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Probabilistic Fracture Mechanics Toolkit for Hydrogen Blends in Natural Gas Infrastructure

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Emerging Fuels Symposium

HyBlend
U.S. DEPARTMENT OF ENERGY

SAND2023-03992C

U.S. DEPARTMENT OF ENERGY
NNSA

Materials activities in HyBlend™ Pipeline Blending CRADA: Structural integrity for hydrogen gas infrastructure

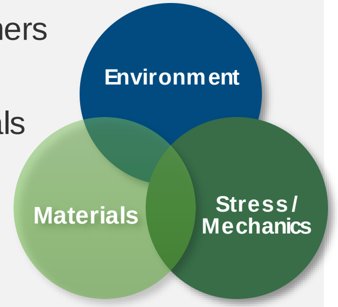
How do we assess structural integrity of infrastructure with hydrogen?

What is the structural risk to NG assets with blended hydrogen?

How do we formulate mechanistic models into predictions?

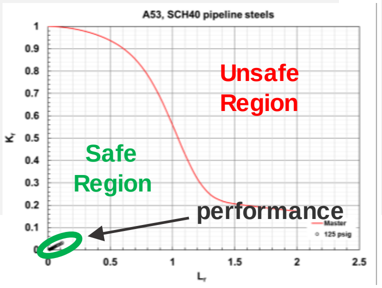
Database of design properties for natural gas (NG) assets with hydrogen

- Assessment of critical parameters determining materials response in hydrogen environments
- Survey of critical materials in ancillary equipment (e.g., pumping stations)
- Long-duration aging of polymers in piping systems
- Evaluation of vintage materials in existing infrastructure



Pipeline Structural Integrity Tool

- Tools to evaluate probability of rupture of NG assets based on Nuclear Regulatory Commission (NRC) framework
- Uncertainty analysis to inform experimental evaluation
- Sensitivity analysis to determine opportunities for system and operational improvements
- Regulations, Codes, and Standards (RCS)-based structural integrity assessment



Physics-based mechanisms of hydrogen embrittlement relevant to NG assets

- Develop deeper understanding of mechanisms of hydrogen embrittlement
- Establish models and framework for implementing physical phenomena into structural integrity tool
- Inform materials selection guidance and establish basis for potential future materials development activity

Guidance on operating conditions

+ partners

Industry-focused probabilistic framework for risk assessment

PRCI EPRI gti

State-of-the-art characterization

H-Mat

International coordination *facilitates* definition of requirements, *reduces* redundancy, *enhances* rigor, and *improves* breadth of structural integrity tools

Outline

Fracture Mechanics Approach

- *What is the fracture mechanics approach and how does it relate to pipeline assessments*

Probabilistic Fracture Mechanics (PFM) Primer

- *What is probabilistic fracture mechanics and why use it*

PFM for Hydrogen Conveyance (and Storage)

- *How can PFM be applied to the pipeline application*

HELPR Demonstration

- *Demonstrate the current PFM for pipelines capability*

HELPR Credibility

- *Why should HELPR predictions be believed*

Next Steps and Summary

Fracture Mechanics Approach

Fracture Mechanics Parameter: Stress intensity factor, *K*

What is this in the stress intensity factor, **K**?

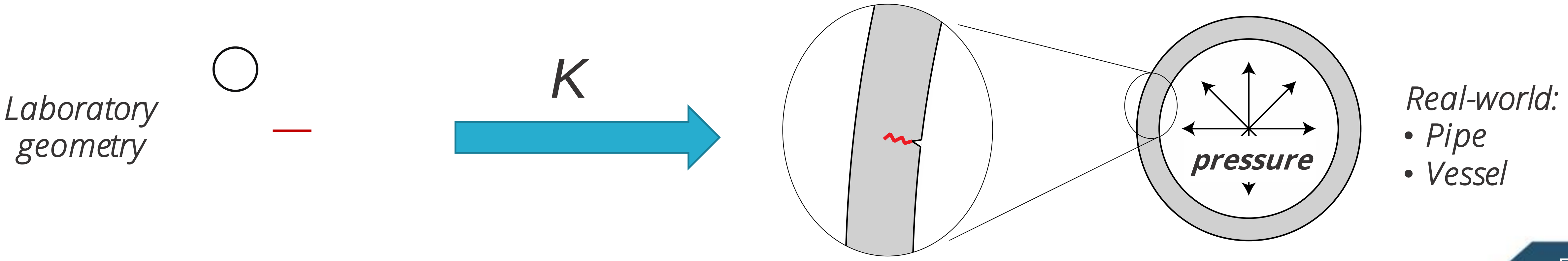
$$K = \sigma\sqrt{\pi a} \times f(geometry) \qquad \sigma = stress \qquad a = crack\ size$$

