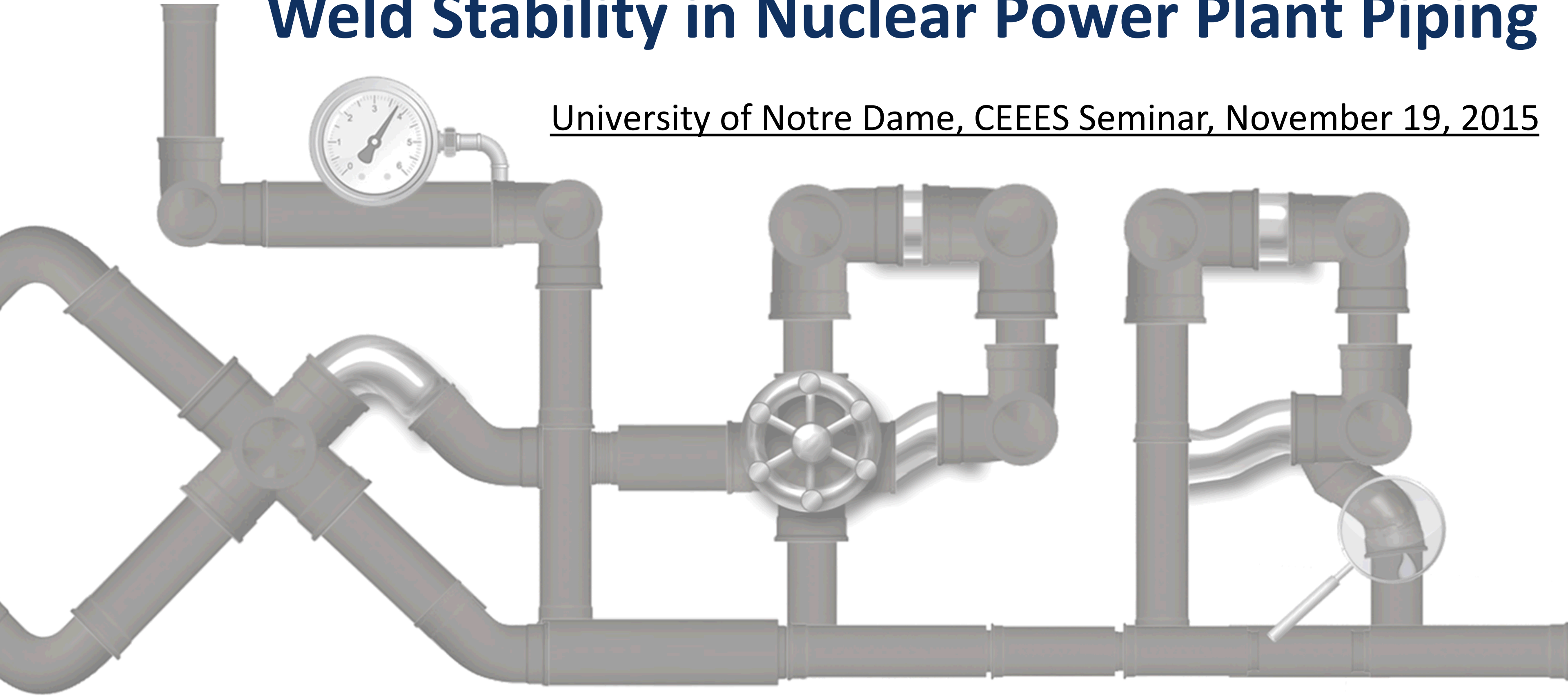
SAND2015-10112PE

A Probabilistic Fracture Mechanics Approach to Weld Stability in Nuclear Power Plant Piping



University of Notre Dame, CEEES Seminar, November 19, 2015

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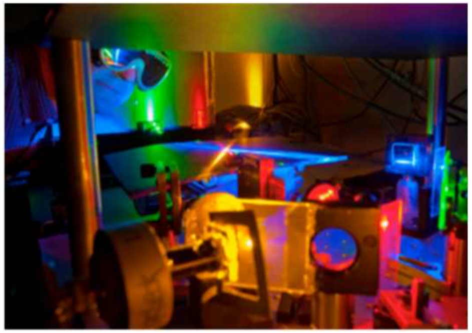

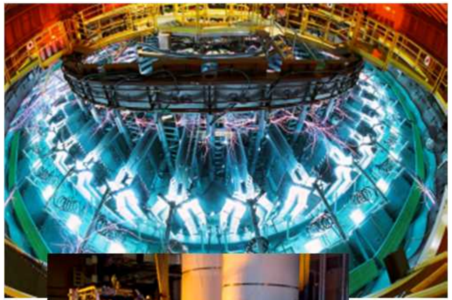

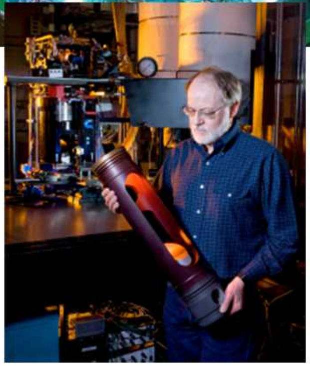

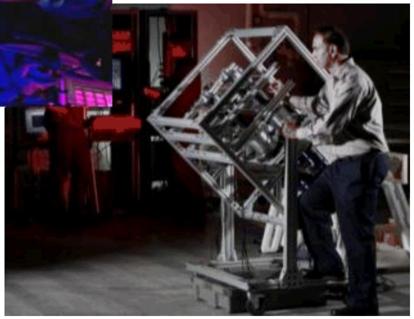

Missions

- Energy and climate
- Nuclear security engineering
- Defense systems
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Energy & Climate

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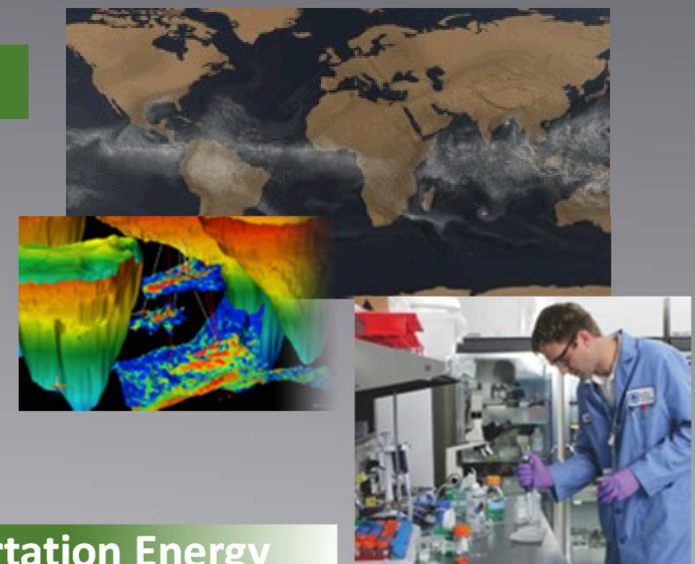
ARPAe, BES Chem Sciences, ASCR, CINT, Geo Bio Science, BES Material Science

Climate & Environment

Measurement & Modeling, Carbon Management, Water & Environment, and Biofuels



Nuclear Energy & Fuel Cycle

Commercial Nuclear Power & Fuel, Nuclear Energy Safety & Security, DOE Managed Nuclear Waste Disposal

Renewable Systems & Energy Infrastructure

Renewable Energy, Energy Efficiency,

Grid and Storage Systems

Transportation Energy & Systems

Vehicle Technologies, Biomass, Fuel Cells & Hydrogen Technology

Outline

- **Why nuclear power?**
- **<u>The LBB problem</u>**
- **Probabilistic Framework**
- **Deterministic Models**
- **Some results**
- **Wrap Up**

Acknowledgements

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Protecting People and the Environment

