Gaps Identified from OECD/NEA Benchmark on Probabilistic Fracture Mechanics for Piping Applications

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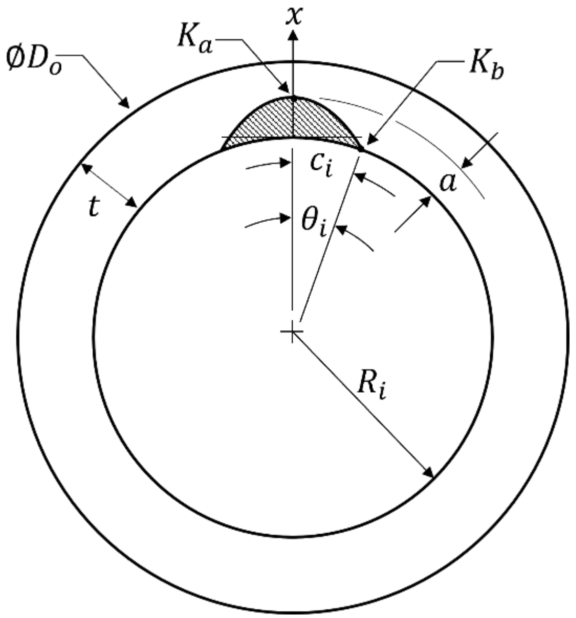
Brief Description of PFM Benchmark

- Sponsored by OECD/NEA WGIAGE Metal Subgroup and led by CEI and USNRC
- Started in late 2020 and completed in early 2024
- Participants from 15 organizations in 12 countries
- 14 PFM codes were used
- Six Objectives
  - ✓ Understand differences in PFM software design
  - ✓ Understand the role of DFM modules
  - ✓ Reconcile deterministic LBB and PFM
  - ✓ Understand the effectiveness of ISI in reducing failure probabilities
  - ✓ Understand the effectiveness of leak detection in reducing failure probabilities
  - ✓ Explore PFM as input for PRA/PSA
- Final Report: NEA/CNSI/R(2024)5

Description of Benchmark Problems

- Butt-weld fabricated from Alloy 182 in a PWR coolant system that is susceptible to PWSCC
- Crack initiation not considered
- Growth from a postulated inside surface crack to through-wall crack until instability

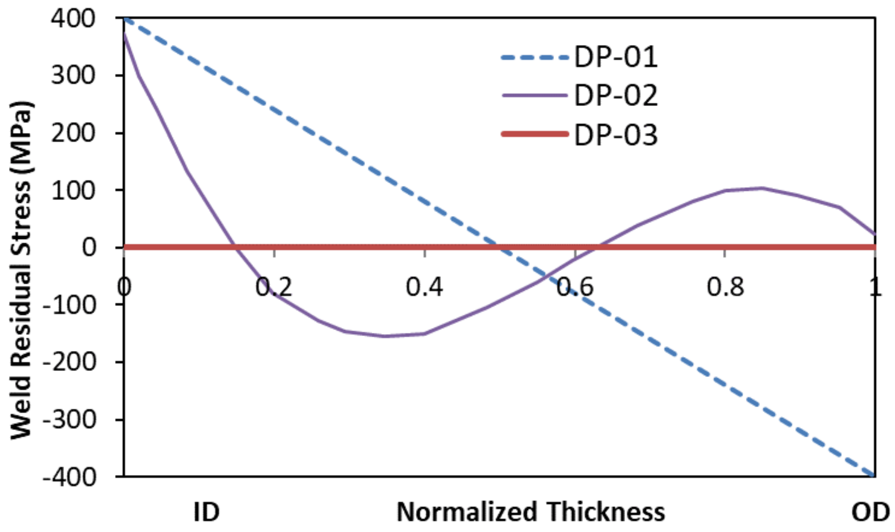


- Outside diameter: 380 mm
- Wall thickness: 40 mm
- Initial crack length: 6 mm
- Initial crack depth: 1.5 mm
- Operating pressure: 15.5 MPa
- Primary membrane stress: 0.117 MPa
- Primary bending stress: 30.05 MPa
- Leak detection limit: 1 gpm
- Weld residual stress: see next slides

