Benchmark on Cast Austenitic Stainless Steel Probabilistic Fracture Mechanics Modeling

Overview and Summary of Current Status

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Background

- Probabilistic fracture mechanics (PFM) codes have been used to perform analyses of cast austenitic stainless steel (CASS) components, which face technical challenges in achieving reliable volumetric nondestructive examination (NDE)
  - MRP-479 (EPRI Report 3002023893)
- A previous benchmark organized by OECD/NEA evaluated differences in modeling of an Alloy 182 dissimilar metal weld in straight piping by subject PFM codes
  - NEA report to be published in 2026 (tentative)
  - Summary provided in PVP2022-84724 and PVP2023-105733
- This EPRI CASS PFM benchmark will build upon the learnings of the OECD/NEA benchmarking effort to investigate differences specific to the modeling of CASS material
  - Focus on crack propagation by fatigue instead of stress corrosion cracking (SCC)
  - Focus on stability of cracks in low toughness material (thermally aged CASS)

Objectives

- Understand the effects of modeling differences among CASS PFM codes under a set of controlled problems
- Understand the differences in CASS PFM software design
- Understand the differences in underlying deterministic models used in CASS PFM codes
- Evaluate the importance of key input parameters for CASS PFM codes
- Understand how differences in analyst input choices affect results

Project Overview

Phase 1:
Capabilities Survey

- Information collection on participant codes via a survey
- Key information areas:
  - General information
  - Models and Inputs
  - Outputs
- Leverage results to develop widely applicable benchmark problems

Phase 2:
Deterministic Benchmark

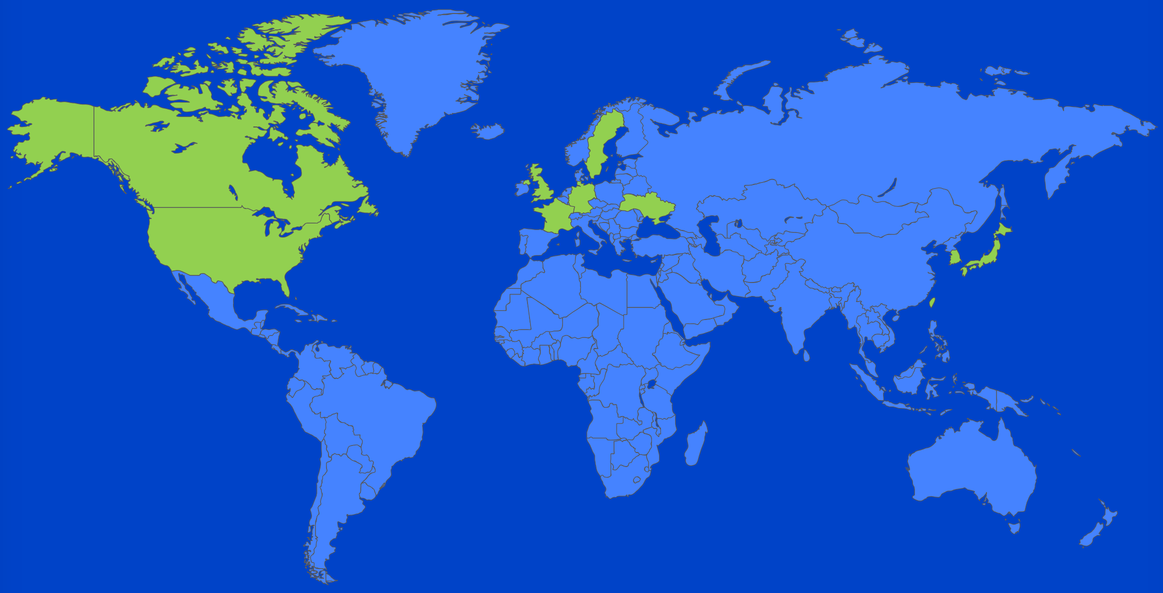
- Develop deterministic problems that each participant evaluates using their code
- Consolidate results for all evaluations and compare key results
- Identify differences in deterministic models between the codes

Phase 3:
Probabilistic Benchmark

- Develop probabilistic problems that each participant evaluates using their code
- Consolidate results for all evaluations and compare key results
- Identify differences in probabilistic modelling approaches between the codes