K characterizes the **stress state at a crack tip**

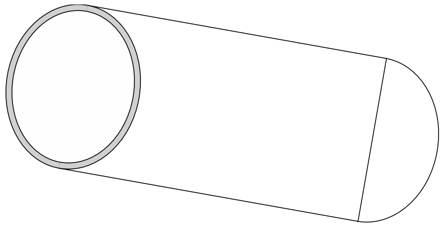
- analogous to the stress, but for the case of cracks in structures

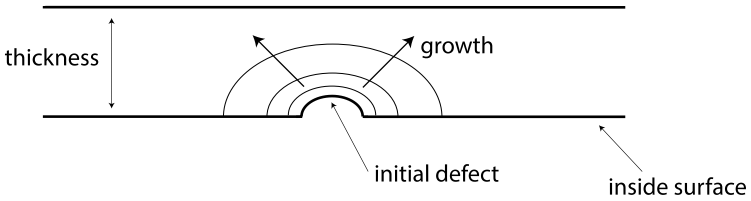
K is a **transferable parameter** that is used to generalize the state of a crack and transfer information between one geometry and another

- for example between a laboratory test and a real-world application



Fracture Mechanics Approach to Pipe Life Assessment with Blends

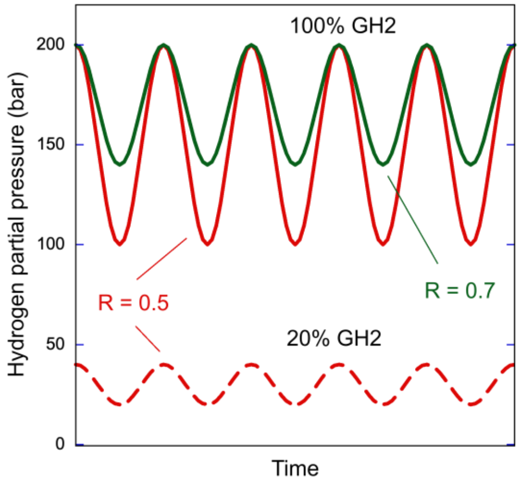




Pipe geometry: diameter, thickness

Pipe material properties: elastic, plastic, fracture, fatigue properties

Initial defects: size, geometry, density



$$\frac{da}{dN} = C_3 \left[\frac{1 + C_4 R}{1 - R}\right] \Delta K^{m_2}$$

Fracture/fatigue mechanisms:

Crack growth due to **pressure cycling** (internal load)

- Amplitude and frequency of pressure oscillations impactful

Effect of H_2 on fracture and fatigue properties

- H_2 partial pressure impacts crack growth rate & reduces fracture resistance

Evolving crack in pipe walls until crack size become unstable

- Unstable / critical crack size **a(crit)** is the crack depth at which the applied K (K_{max}, due to hoop stress) is equal to fracture resistance (K_{IH}) of the material

Probabilistic Fracture Mechanics Primer

Probabilistic Fracture Mechanics (PFM)

PFM = FM + P

Fracture mechanics (FM)

- FM is a methodology to deterministically assess defects (cracks) in highly-loaded structures
- FM is incorporated in a number of codes and used in Fitness-for-Service assessment of pressure structures
  - American Society of Mechanical Engineers: ASME BPVC, B31.12
  - American Petroleum Institute: API 579
  - British Standards: BS 7910

Probabilistic (P)

- Use probability to assess the range of possible outcomes
- Quantify impact of variability and uncertainty
- Increase understanding of performance margins

Margin of Safety: The Deterministic Approach

Assumes all significant parameters defining the problem are known

Where uncertainties exist (e.g., materials properties) **conservative bounding values** are assumed