Analysis Matrix

Deterministic Analysis

Case	WRS
DP-01	Linear
DP-02	3rd Polynomial
DP-03	No WRS

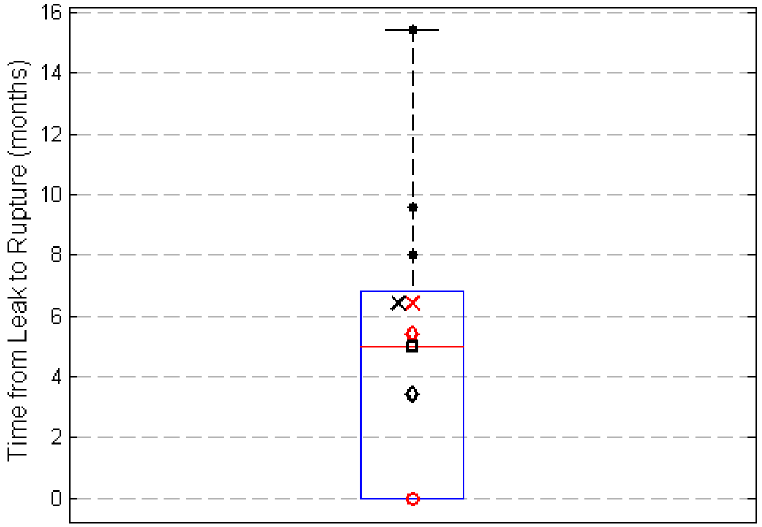


Probabilistic Analysis

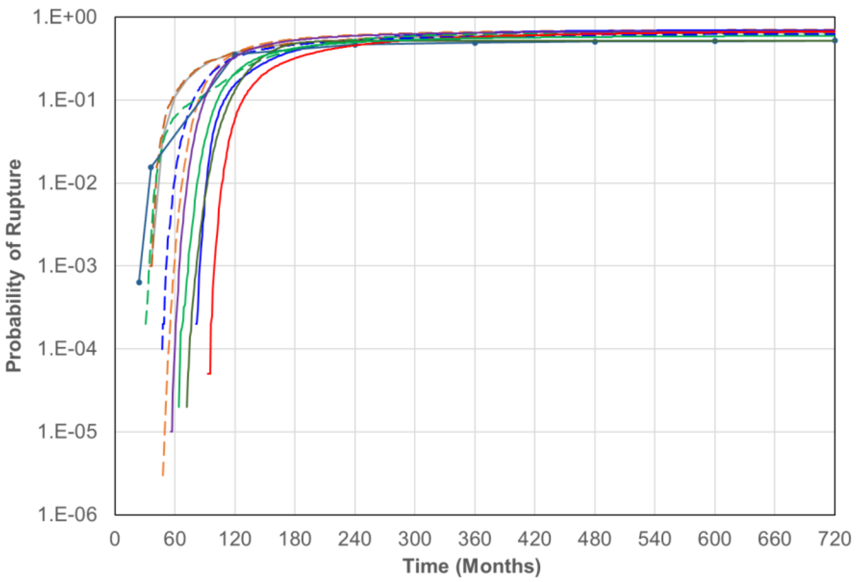
Case	Growth Rate	WRS	Leak Detection	Inspection
PP-01	Random	Deterministic	No	No
PP-02	Random	Deterministic	Yes	No
PP-03	Deterministic	Random	No	No
PP-04	Deterministic	Random	Yes	No
PP-045	Deterministic	Random	No	Yes
PP-05	Deterministic	Random	Yes	Yes
PP-06	Random	Random	Yes	Yes
PP-07	Random	No WRS	No	No

Reconcile LBB with PFM Results

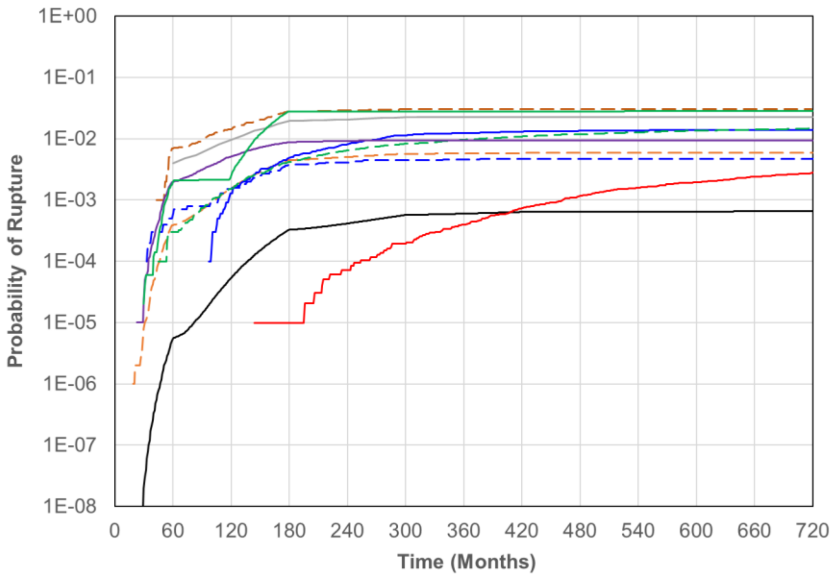
- Codes predicting BBL behavior in the deterministic problem also predict higher rupture probabilities in the probabilistic problem
- Probabilistic approach has the advantages of modeling the time-dependent aspects of a problem with explicit representations of uncertainties
- CEI’s PRAISE-CANDU Version 2.1.1 was used