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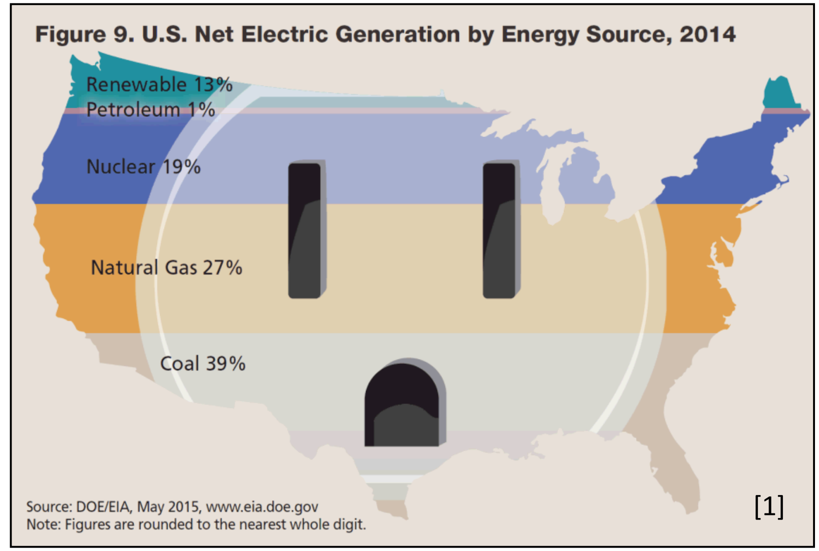
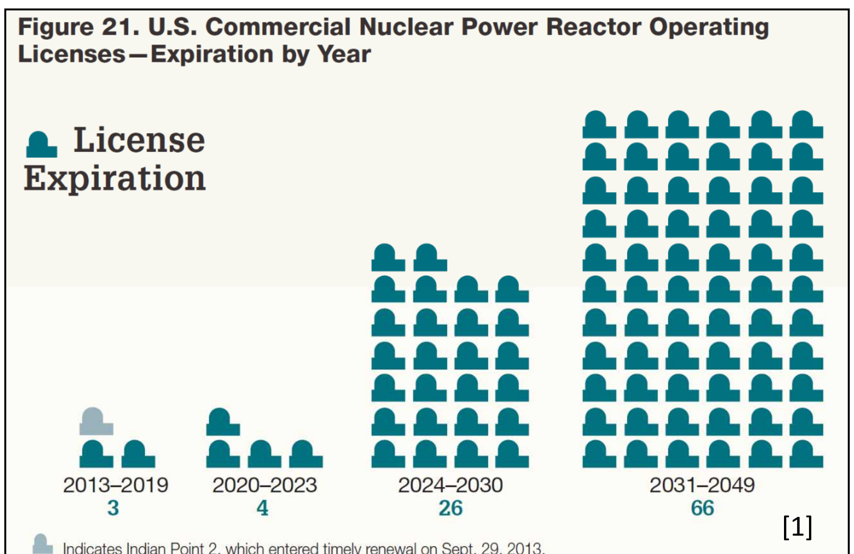
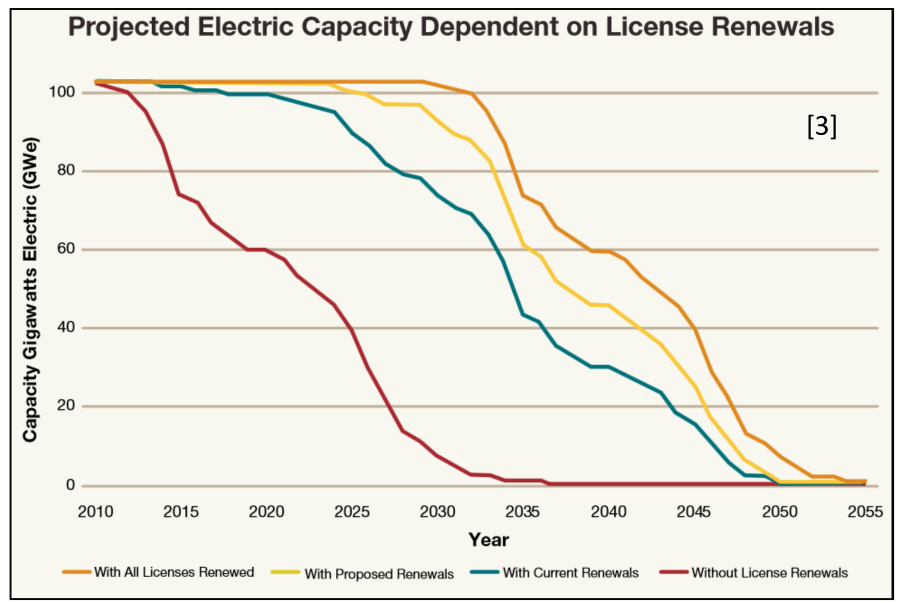
Nuclear Power - Importance

- 19% of electricity generated in the US[1]
- 63% of emissions-free electricity[2]
- Licenses will be expiring; power lost if not renewed
- New plants are costly



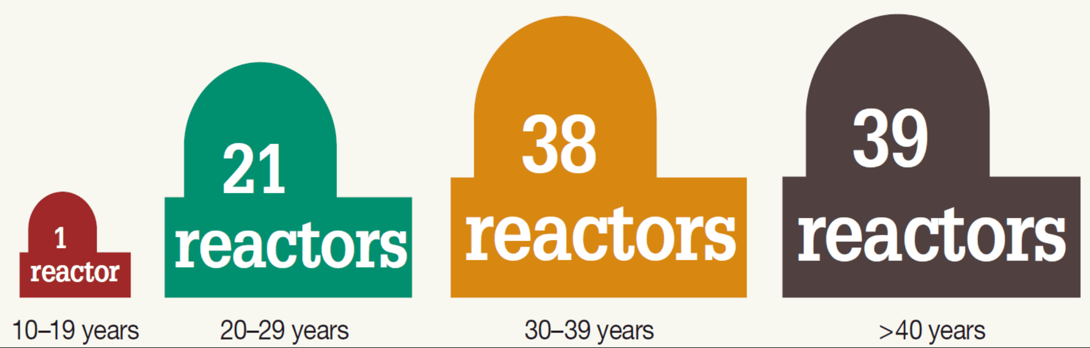


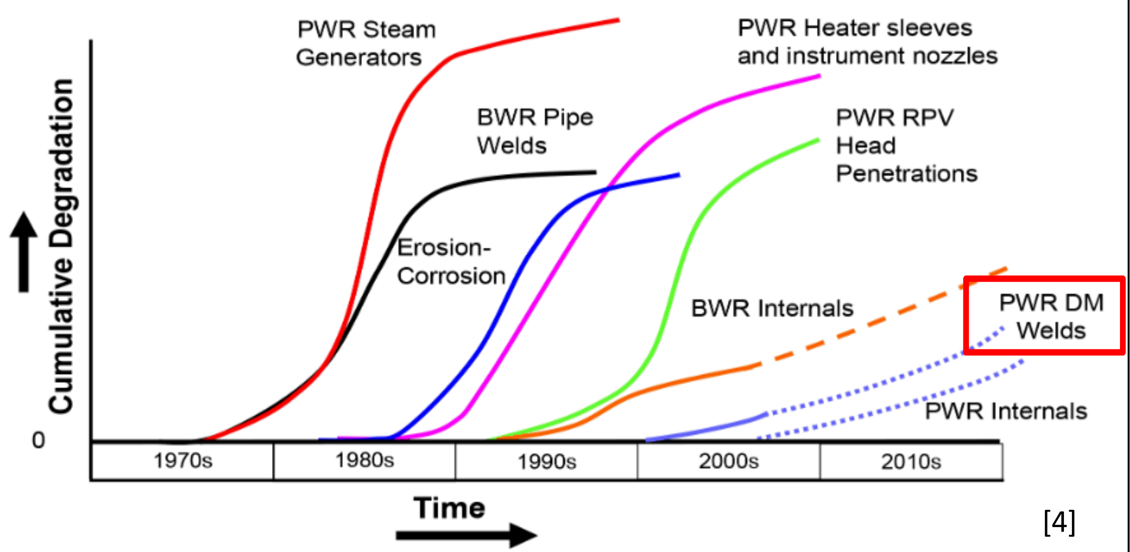


Nuclear Power - Aging

- **Many plants are old**
- **Materials aging and degradation have brought about some unique challenges**

Figure 20. U.S. Commercial Nuclear Power Reactors—Years of Operation by the End of 2015 [1]





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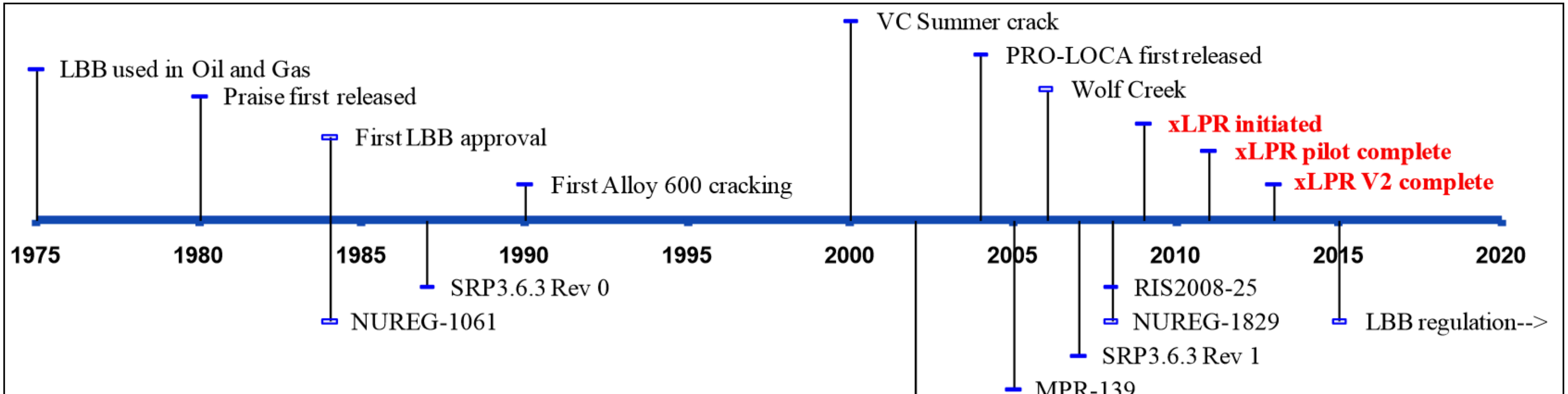
Leak Before Break (LBB) Problem

- **10CFR50 Appendix A General Design Criterion 4: local dynamic effects of piping rupture may be excluded from design basis**
- **LBB procedure used to justify approval of plant design excluding dynamic effects (no pipe whip restraints)**
  - **Assumes no active degradation mechanisms exist**
  - **However, after approval of LBB primary water stress corrosion cracking (PWSCC) was observed in many weld locations**

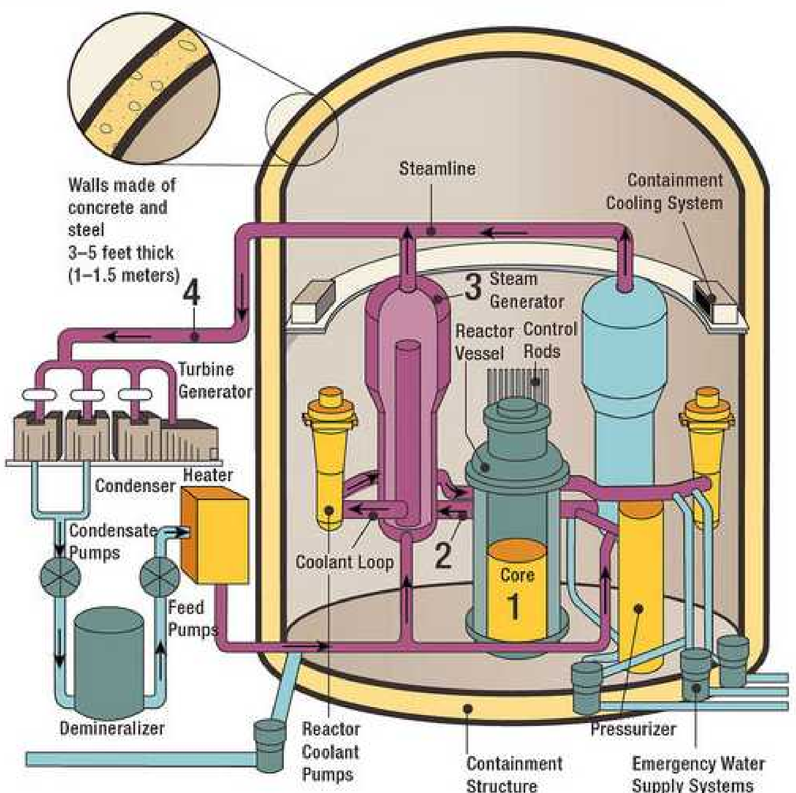
- **eXtremely Low Probability of Rupture (xLPR)** ← **Language in regulation**

