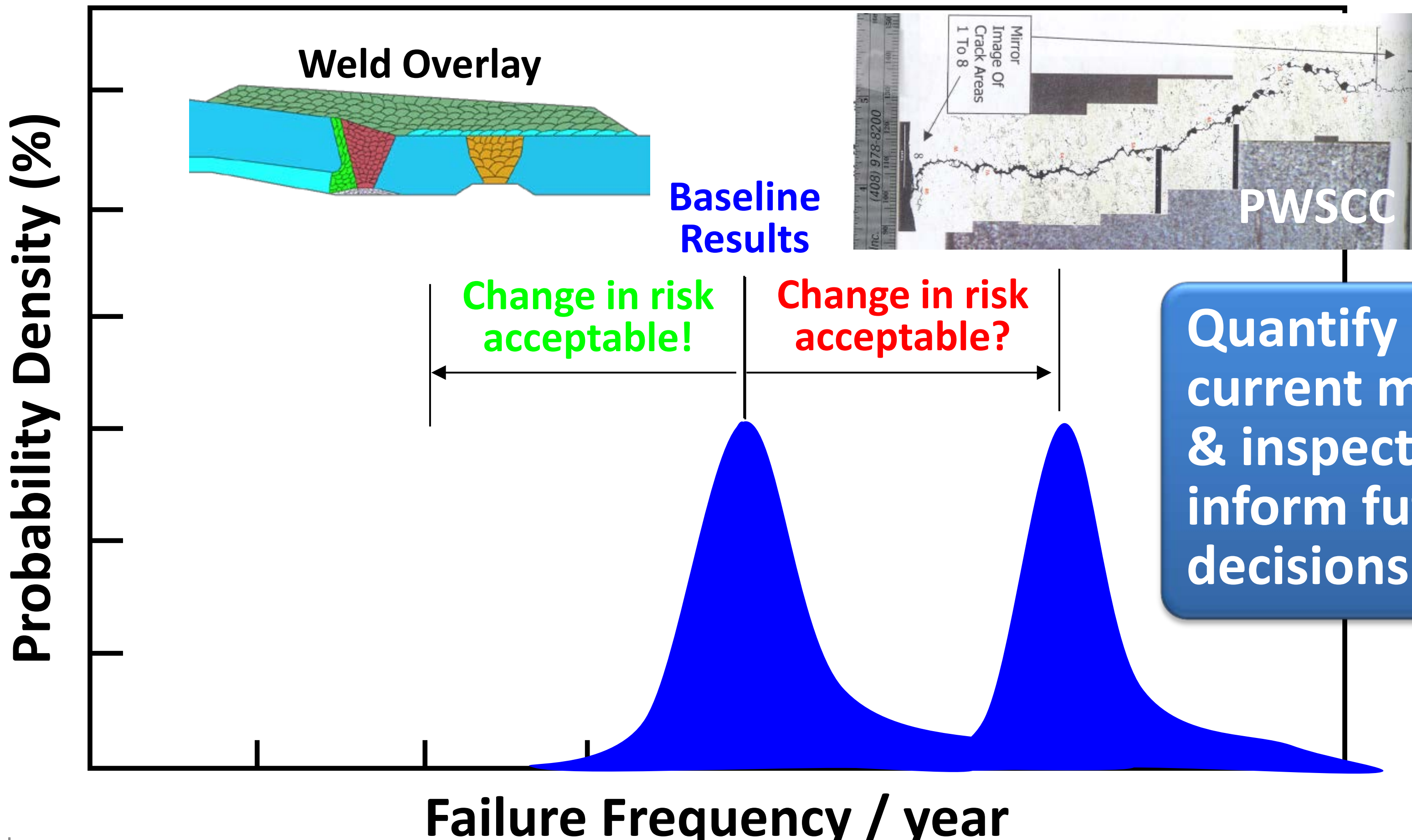
> **Criterion 4**: Structures, systems, and components important to safety shall … shall be appropriately protected against dynamic effects. … ***However, dynamic effects associated with postulated pipe ruptures in nuclear power units may be excluded from the design basis when analyses … demonstrate that the probability of fluid system piping rupture is extremely low …***



Technical Scope of xLPR Project

xLPR = eXtremely Low Probability of Rupture

- Conduct analyses with baseline conditions (per SRP 3.6.3)
- Conduct analyses with modified condition