DP-02



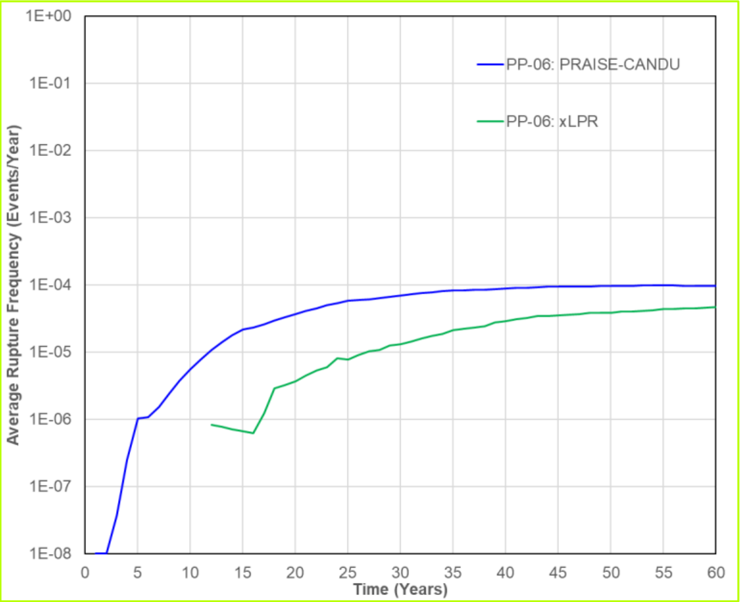
PP-03 (without LD)



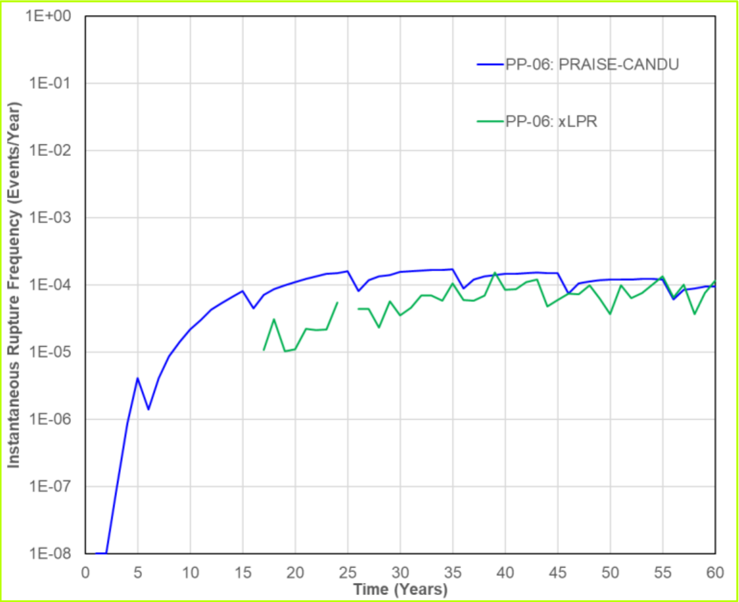
PP-04 (with LD)