  Probabilistic fracture mechanics tool that fully addresses and quantifies uncertainties and may be used to directly assess compliance with GDC-4



[5]

Primary Water Reactor Welds



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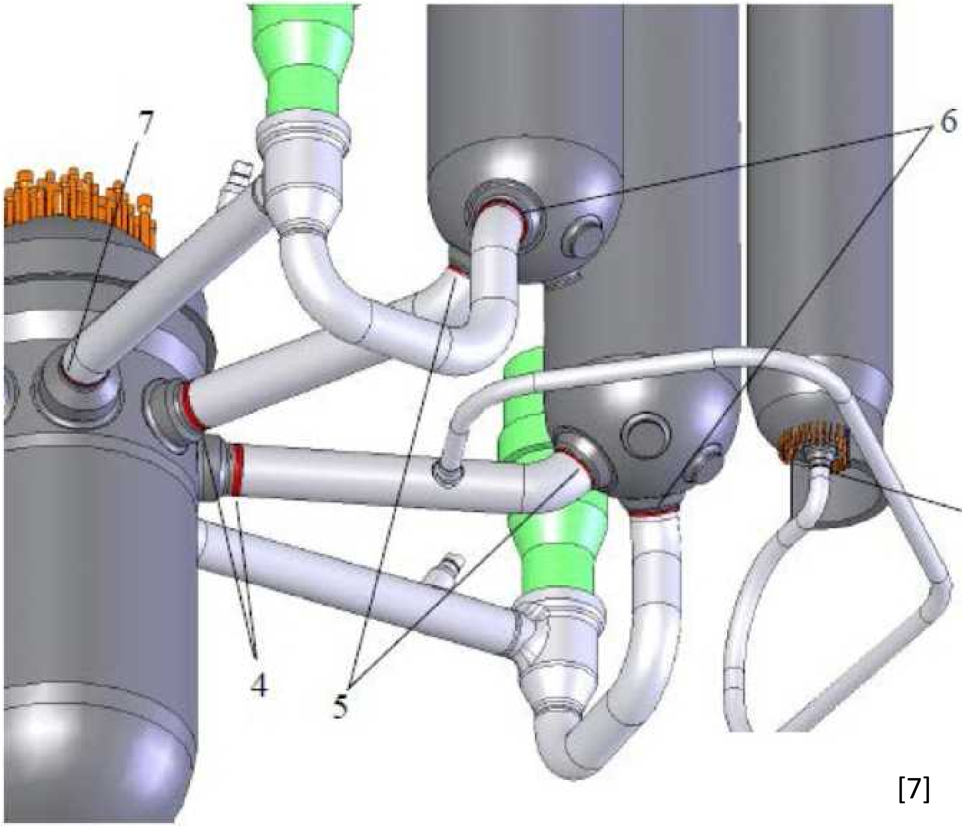
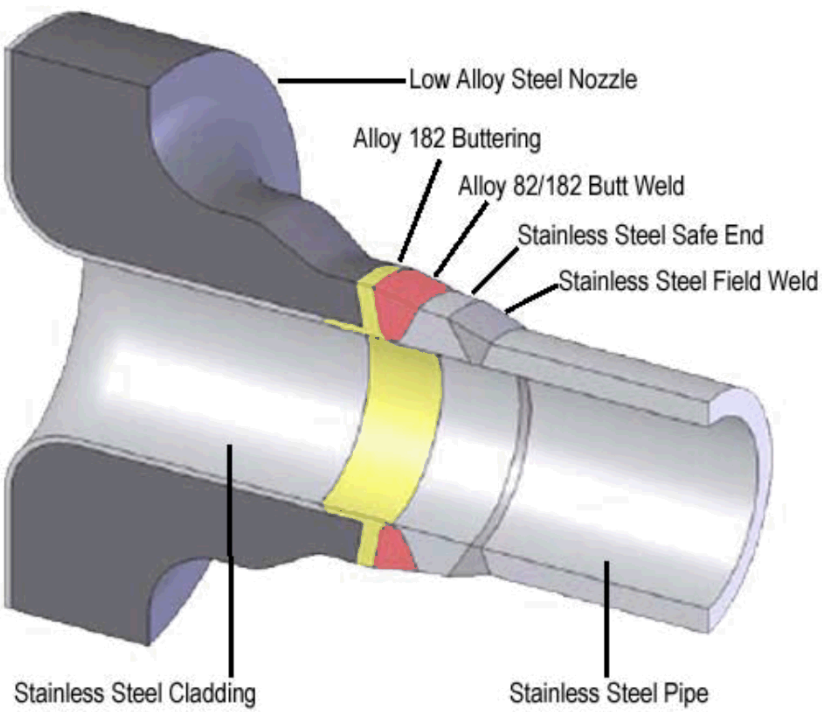


[7]

Example Dissimilar Metal Weld
Pressurizer Surge Nozzle



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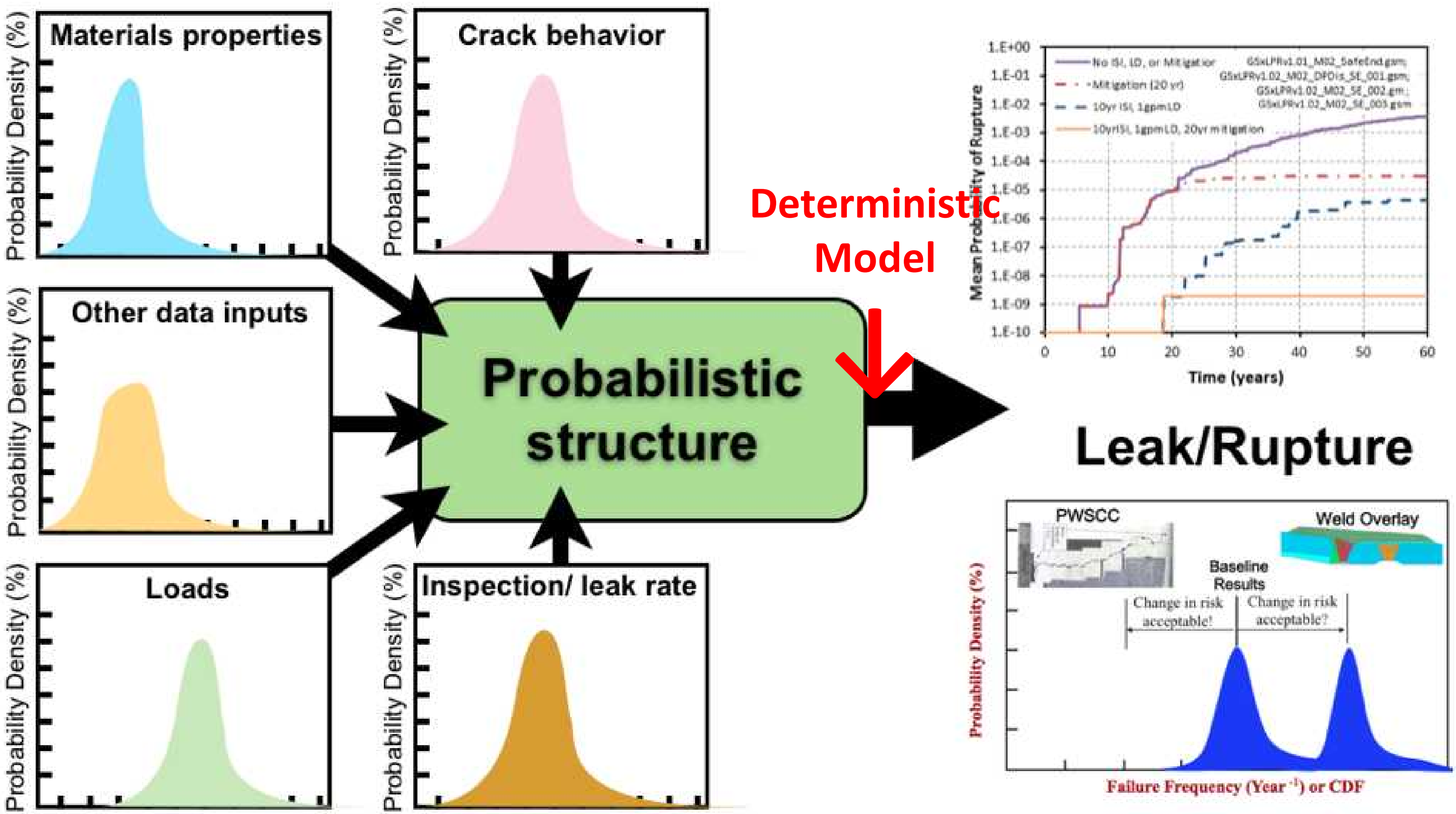
Probabilistic Fracture Mechanics

- To demonstrate an extremely low <u>probability</u> of rupture a probabilistic approach is necessary



Uncertainty representation in xLPR

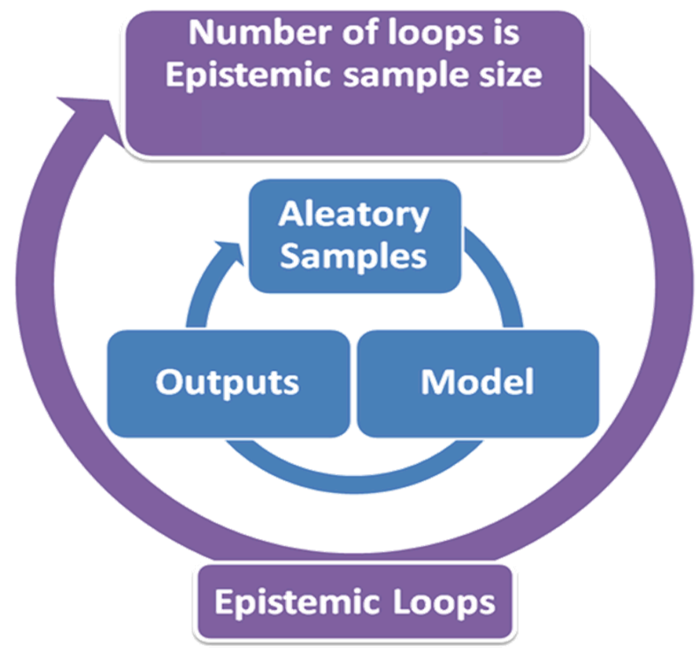
- **Aleatory uncertainty**
  - Inherent randomness. Represented with probability distributions.
- **Epistemic uncertainty**
  - Uncertainty originated from lack of knowledge on a fixed quantity. Represented with probability distributions.
- **Experts disagree on how to categorize certain inputs**
- **Inner aleatory loop**
- **Outer epistemic loop**
  - Allows evaluation of epistemic (model) uncertainty.