Quantify effect of current mitigations & inspections to inform future decisions

xLPR
Status & Team Members

- **Pilot study [Complete]**
  - To demonstrate feasibility
  - Determine appropriate probabilistic framework
  - Develop plan for future version
- **V2.0 [Underway]**
  - Develop tool for use in LBB Reg. Guide development
  - Permit quantitative assessment of compliance with GDC-4
  - Prioritize future research efforts
- **LBB Reg. Guide [Future]**
  - Effort beginning in 2015
  - Possible replacement or augmentation to SRP 3.6.3

xLPR Technical Flow

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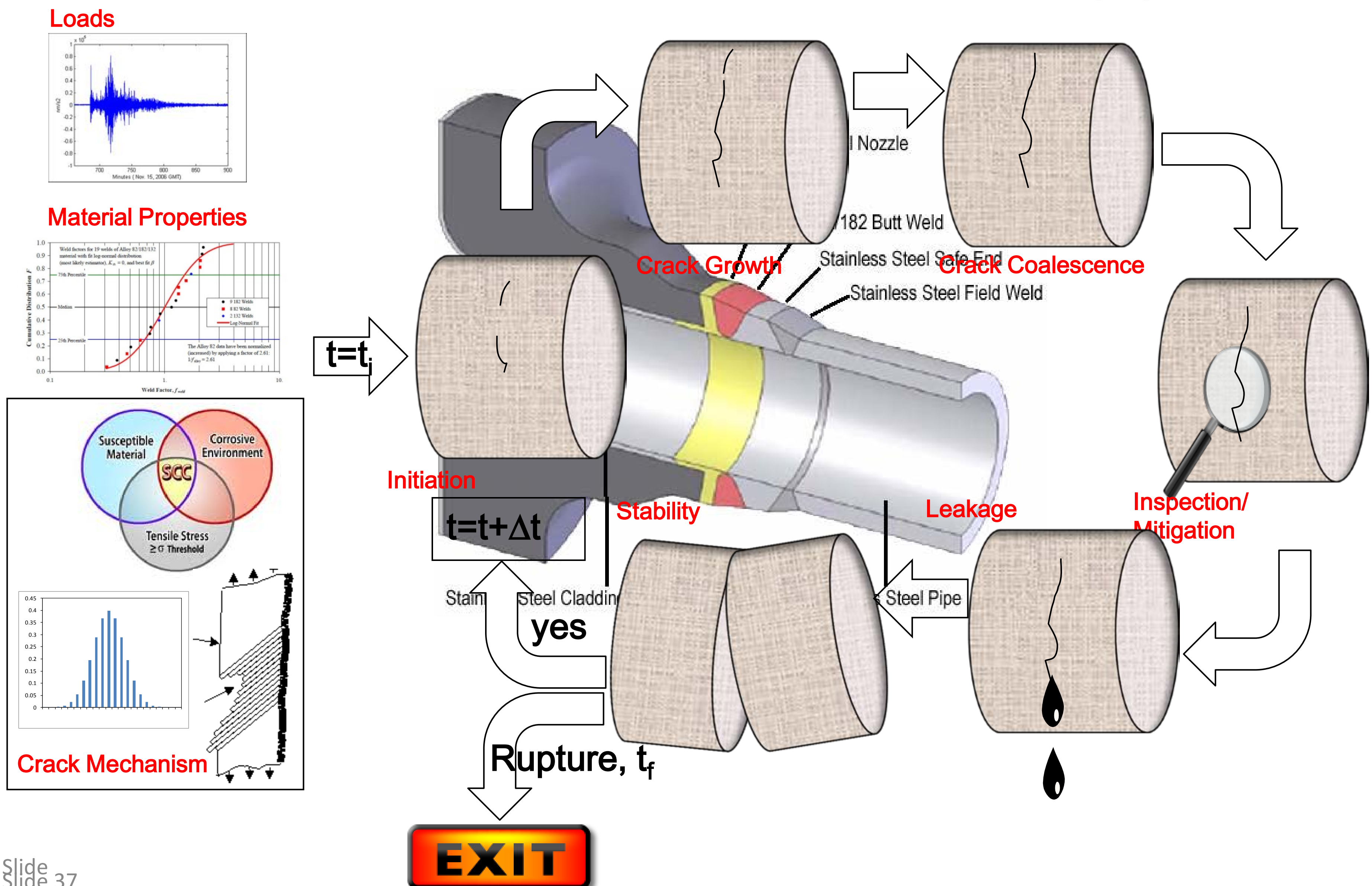