PFM as Input for PSA

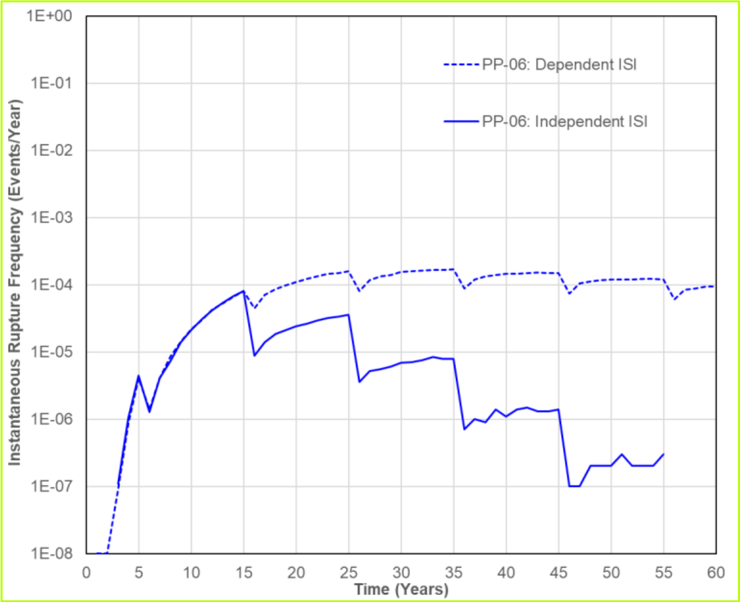
- Average frequency: $p(t_a)/t_a$
- Instantaneous frequency: $[p(t_a)-p(t_b)]/[1-p(t_a)]/(t_a-t_b)$, effective in revealing the effects of various mitigations, such as ISI.
- Comparison between xLPR 2.1 and PRAISE-CANDU 2.1.1