Safety factors are imposed to ensure satisfactory margins against uncertainties

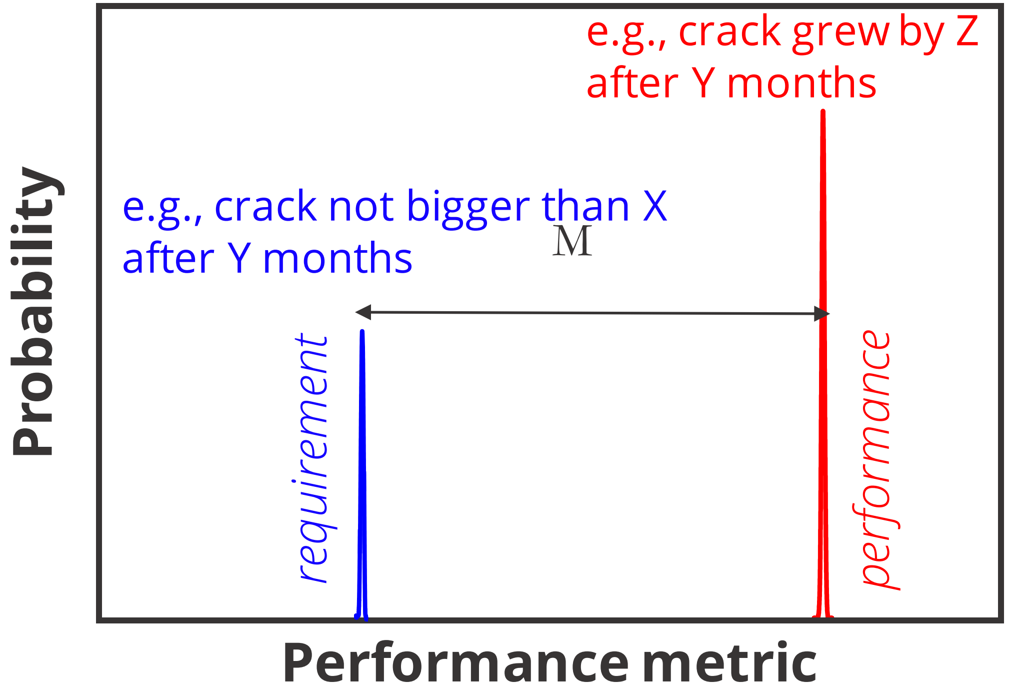


Figure: *Margin is distance in performance metric space between a requirement and realized performance*