Participants and Codes

Country	Organization	Codes
USA	EPRI / DEI	xLPR
		PIPER-CASS
USA	SIA	CASSPAR / pc-CRACK
Japan	JAEA	PASCAL-SP2
Japan	CRIEPI	PEDESTRIAN
Korea	KAERI	PROFAS-PIPE
Korea	KHNP/SNUST	xLPR
Germany	GRS	PROST
Canada	Atkins Realis	PRAISE-CANDU
UK	Amentum	PROBLBB
Taiwan	NARI	PRO-LOCA
Ukraine	IPP-Centre	SIF-Master
France	EDF	OpenTURNS / OAR
Sweden	KIWA	NURBIT



- 10 Countries
- 13 Organizations
- 13 Codes

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Phase 1: Capabilities Survey

Summary of Results

Phase 1 (Survey) Overview

- Responses received from all participants
- Key survey findings:
  - Nearly all codes can perform probabilistic evaluations
  - All codes can model EPFM stability of circumferential cracks
  - Modeling of crack growth by fatigue available in codes from 10 of 13 codes
  - All codes implement 1 of 3 general material models
  - Time history results available for most codes
  - Not all participating codes can model axial cracks
- Capabilities of each code considered in development of benchmark cases to maximize participation

EPRI CASS PFM Benchmark Capabilities Survey - General Information		
Lead Investigator	Name	
	Email	
	Organization	
General Description of Code	Name	
	Version and Release Date	
	Supported Operating System(s)	
	Applicable Quality Assurance Standards and Versions	
	Proprietary Status	
	Coding Language(s)	
	Support for Probabilistic Modeling	
	Support for Parallelized Processing	
	Runtime Optimization Efforts Made in Code Development	
	Time Step	
	Supported Component Type(s)	
	Supported Crack Orientation(s)	
	Supported Crack Shape(s)	
	Degradation Mechanism(s) Modeled	
	Spatial Discretization	
	Supported Input Distribution(s)	
	Supported Sampling Algorithm(s)	
	Type 1 Uncertainty	
	Type 2 Uncertainty	
	Type 3 Uncertainty	
	Acceptance Criteria	
	General References	

CASS Material Modeling Capability Comparison

Input/Category	PRAISE-CANDU	PEDESTRIAN	PROBLBB	PASCAL-SP2	PROFAS-PIPE	PRO-LOCA	pc-CRACK (CASSPAR)	PROST	SIF-Master	xLPR	PIPER-CASS	OAR
Toughness Modeling Approach	1	1	3	1	3	1	1 or 3 (2)	3	1	1	1 or 2	1
Time-Dependent Material Aging	Yes	No	No	Yes	No	No	No (No)	No	No	No	No	No
Available Correlations	S_y-S_f, S_f-C, S_f-D	No	No	No	No	S_y-S_u	No (S_y-$J_{0.08}$)	No	S_y-S_u	S_y-S_u, C-J_{IC}	S_y-S_u, S_y-C_{vsat}, S_u-C_{vsat}	No

- All codes input material toughness using one of three approaches:
  1. Direct specification of J-R curve parameters (C_R, m, J_{IC})
  2. NUREG/CR-4513 approach (derive J-R curve parameters from delta ferrite content and material composition)
  3. Direct specification of LEFM fracture toughness
- Two codes can model time-dependent material aging

S_y = Yield strength, S_u = Ultimate strength, C = J-R curve coefficient, D = Ramberg-Osgood coefficient,
J_{IC} = Tearing resistance at crack initiation, C_{vsat} = Charpy impact energy at saturated thermal aging

Phase 2: Deterministic Benchmark
Overview and Status

Phase 2 (Deterministic) Overview

- Deterministic benchmark consists of two sets of cases:
  - Fatigue crack growth of a postulated flaw until prediction of rupture
  - Reporting crack sizes at the stability limit for different material inputs

- Participants encouraged to submit results for whichever cases their codes are capable of evaluating