Aleatory (Irreducible)

- Crack size
- POD detection
- Material properties
- Crack growth parameters (Q/R,c,P)

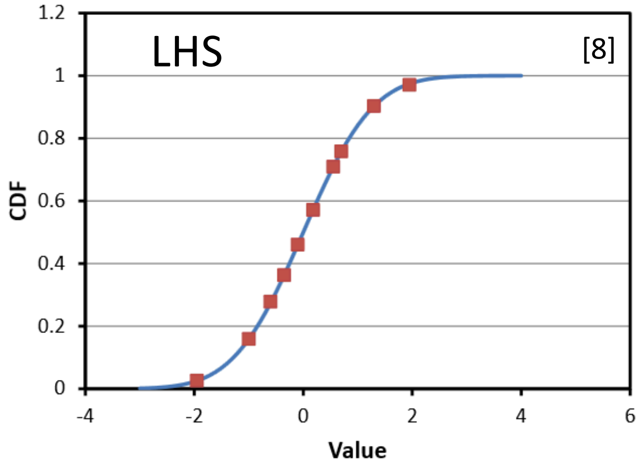
Epistemic (Lack of knowledge)

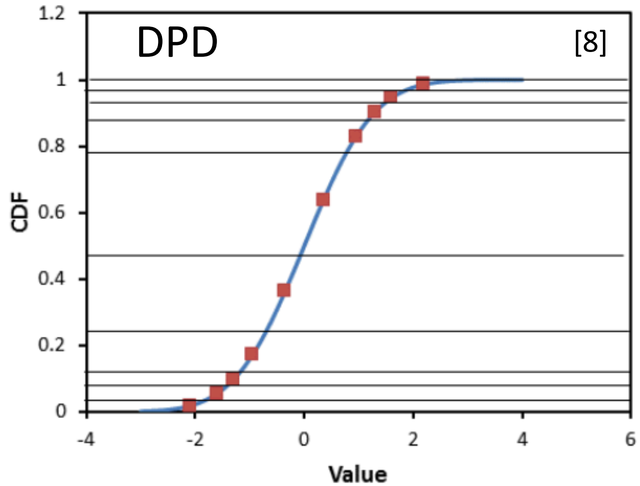
- Loads
- WRS
- Crack growth (fweld)
- Crack initiation parameters
- POD parameters



xLPR V2.0 – Sampling strategy

- **For each loop, the xLPR allows:**
  - **Simple random sampling (sometimes called Monte Carlo)**
  - **Latin Hypercube Sampling (LHS)**
    - dense stratification of each input into equal probably intervals, then **random sample** in interval
  - **Discrete Probability Distribution (DPD)**
    - dense stratification of each input into equal probably intervals, then **use conditional mean** in interval
    - better multidimensional coverage than LHS – better if variables are important *conjointly* and a reasonable range of values (not as dense as LHS) is required/sufficient
  - **Importance sampling applied to selected values**

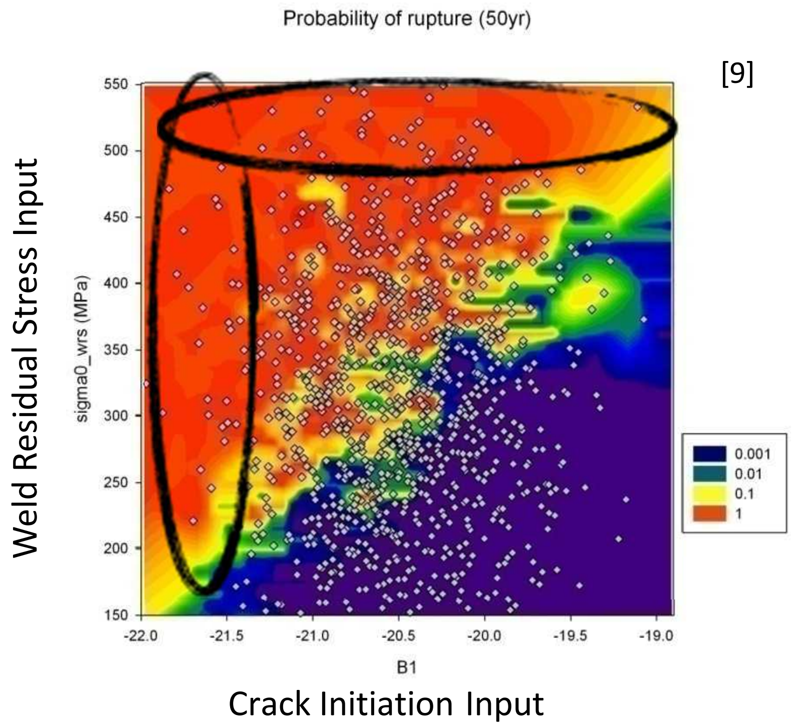




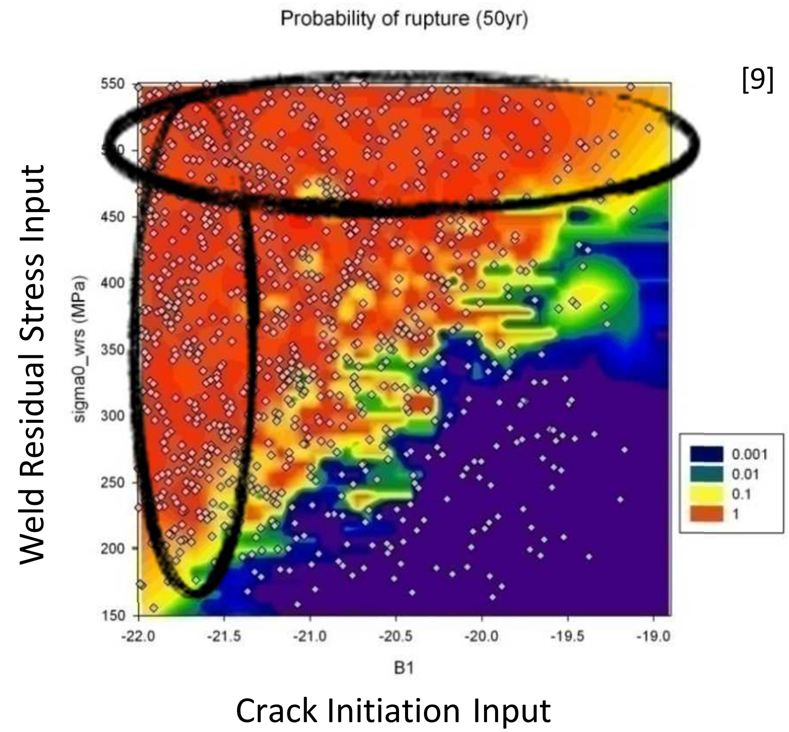
xLPR V2.0 – Sampling strategy

- **For each loop, the xLPR allows:**
  - **Importance sampling applied to selected values**
    - Define regions to focus sampling on but reduce the weights applied to those results

Areas poorly covered by sampling



A lot more sampling in the critical regions



xLPR V2.0 – Conceptual flow

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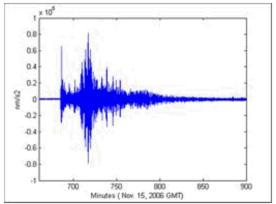
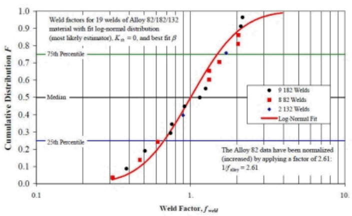
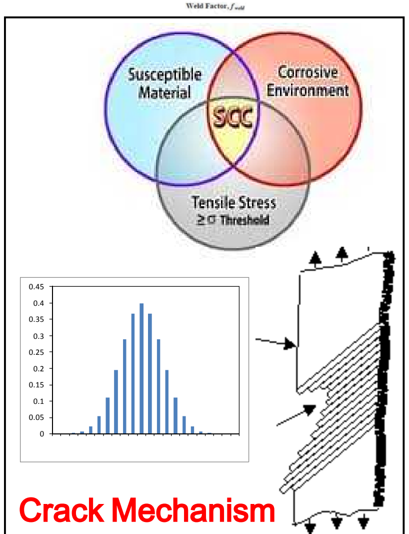
Deterministic Model Within Probabilistic Framework