Slide 37

xLPR Pilot Study

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OBJECTIVES

- Develop and assess xLPR management structure
- Determine appropriate probabilistic framework
- Assess the feasibility of developing a modular PFM code

FEATURES

- Focused on pressurizer surge nozzle DM weld with PWSCC
- Used comprehensive configuration management
- Developed detailed program plan for future activities

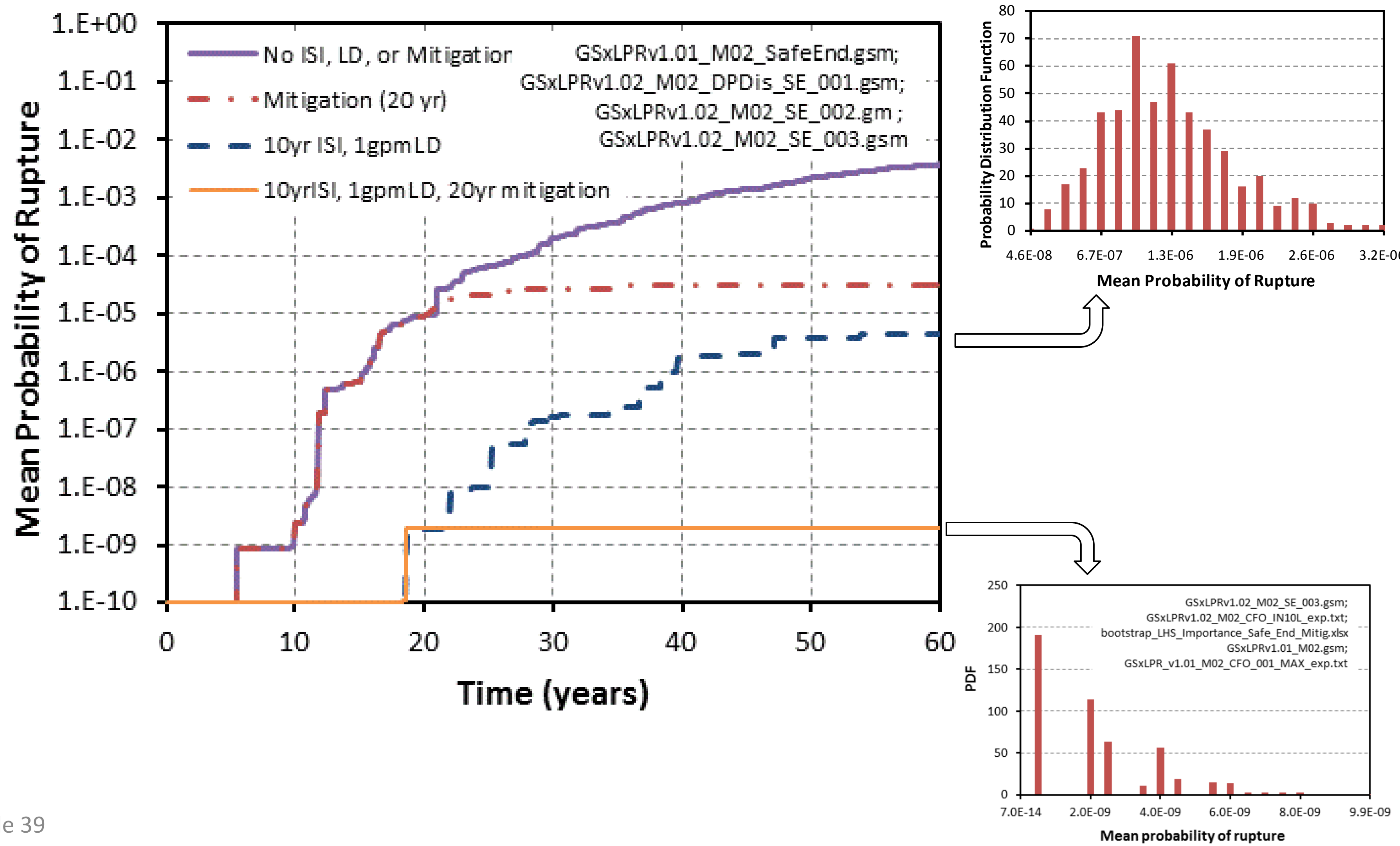
RESULTS

- Demonstrated it is feasible to develop a modular-based probabilistic fracture mechanics code within a cooperative agreement while properly accounting for the problem uncertainties
- Identified potential efficiency gains in the program management structure
- Selected commercial software as the computational framework