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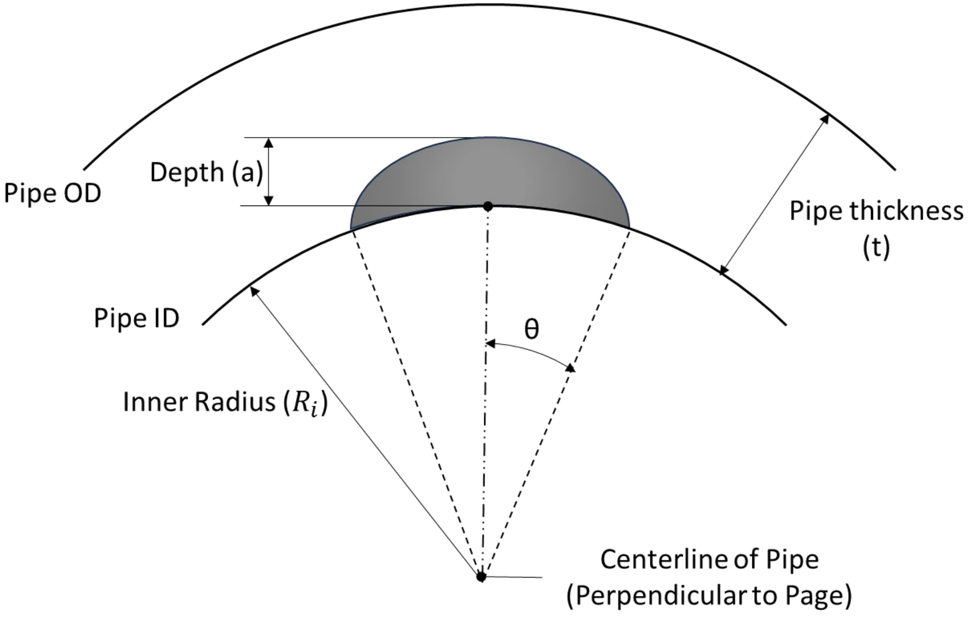
Fatigue Crack Growth (FCG) Problem Overview

- Model a single circumferential crack in CASS piping
- For many inputs, one set of values applied for all deterministic problems
  - Representative geometry, loading, weld residual stress, and transients
- Material properties and initial flaw sizes varied:
  - Material property sensitivities include high toughness/low strength (Case F1) and low toughness/high strength CASS materials (Case F2)
  - Case F4 allows participants to apply their own material aging model
  - Flaw size sensitivity Case F3 evaluates a narrower initial flaw aspect ratio
- Optional axial fatigue crack growth: Case F5



Case ID	Description
F1	Baseline fatigue crack growth case
F2	CF8M material properties
F3	Reduced aspect ratio
F4	Custom material aging model
F5 **(optional)**	Axial cracking

Stability Evaluation Problem Overview

- Determine the critical size for EPFM instability of a circumferential flaw, both for a through-wall flaw and for a surface flaw with depth of 75% through-wall
  - Evaluate for varying material toughness inputs (J-R curves) given a constant yield and ultimate strength (Case S1)
  - Evaluate for varying yield and ultimate strengths given a constant material toughness (J-R curve) (Case S2)
- Optional evaluations of EPFM critical size of axial flaws applying the same material property sets (Cases S3 and S4)

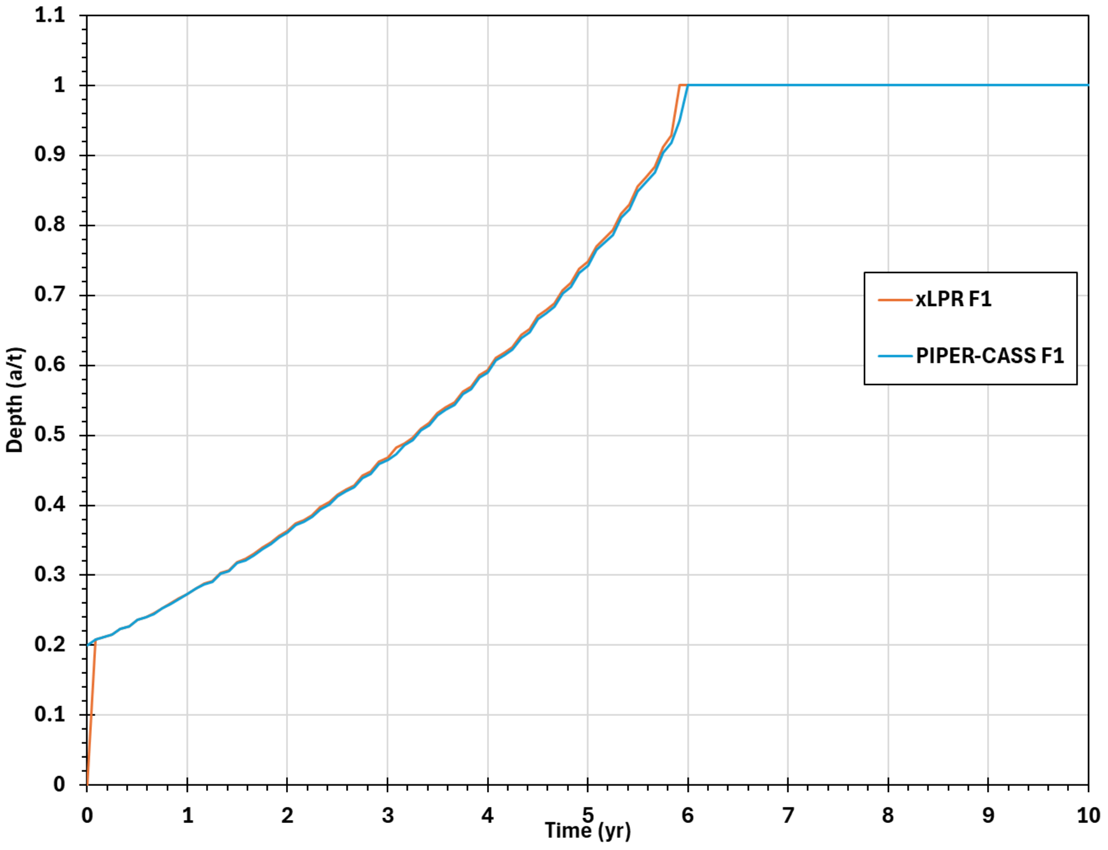
Case ID	Description
S1	Evaluate circ crack stability as function of toughness
S2	Evaluate circ crack stability as function of **strength**
S3 **(optional)**	Evaluate **axial** crack stability as function of toughness
S4 **(optional)**	Evaluate **axial** crack stability as function of **strength**