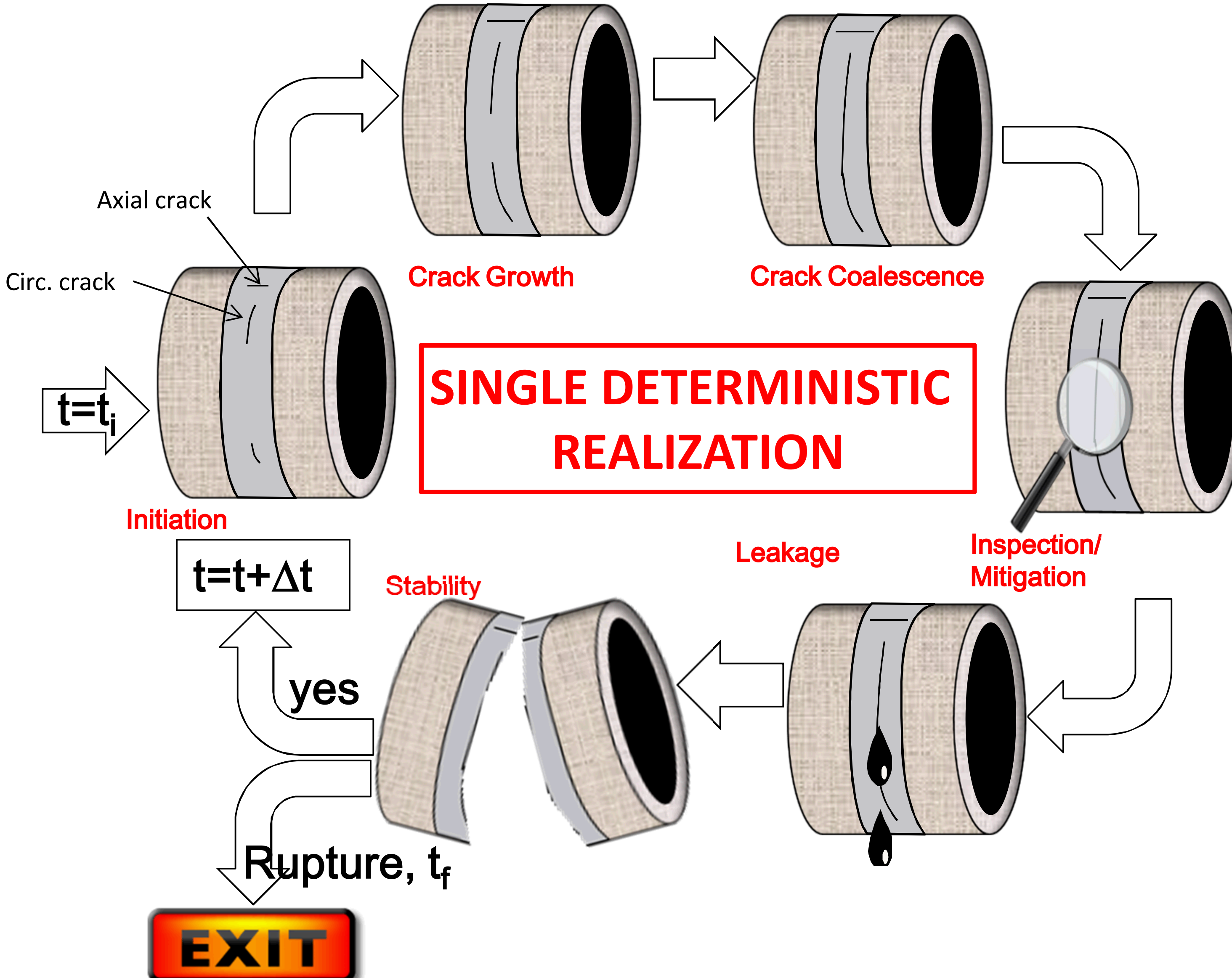
Loads



Material Properties

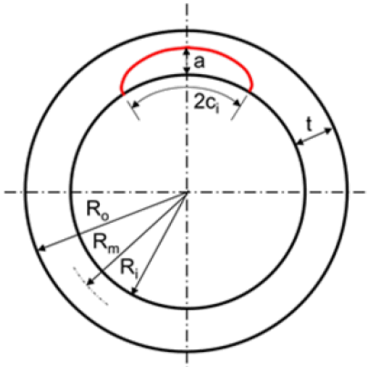




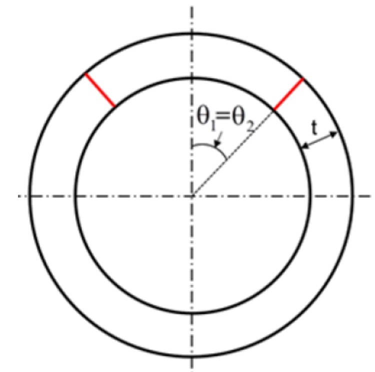


Deterministic Model

- **Must be realistic representation of physical phenomena *but* also fast enough to run ~10^6 realizations**
- **Key assumptions**
  - **Cracks can be either circumferential (circ.) or axial oriented cracks**
  - **Idealized crack shapes**
  - **No interaction between circ. and axial cracks**
- **Each deterministic model individually validated against available data (field data, lab data, other models, etc.)**
- **Probabilistic framework ties deterministic models together and evolves cracks through time**



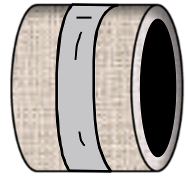
Ideal surface crack (SC)



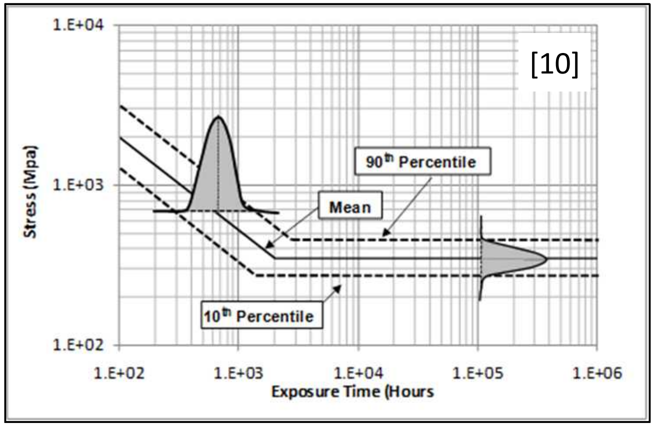
Ideal through wall crack (TWC)

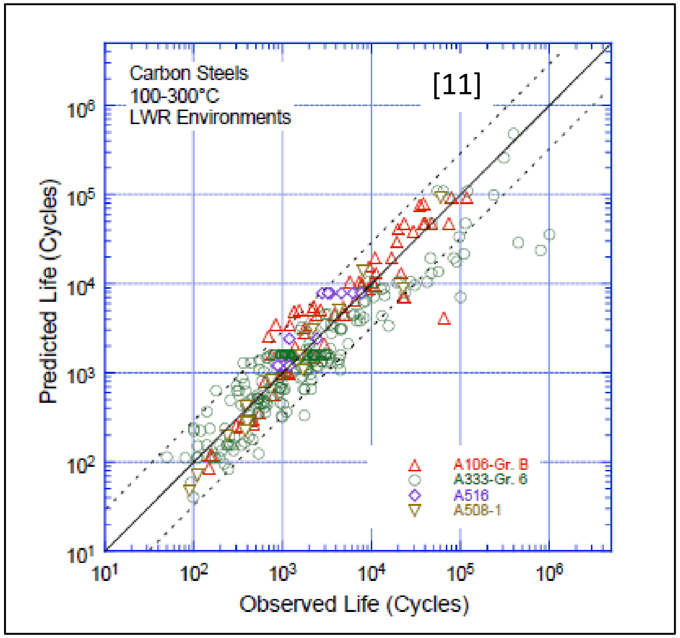
Deterministic Model

Crack Initiation



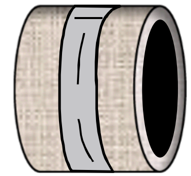
- **PWSCC**
  - 3 models available
  - Calibrated to field data
- **Fatigue**
- **Initial Flaw (pre-existing)**
- **Flaw is initiated at engineering size**





Deterministic Model

Crack Growth



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- **Loads – WRS, bending, axial, transients, etc.**
- **Stress intensity factors – "K"**
  - **Many solution methods available for ideal crack geometries**
- **K drives Growth**
  - **General PWSCC form**

$$\dot{a}_{PWSCC} = \begin{cases} \alpha f_{comp} f_{flaw} e^{-\frac{Q_g}{R_{gas}}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)} \left(K_{\mathrm{I}} - K_{th}\right)^{\beta} & K_I > K_{th} \\ 0 & K_I \le K_{th} \end{cases}$$

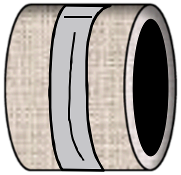
  - **General fatigue form**

$$\dot{a}_{fatigue,i} = \frac{1}{\Delta t}\left[\frac{da_i}{dN} \cdot N_{cyc,i}\right]$$

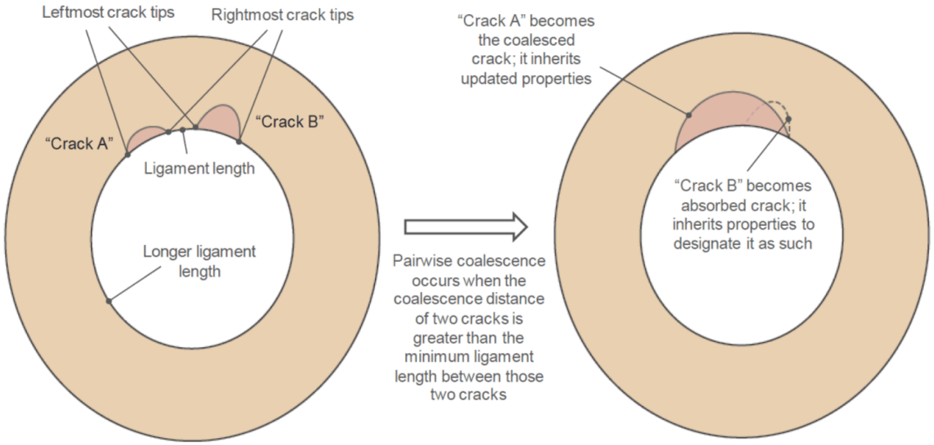
$$\frac{da_i}{dN} = C_{cstm} \tau_{r,i}^{p_{cstm}} \left(\frac{\Delta K_i}{\left(1 - a_{cstm} R_i\right)^{b_{cstm}}}\right)^{m_{cstm}}$$

Deterministic Model

Crack Coalescence

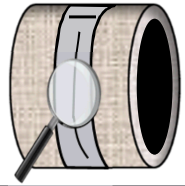


- **Only applicable to circumferential cracks**
- **Cracks assumed to be in the same plane**
- **Rule based to determined if two cracks are close enough to interact**