Average Frequency



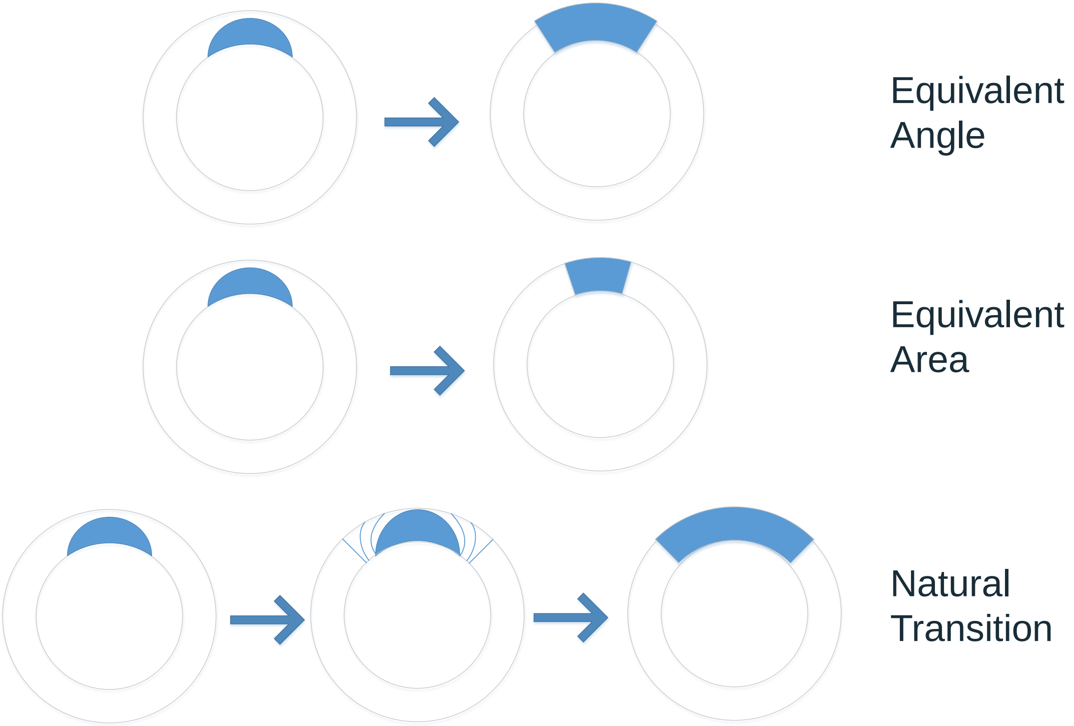
Instantaneous Frequency



Instantaneous Frequency

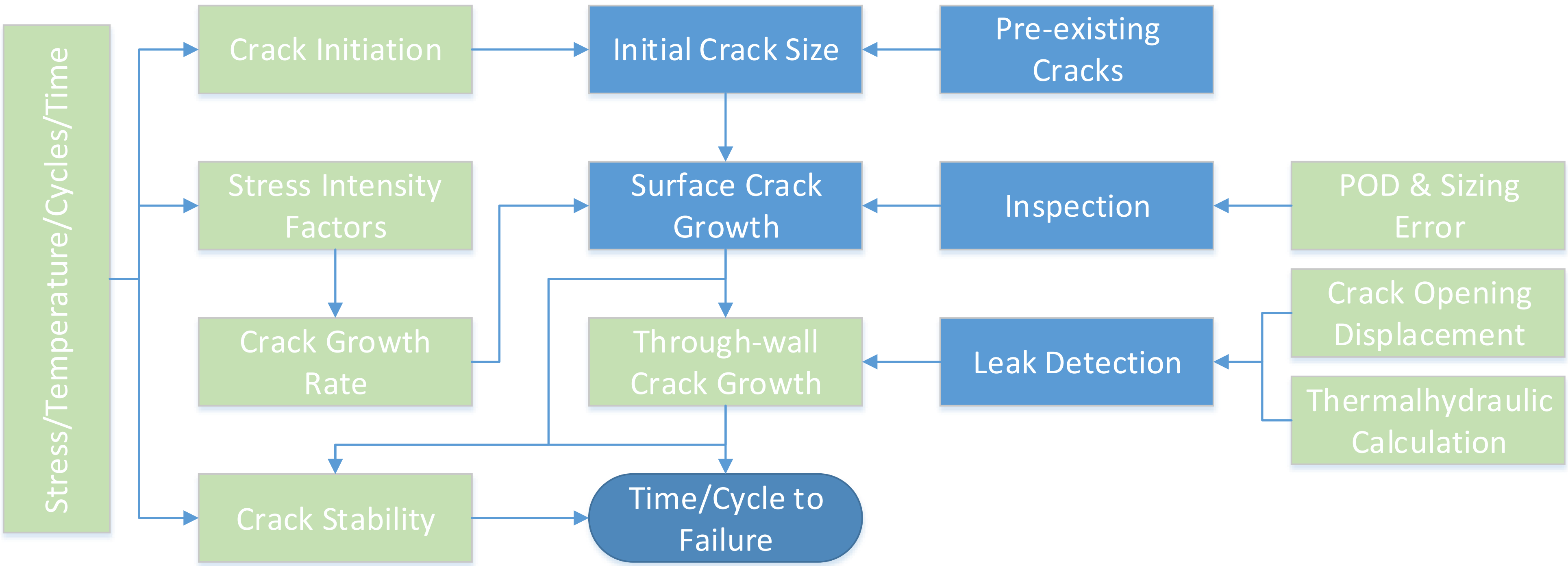
Summary of Differences

- There are large scatters in both deterministic and probabilistic results
- The scatter are attributed to different models used by each PFM code
  - ✓ K-solutions for surface and through-wall cracks
  - ✓ Transition from surface crack to through-wall crack
  - ✓ Implementation of WRS
  - ✓ Treatment of ISI: dependent vs independent
  - ✓ Treatment of ISI: in-loop vs postprocessing
  - ✓ Stability model
  - ✓ Treatment of crack face pressure
  - ✓ Crack opening displacement model
  - ✓ Thermalhydrualic model for leak calculation
  - ✓ Coding language
  - ✓ Computer platform
  - ✓ Sampling algorithms



Deterministic Modules

- Typical deterministic modules shown below
- Multiple models are available for module with green background