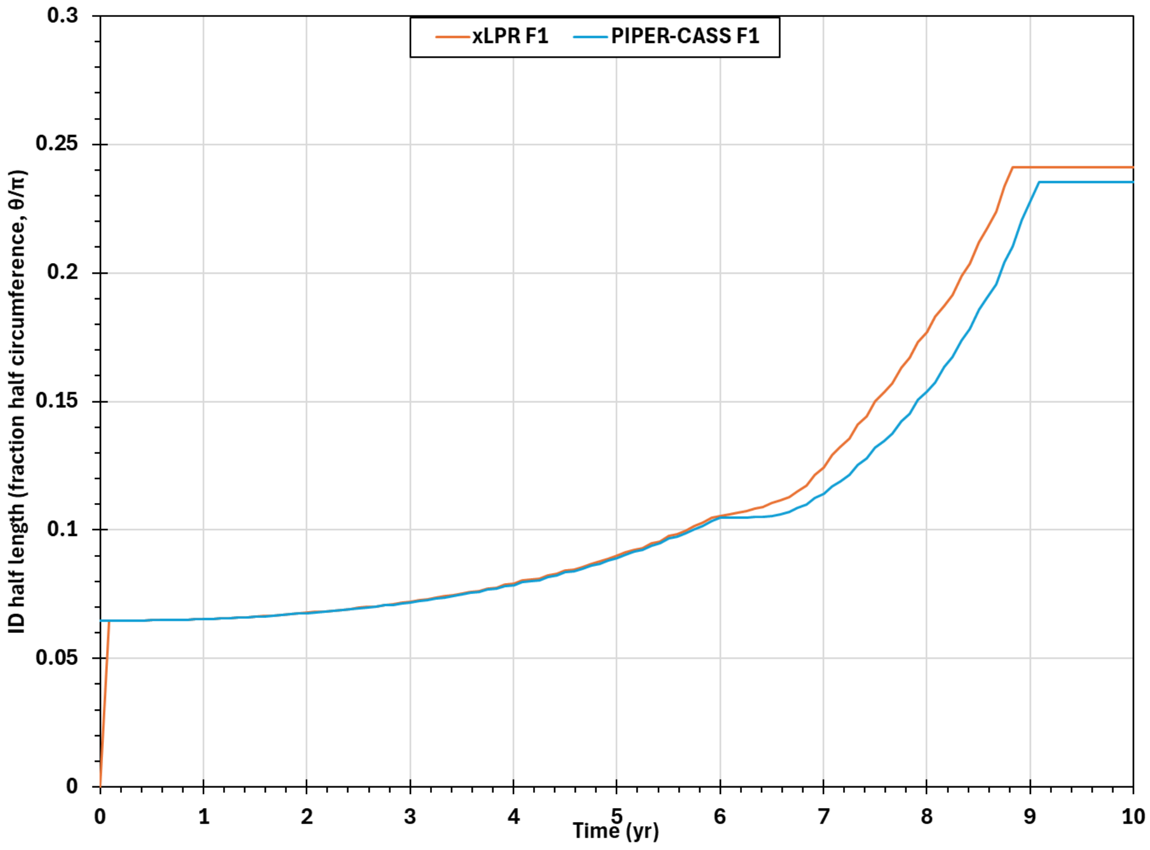
Current Status of Deterministic Benchmark