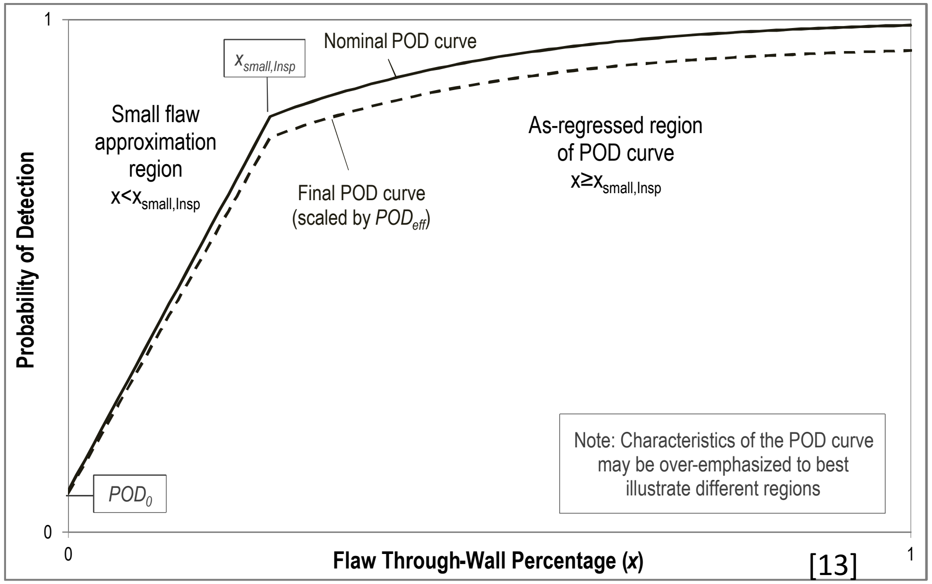


[12]

Deterministic Model
Inspection and Mitigation



- **Ultrasonic test inspection**
- **Given a flaw of certain depth:**
    - What is the probability of detection?
    - What is the "depth" evaluated from the inspection?
  - **Repair weld if evaluated depth is > some threshold**
- **Mitigation**
  - **Stress/structural: Inlay, Onlay, MSIP**
  - **Chemistry: H2, Zinc**



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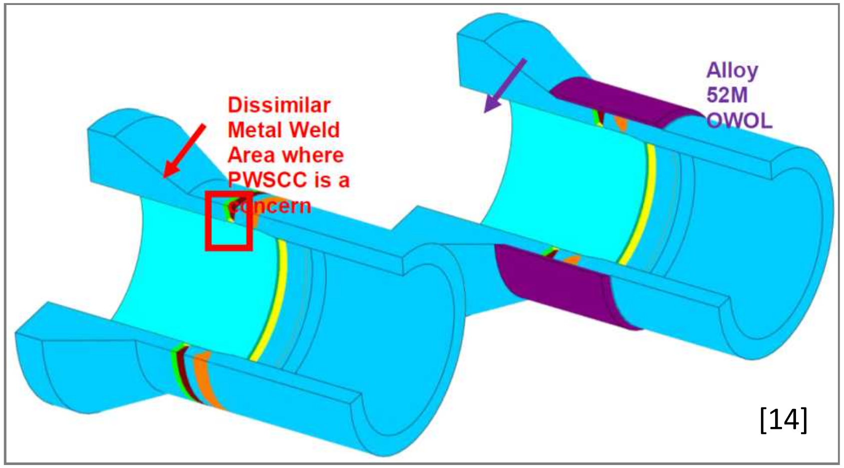
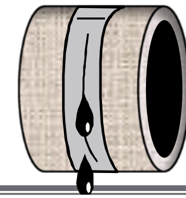


[14]

Deterministic Model

Leak Detection



- **For ideal shaped TWCs under given loads:**
  - crack opening displacement (COD) obtained by analytical solutions that have been benchmarked against finite element analyses
  - COD → COA
- **LEAPOR (leak rate preprocessor) generates look-up tables prior to running simulation**

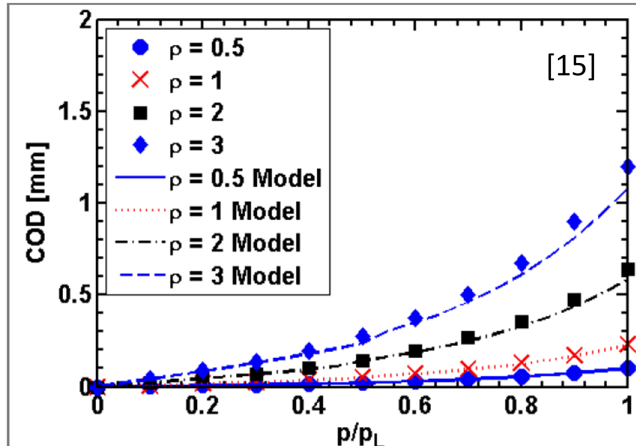
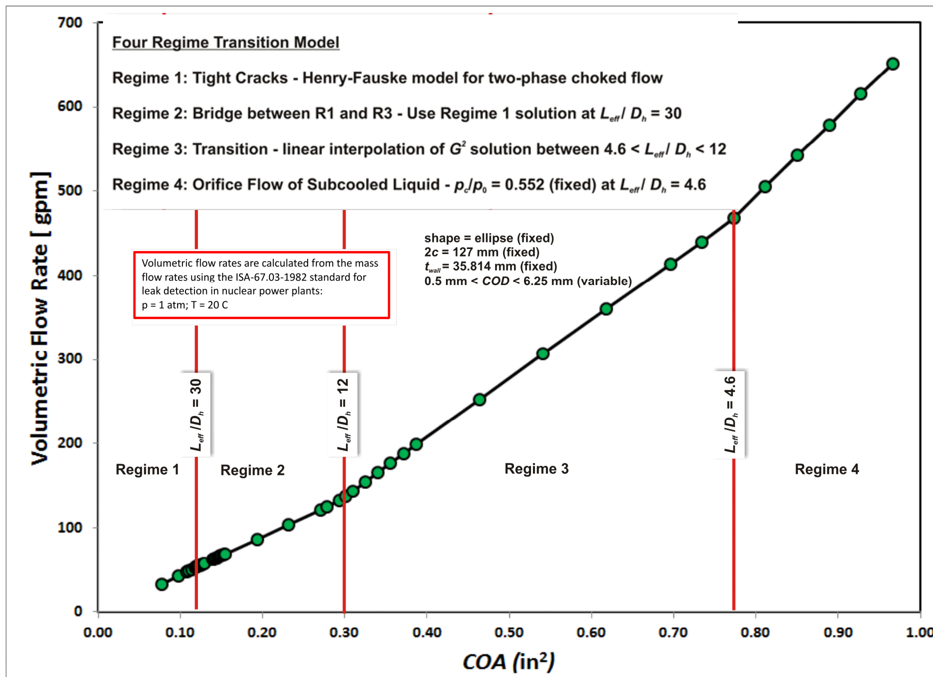
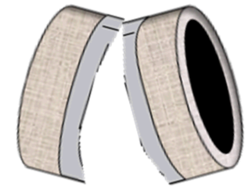


Figure 12: Comparison for R/t=10, n=5, and OD Location



[16]