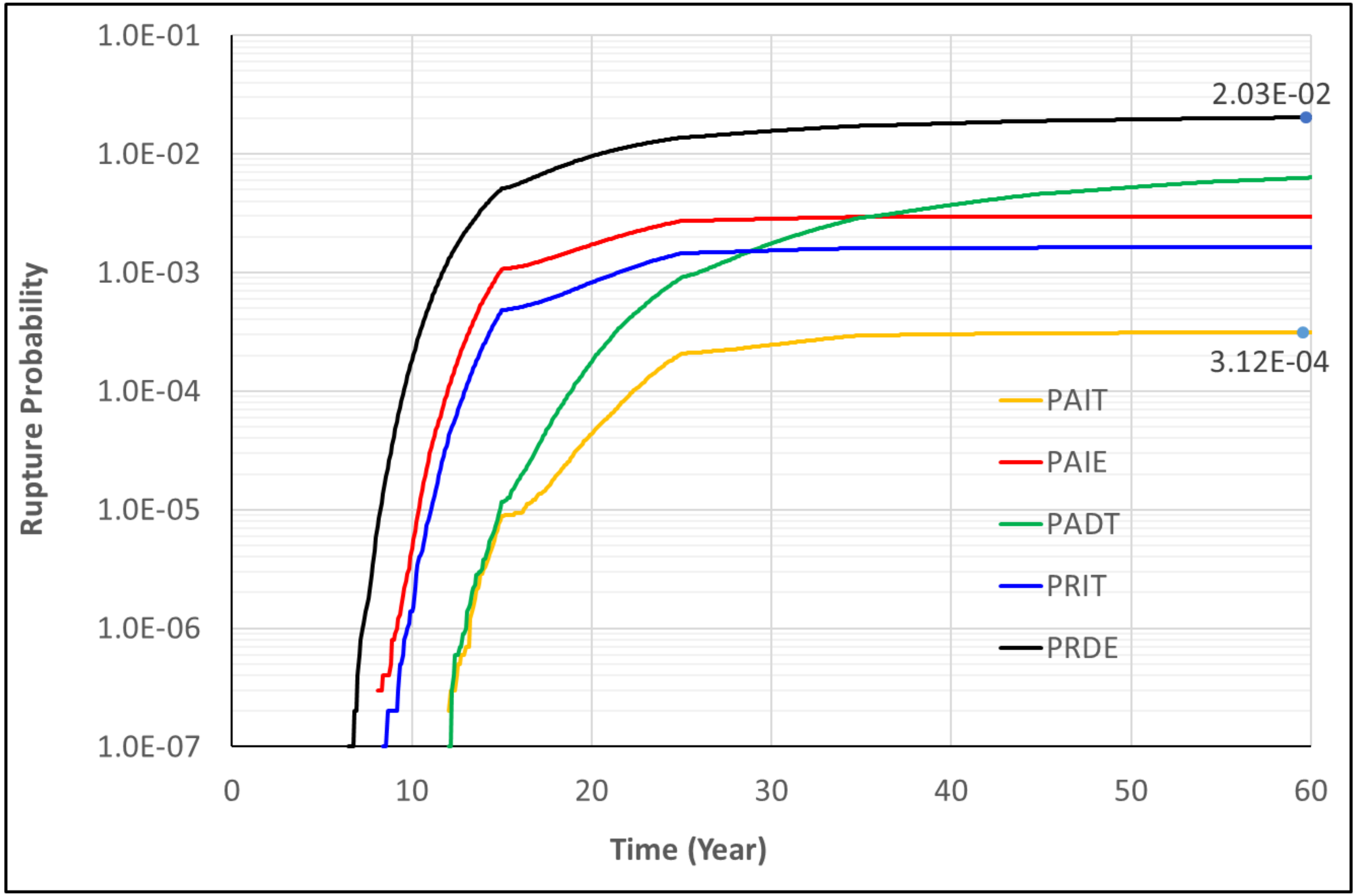
Surrogate Benchmark

- PRAISE-CANDU 3.0 Alpha was developed by CEI to implement different models
  - ✓ To eliminate the scatter caused by different Codes
  - ✓ Analysis matrix shown below
  - ✓ PAIT was reported in the PFM Benchmark report (PP-05) based on PRAISE-CANDU 2.1.1

Case ID	WRS Model		Surface K Solution		Inspection		Crack Transition	
	Polynomial	JAEA	ASME2021	R6	Dependent	Independent	Transition	Eq. Angle
PAIT	✓		✓			✓	✓	
PAIE	✓		✓			✓		✓
PADT	✓		✓		✓		✓	
PRIT	✓			✓		✓	✓	
PRDE	✓			✓	✓			✓
JAIT		✓	✓			✓	✓	
JAIE		✓	✓			✓		✓
JADT		✓	✓		✓		✓	
JRIT		✓		✓		✓	✓	
JRDE		✓		✓	✓			✓