xLPR Pilot Study

Example Results

Pressurizer surge nozzle dissimilar metal weld – PWSCC only



xLPR Version 2.0

Goals

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- Version 2.0 is expanded to handle welds within piping systems approved for LBB
  - Appropriate materials, loads, degradation mechanisms, mitigation, inspection, leak detection
- Rigorous quality assurance including verification and validation (V&V) process
- Capabilities of Version 2.0 will meet requirements for LBB lines, but must stay within available cost and schedule limitations
- Model inclusion in xLPR Version 2.0 does not guarantee regulatory approval.

xLPR Version 2.0

High Level Flow Chart

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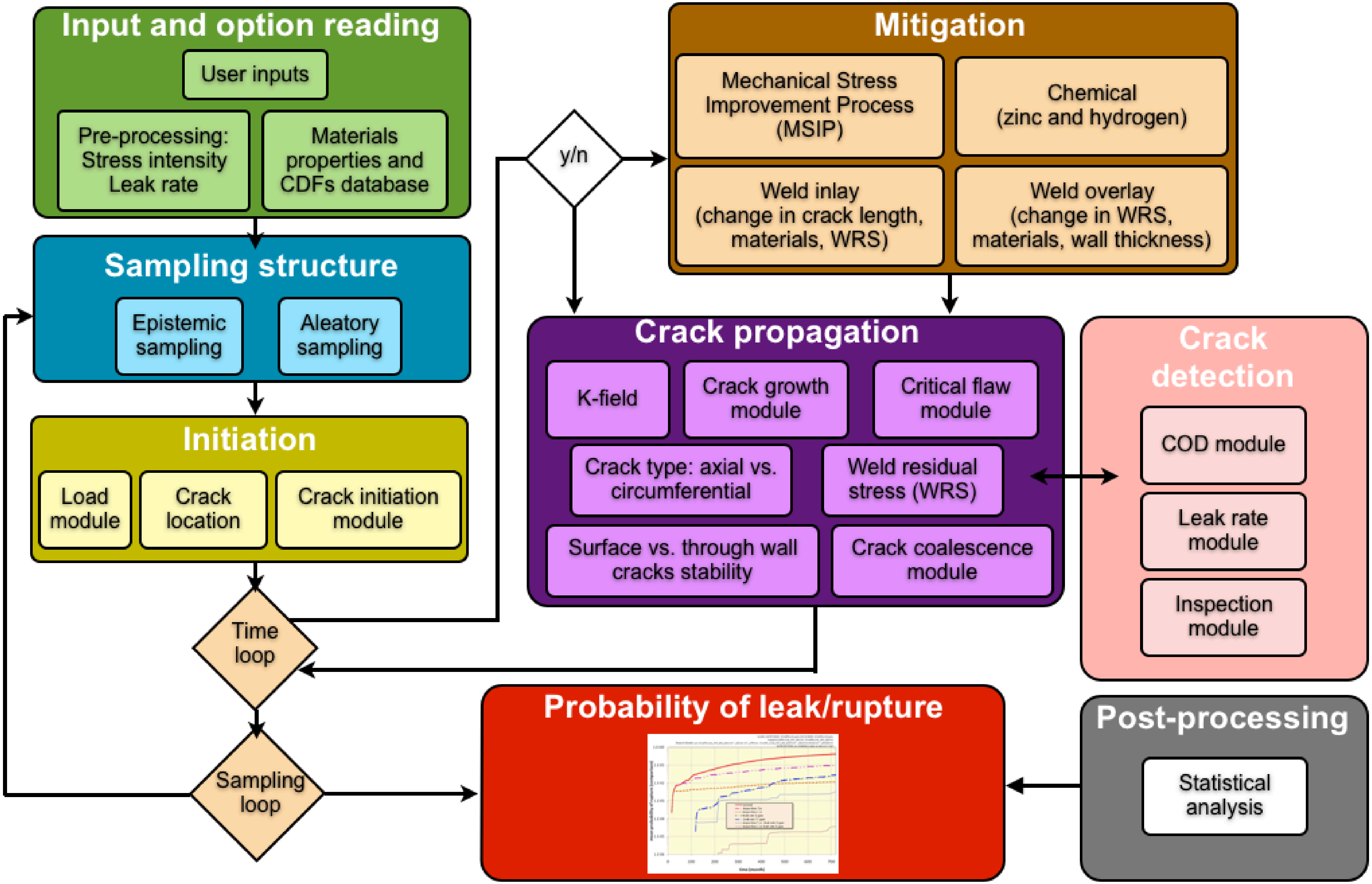