Margin of Safety: The Probabilistic Approach

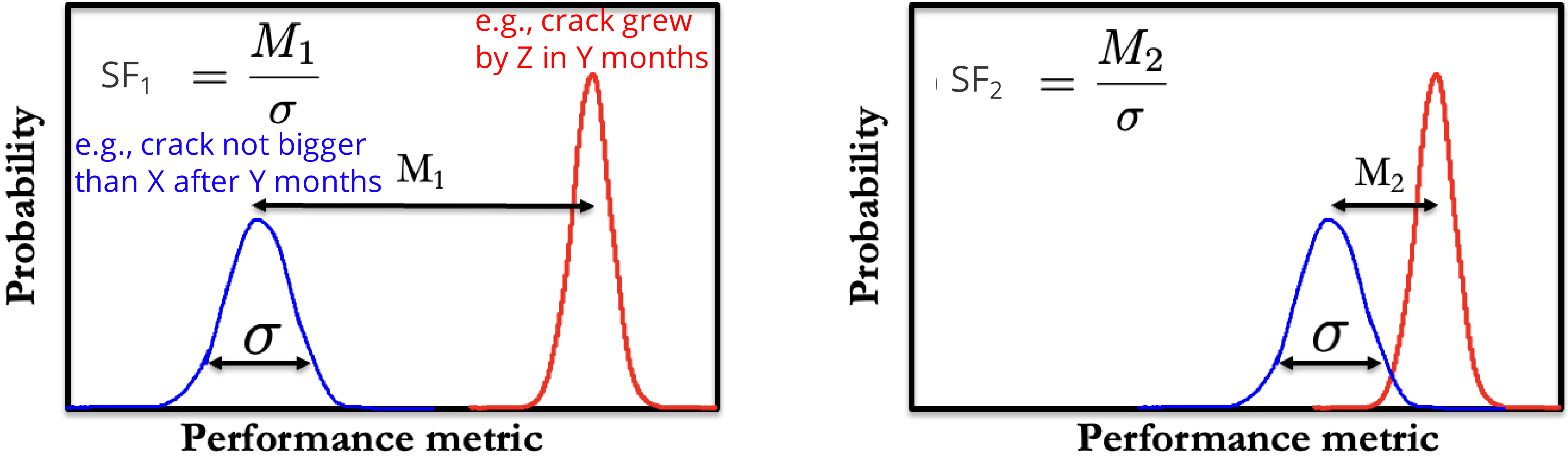
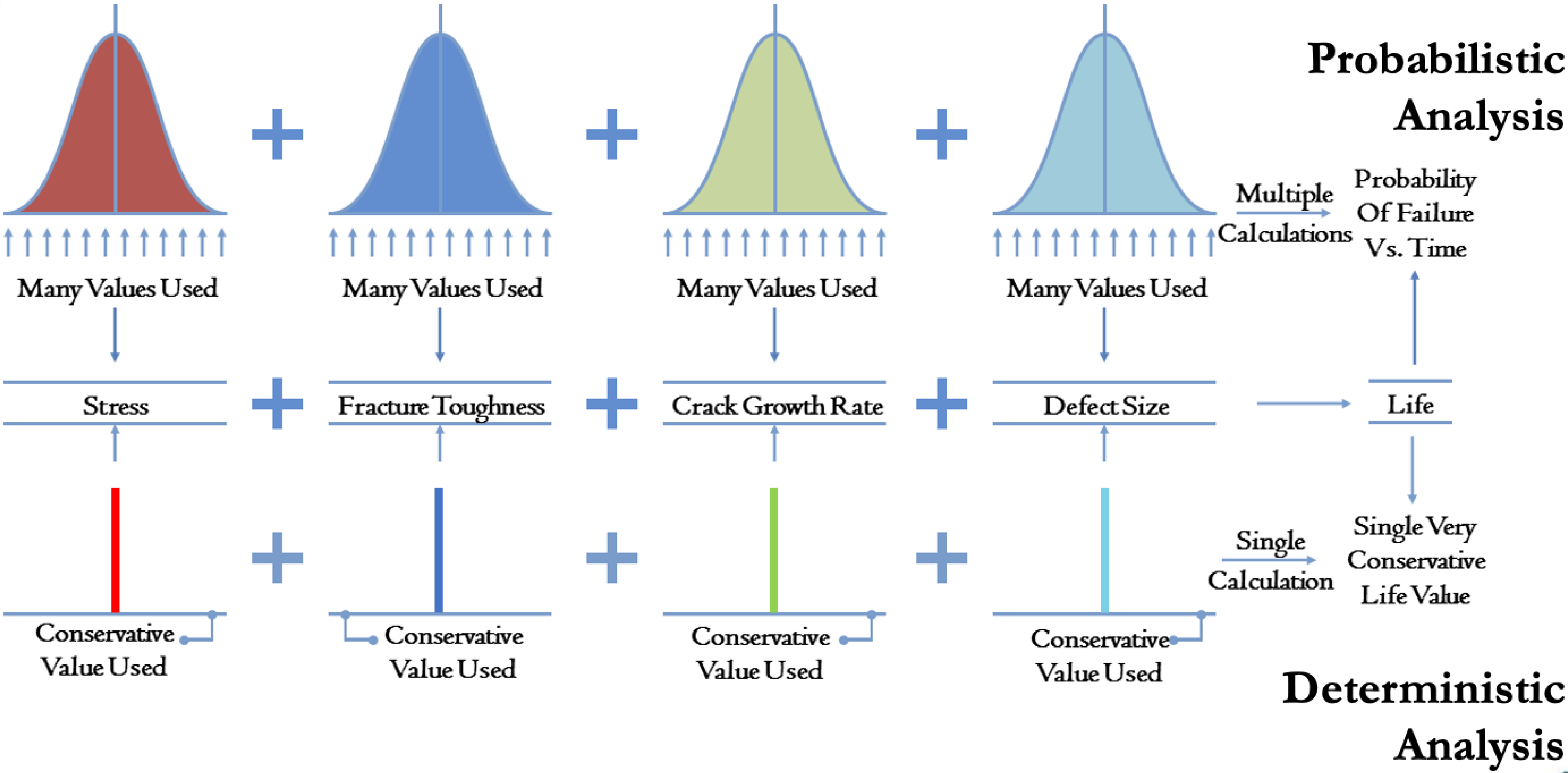


Figure: *Margin of safety can incorporate uncertainty information when using probabilistic approach. Normalizing margin (M) by uncertainty measure (σ) quantifies the margin in terms of certainty. On the left is a scenario when the margin is large compared to uncertainty, while on the right is a scenario where the margin and uncertainty are of similar magnitude.*

Statistical distributions are assigned to variables which have a significant effect on the problem (random variables)