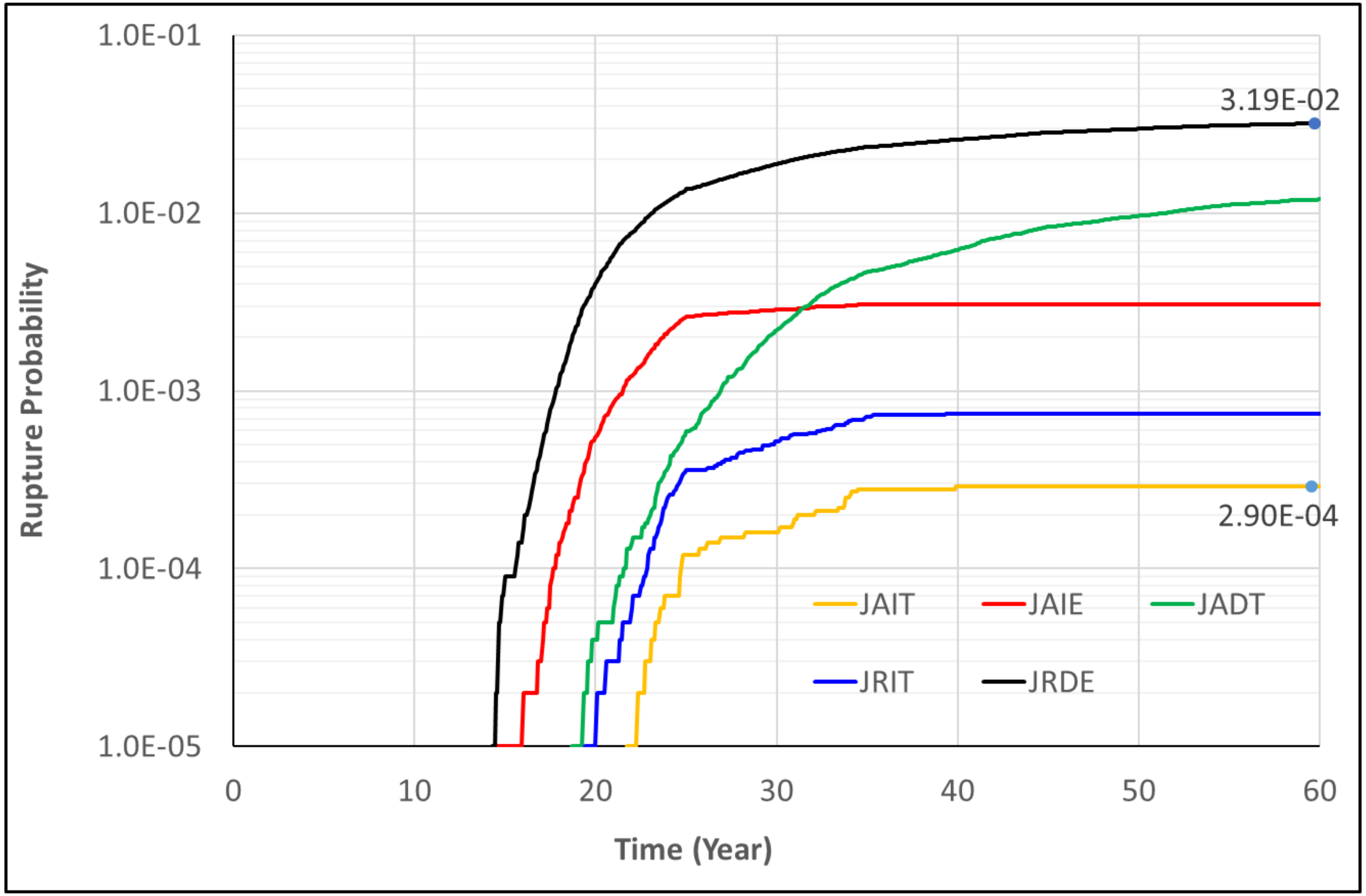
New Results based on Polynomial WRS

- Two-order difference was observed with combination of different models



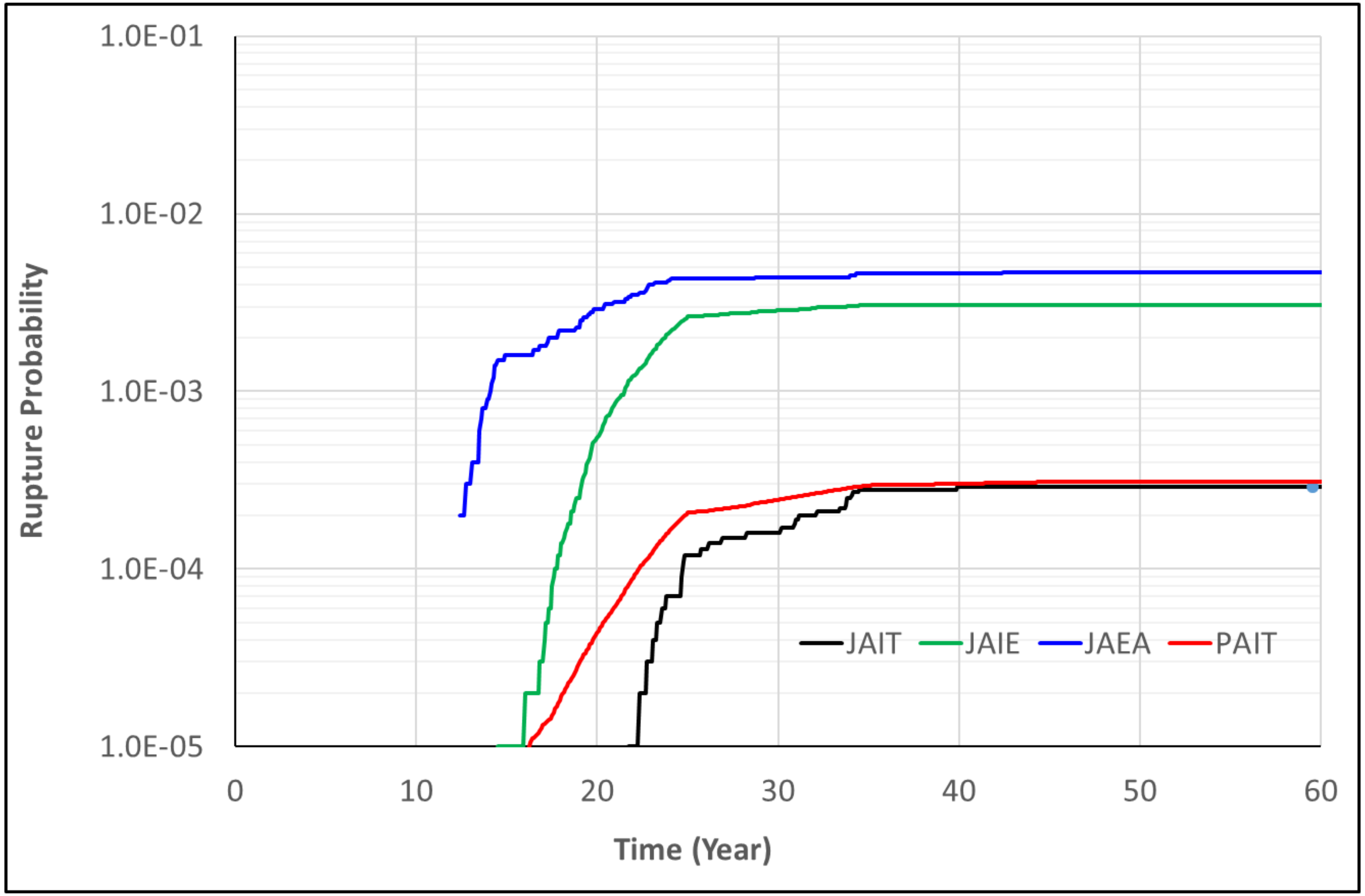
New Results based on JAEA WRS Model

- Akihiro Mano et al., A New Probabilistic Evaluation Model for Weld Residual Stress, International Journal of Pressure Vessels and Piping, 179 (2020) 103945.
- Same trend as previous slide but with slightly large scatter



CEI vs. JAEA Results

- **PAIT**: PRAISE-CANDU 2.1.1 results as reported in NEA/CNSI/R(2024)5
- **JAIT**: PRAISE-CANDU 3.0 results with JAEA WRS Model
- **JAIE**: PRAISE-CANDU 3.0 results with JAEA WRS Model and Equivalent Angle
- **JAEA**: PASCAL-SP results as reported in NEA/CNSI/R(2024)5
- PRAISE-CANDU 3.0 results are close to PASCAL-SP results when the same WRS and crack transition models are used



Takeaway Questions

- How to deal with model uncertainties, especially combination of fracture toughness models from different nuclear standards?
- Are there any guidelines or best practice document for selecting and COMBINING models?
- Do we need to run multiple codes to cross-check the results in the regulatory submission? Or do we need to run one code with different combinations of models?
- How could deterministic calculations be used to make sense of PFM results?

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thank you

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