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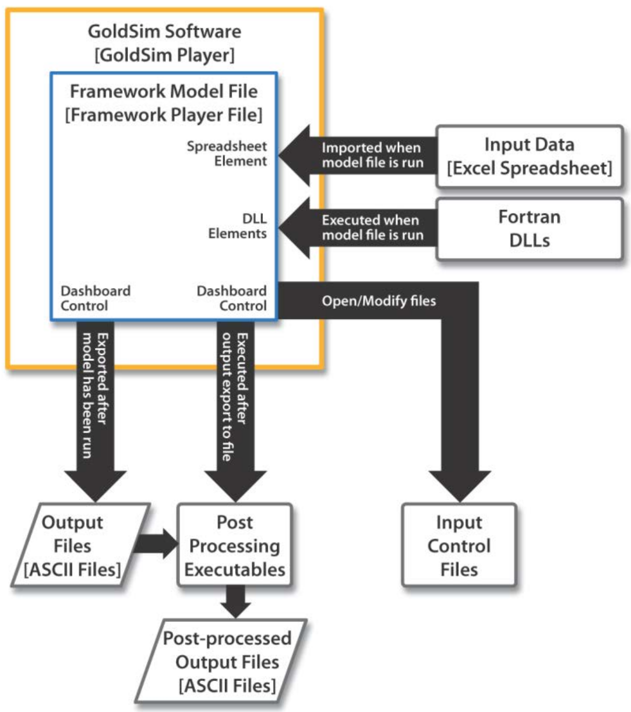
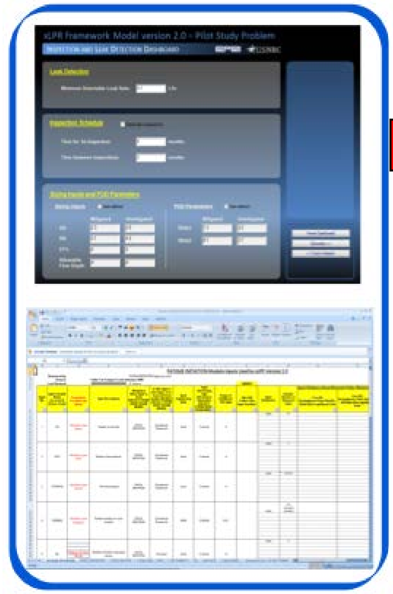
xLPR Version 2.0

Framework

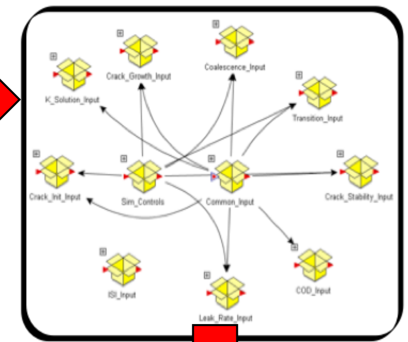


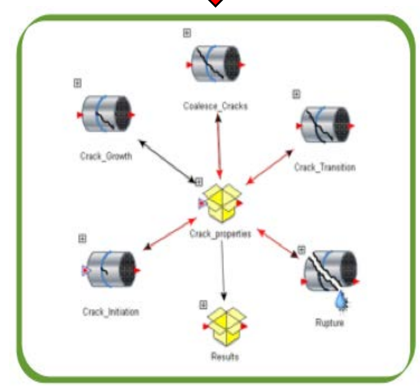
GoldSim software



GUI/Input database

Landing platform





Physical models

This strategy allows for multi-entities to share and work on the framework development in an efficient and parallel manner.

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Closing Remarks

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

- **PFM in General**

  A logical process for realistic assessment of structural reliability.

- **RPV Integrity**

  Successfully applied to PTS. Work is in-progress in other areas (normal heatup & cooldown).

- **Primary Piping Integrity**

  Work underway to apply PFM insights to LBB regulations and requirements.