Deterministic Model
Stability

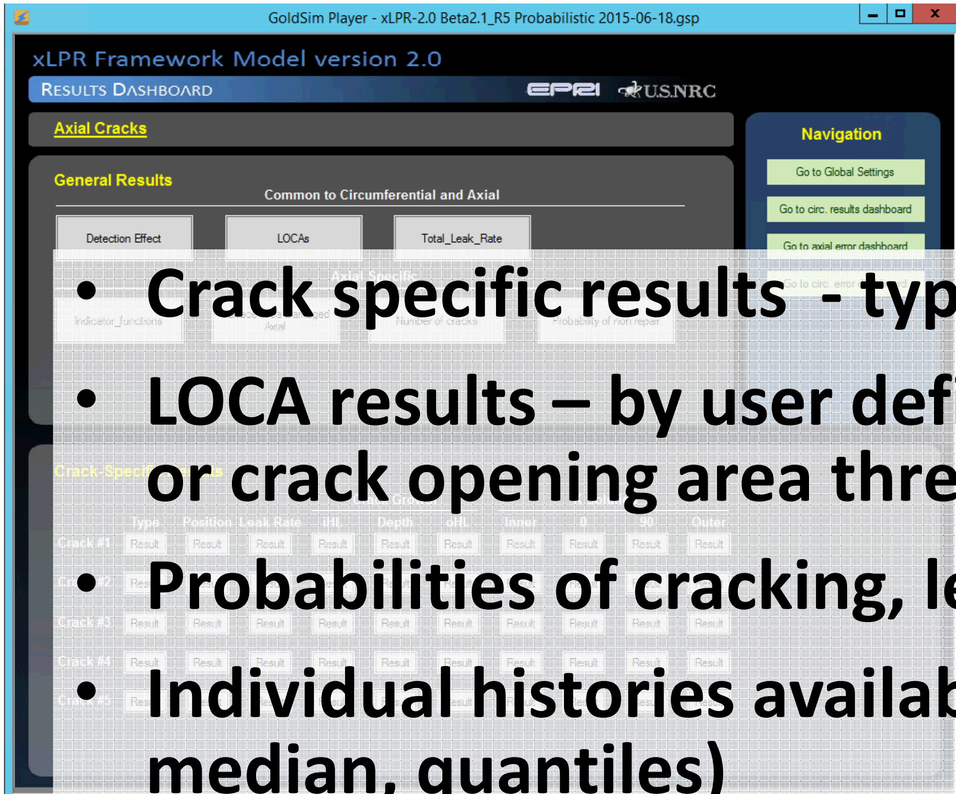


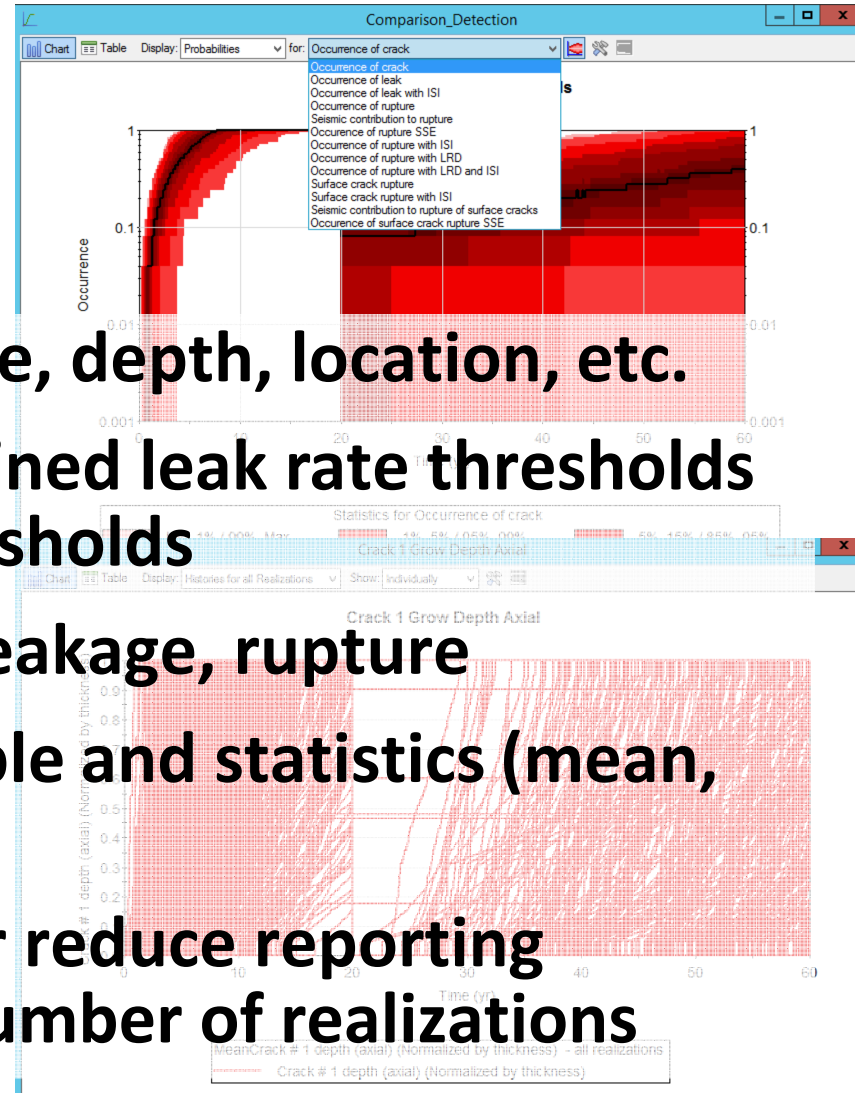
- **Loads on cracked pipe are greater than the remaining section can maintain**
  - **With and without Safe Shutdown Earthquake loads**
- **Circumferential cracks**
  - **Surface Crack (SC) – Net Section Collapse**
  - **Through Wall Crack (TWC) – Net Section Collapse and/or elastic-plastic tearing instability**
- **Axial cracks**
  - **SC – limit load analysis in Ductile Fracture Handbook**
  - **TWC – limit load and elastic-plastic tearing instability**

Deterministic Model – Crack Stability

- Circumferential cracks
  - Surface Crack (SC) – Net Section Collapse
  - Through Wall Crack (TWC) – Net Section Collapse and/or elastic-plastic tearing instability
- Axial cracks
  - SC – limit load analysis in Ductile Fracture Handbook [21]
  - TWC – limit load and elastic-plastic tearing instability
- For Dissimilar Metal (DM) welds material properties used in stability modules are a combination of the base metal material properties
- Stability checked with/without SSE loads

Results Available form xLPR Runs



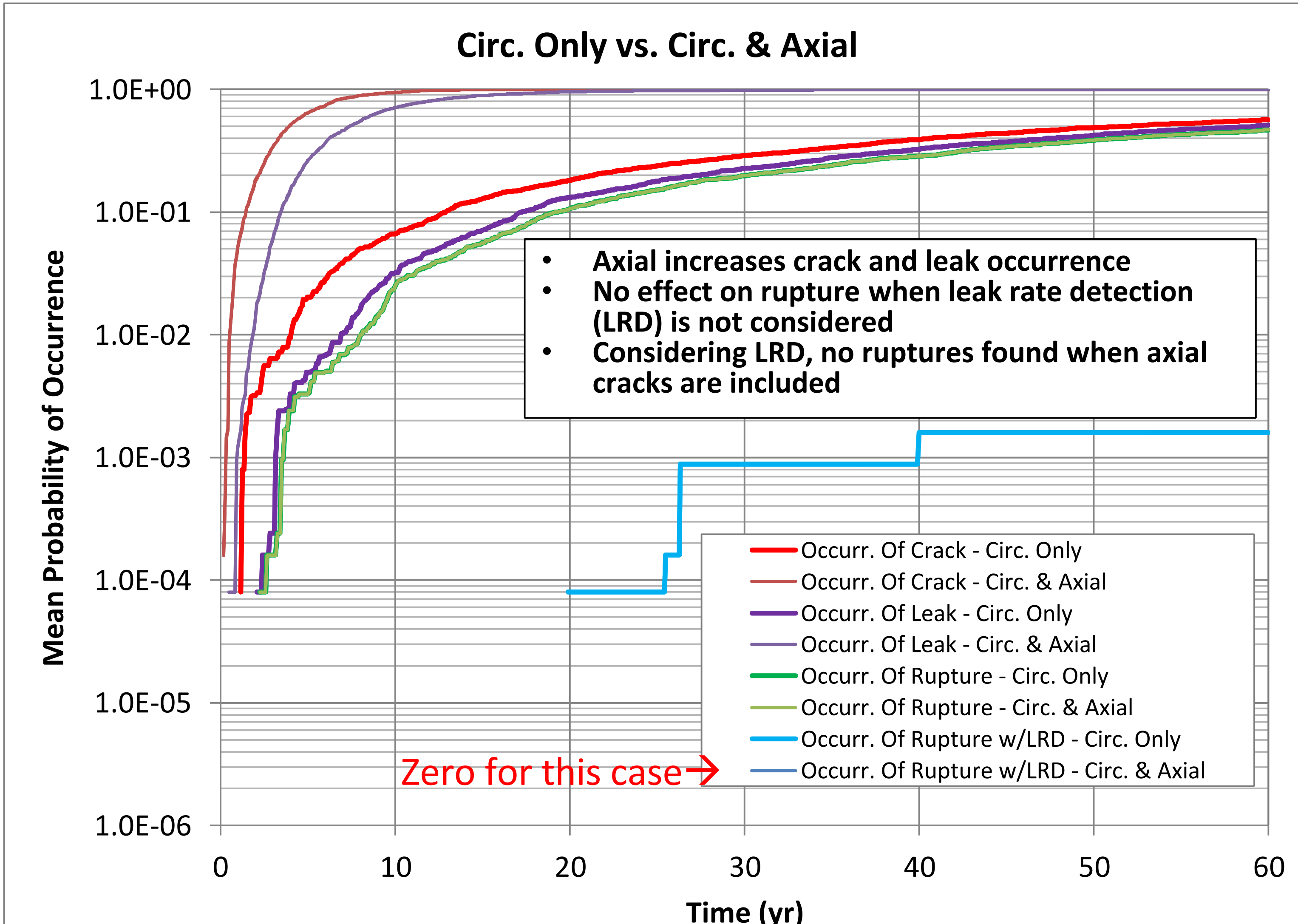


- Crack specific results - type, depth, location, etc.
- LOCA results – by user defined leak rate thresholds or crack opening area thresholds
- Probabilities of cracking, leakage, rupture
- Individual histories available and statistics (mean, median, quantiles)
- Can turn results off and/or reduce reporting frequency for very large number of realizations