- 11 of 13 participants have submitted results for the deterministic problem set
- Notable differences among the initial deterministic results submissions
  - Additional information on approaches taken was requested to fully understand differences in results
  - Common sources of differences in fatigue crack growth results include:
    - Calculation and/or application of fatigue crack growth rate coefficients (e.g., not all codes model load ratio, *R*, dependence)
    - Method of determining time of occurrence of transients given input transient event frequencies
    - Calculation of transient stress intensity factors, including identifying minimum and maximum stresses
  - Common sources of differences in stability evaluation results include:
    - EPFM models
    - Selection of Ramberg-Osgood parameters, for EPFM models based on J-integral methods
    - Application of input loads
- Lessons learned from Deterministic Phase activities:
  - Nuances in transient stress intensity factor calculations can have significant impact on the fatigue crack growth
  - More participant-specific information necessary in the problem statement when it is intended for all participants to take the same approach
  - Reduction of complexity (e.g., fatigue crack growth coefficient as constant instead of $f(R, T)$) in baseline case would have allowed for more efficient resolution of differences in results

Sample FCG Results

Case F1 Crack Size Time History Comparison

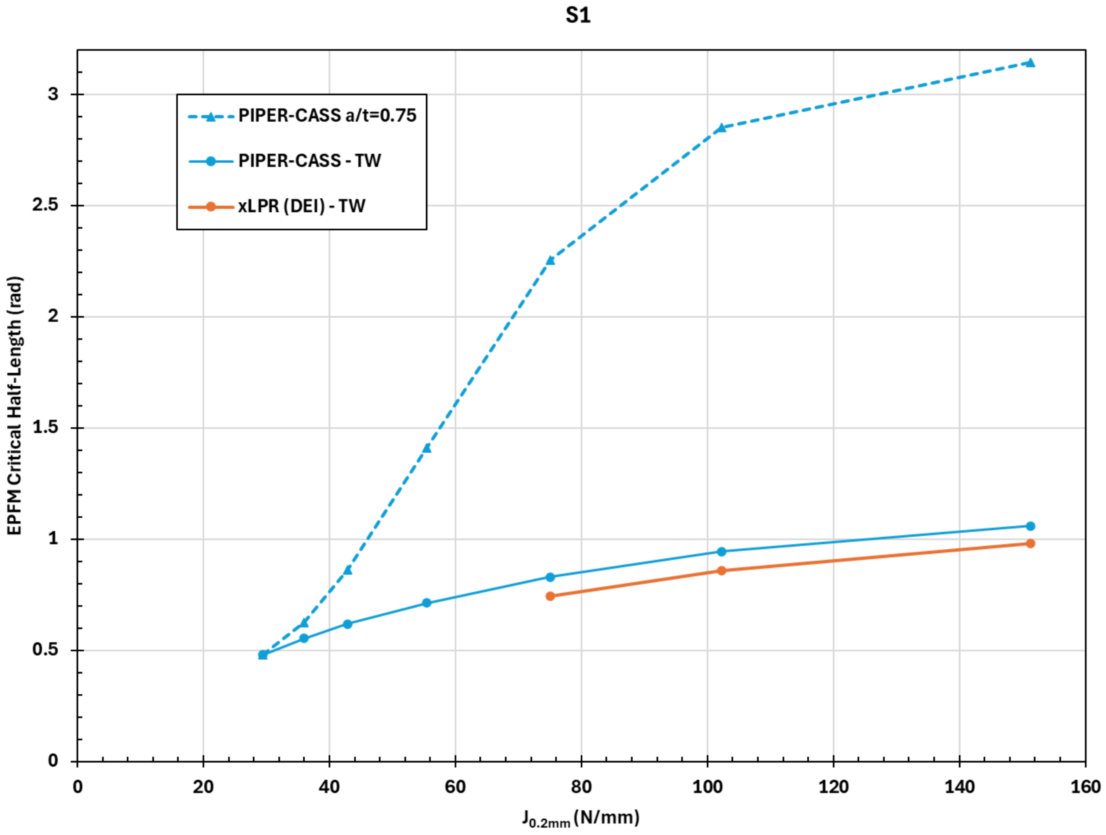


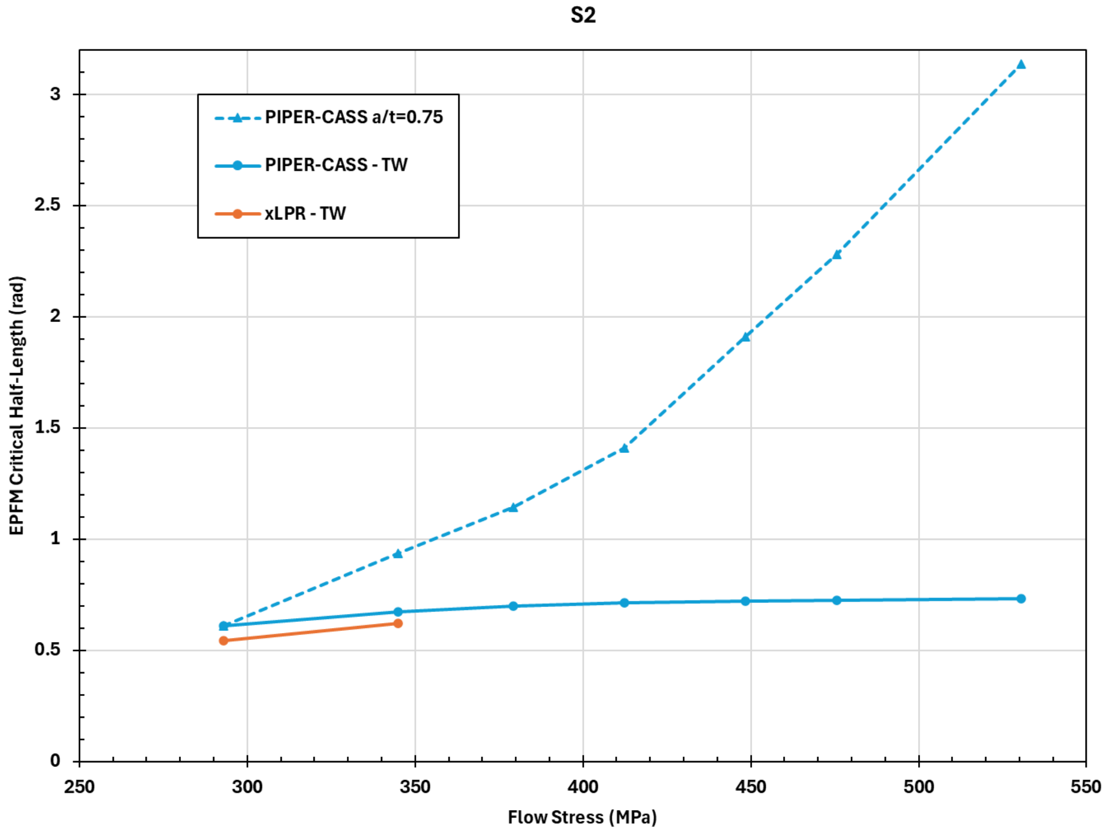


Benchmark inputs chosen to yield artificially fast fatigue crack growth

Sample Stability Evaluation Results

Critical Crack Size vs. Material Toughness/Strength





xLPR results included only for runs that return a converged solution

Overall Project Schedule

Phase	Schedule Item	Date
1	Release survey to participants	November 14th, 2024
	Survey responses due	January 10th, 2025
	Hold virtual meetings to discuss survey responses	March 6th/7th, 2025
2	Release deterministic benchmark problem to participants	April-May 2025
	Execute deterministic benchmark problems	May-September 2025
	Hold virtual meetings to discuss deterministic benchmark results	September 2025
	Share summary of deterministic benchmark results	October 2025
3	Release probabilistic benchmark problem to participants	October 2025
	Execute probabilistic benchmark problems	October 2025-January 2026
	Hold virtual meetings to discuss probabilistic benchmark results	January 2026
	Share summary of probabilistic benchmark results	January 2026
	Provide draft report for participant comments	February 2026

Final report will be publicly available on EPRI.com

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