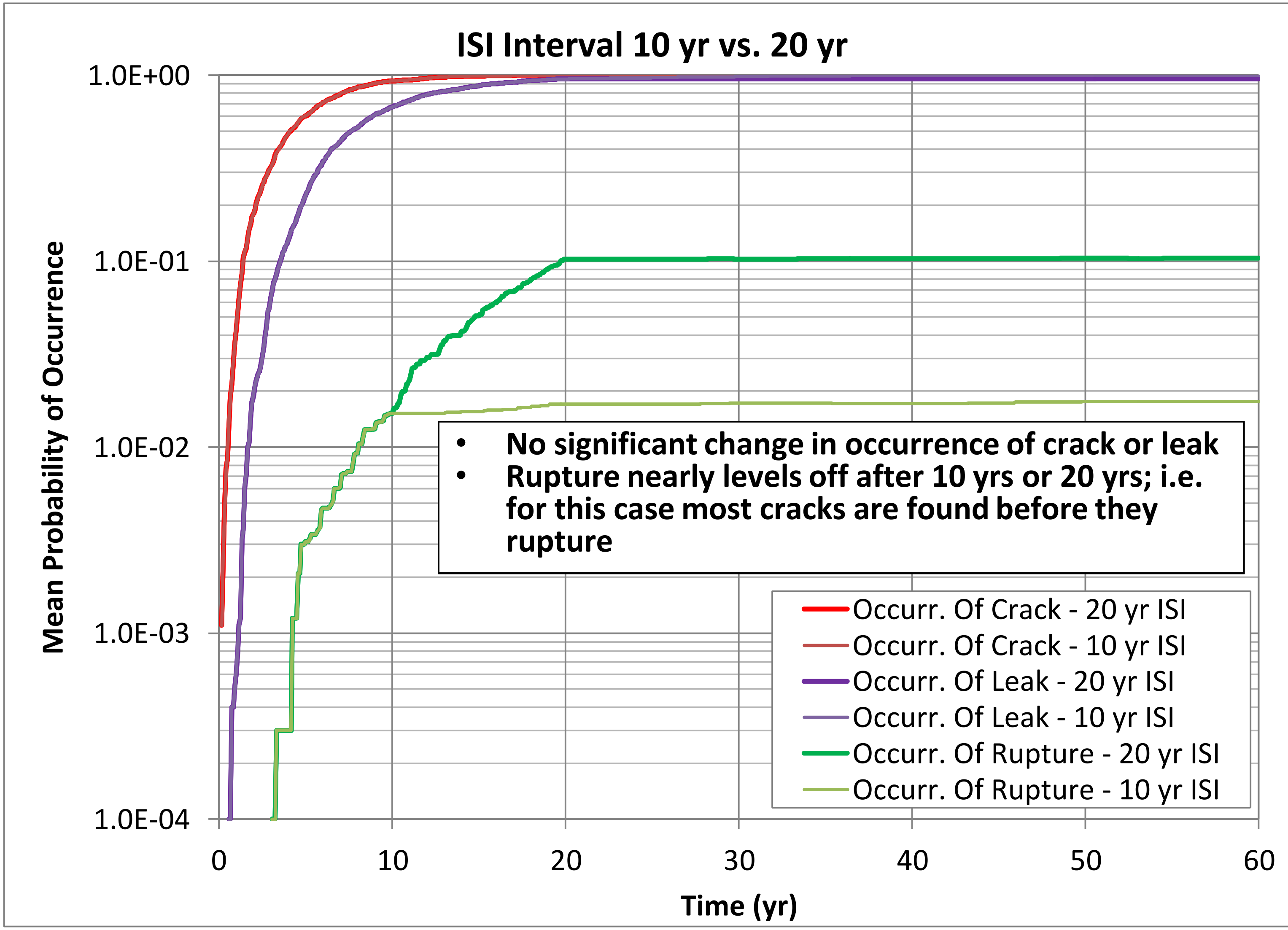
Some Example Results

- The following results are meant to demonstrate different options available in the code and their effects on the important results.
  - Beta version of the xLPR V2.0 code – bugs may still exist
  - Not all inputs may be realistic – input databases still being created
- The results presented are based on a dissimilar metal weld for a reactor pressure vessel nozzle
  - Base metals - SA-508 and SA-182
  - Weld material – Inconel 182
- Same geometry, materials, loads (except transients), WRS, and sample size used for all the following demonstrations

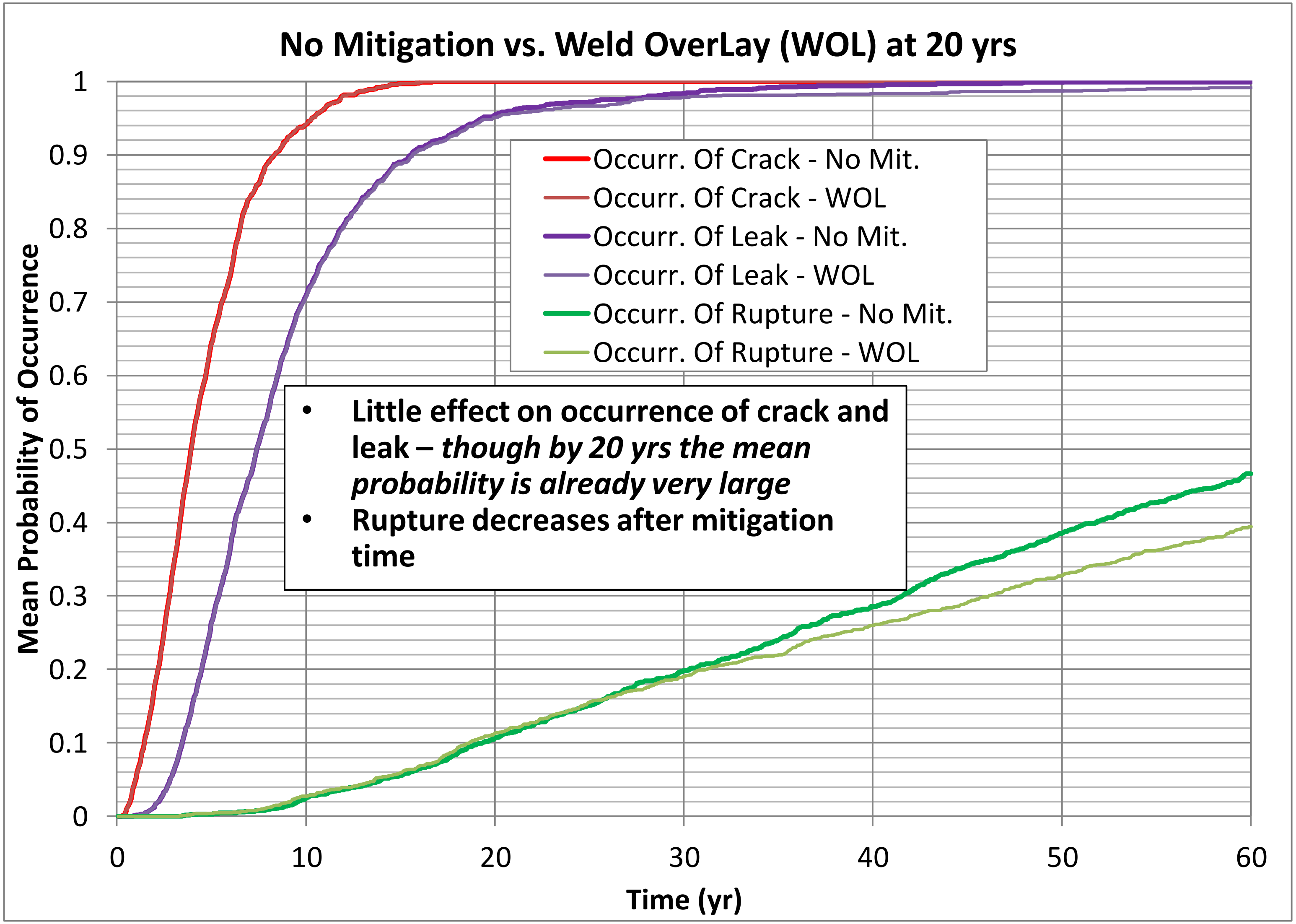
Effect of Including Axial Cracks



Effect of ISI Interval

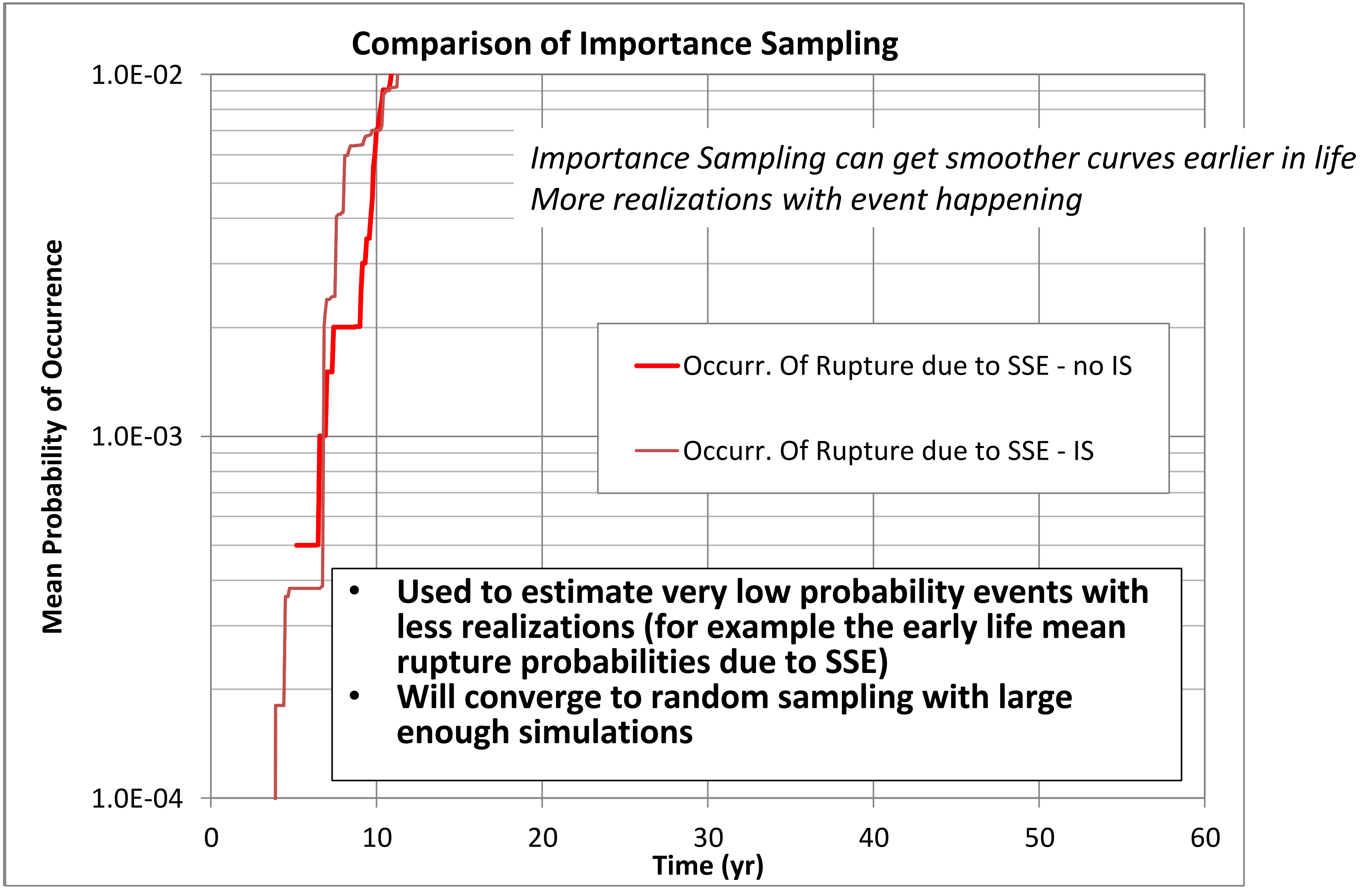


Effect of Mechanical Mitigation



- **Little effect on occurrence of crack and leak – *though by 20 yrs the mean probability is already very large***
- **Rupture decreases after mitigation time**

Use of Importance Sampling



- **Used to estimate very low probability events with less realizations (for example the early life mean rupture probabilities due to SSE)**
- **Will converge to random sampling with large enough simulations**

Wrap Up

- LBB Problem
- Probabilistic Approach
- Deterministic Models
- Some results
- Questions

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