Problem is solved to determine **probability of desired results**

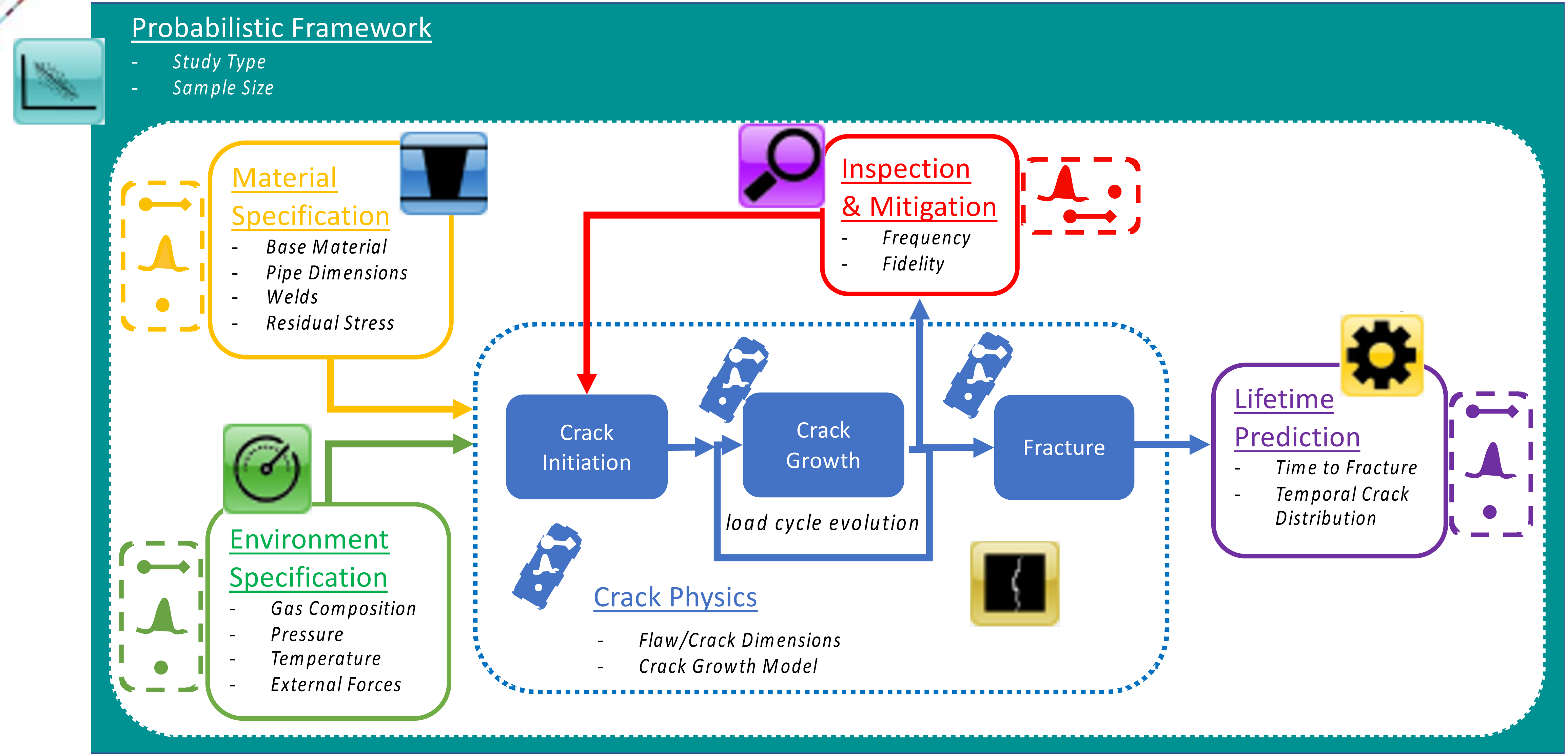
Deterministic vs Probabilistic



PFM for Hydrogen Transport

Conceptual Overview

Basic Components of HELPR



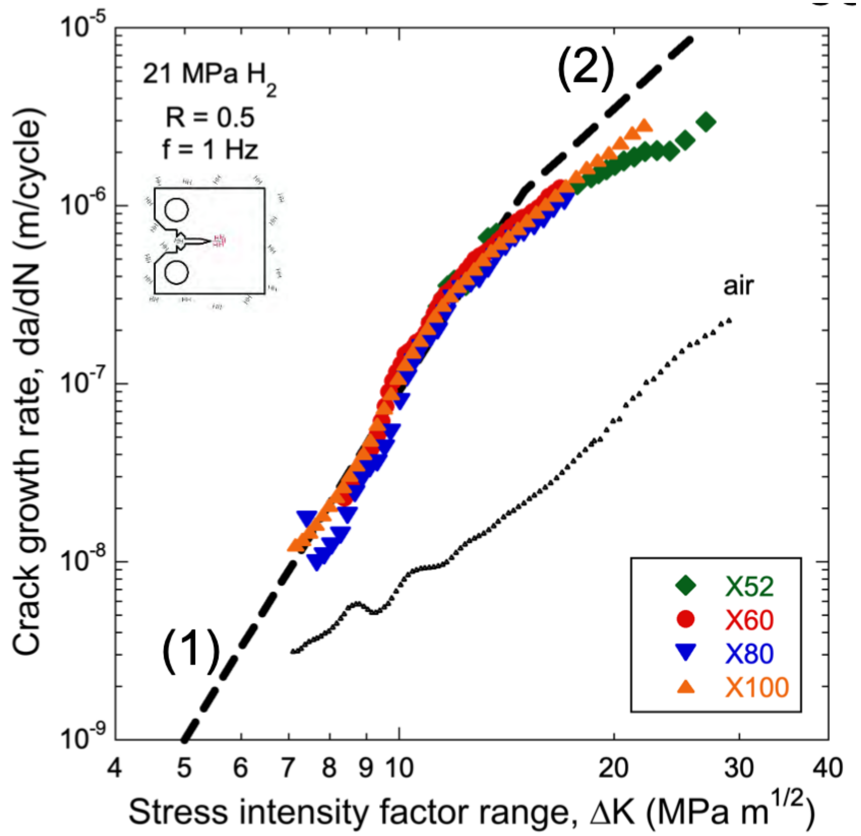
Deterministic Fatigue Model

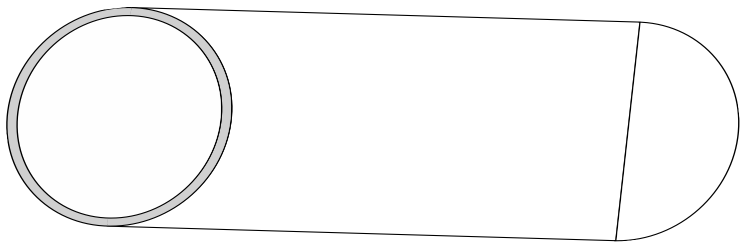
Fast enough to reach **low probability events**

Each deterministic model is/must be **validated** and **calibrated** against field/lab data

Key **assumptions** to conceptualize the fracture process

- *i.e., idealized crack shape, crack interaction, etc.*
- *Use ASME CC2938 design curves to model crack growth rate (with addition of pressure compensation term)*





(2) $$\frac{da}{dN} = 1.5x10^{-11}\left[\frac{1+2R}{1-R}\right]\Delta K^{3.66}$$

(1) $$\frac{da}{dN} = 3.5x10^{-14}\left[\frac{1+0.4286R}{1-R}\right]\Delta K^{6.5} g(P)$$

g(P) **is hydrogen partial pressure dependent term**

Ref: San Marchi, SAND2023-00924O

Coming Soon: **Fracture** integration through failure assessment diagram

Characterization of Uncertainty

Aleatory uncertainty: (perceived) randomness in the occurrence of future event. Cannot be reduced.

Epistemic uncertainty: Lack of knowledge w.r.t. the appropriate value to use for a quantity that has a poorly known value.

Spatial variability: Inherent variability over space of a quantity, that usually cannot be measured precisely or at the expected scale. Spatial variability is EITHER aleatory or epistemic.

Probability distribution functions usually used to characterize both aleatory and epistemic uncertainties and spatial variability.

HELPR Demonstration

Deterministic Problem Specification: Inputs

Pipe Material

- X52
- 52 ksi yield strength
- 36 in outer pipe diameter
- 0.406 in thick walls
- 55 MPa $m^{1/2}$ fracture resistance (K_{IH})
  - *ASME B31.12*

Initial Flaw (crack)

- 25% flaw depth (a/t)
  - *Starts out being 25% through pipe thickness*
- 40 mm flaw length

Gas Environment

- 100% H_2
- 850 psi maximum pressure in oscillatory fluctuations
- R = 0.75
  - *638 psi minimum pressure*
- 293°K temperature (20°C)

Quantities of Interest (QoI)

- critical crack size as well as ASME based criteria
  - *cycles to 25% critical crack size*
  - *½ cycles for critical crack size*

Deterministic Problem Specification: Results

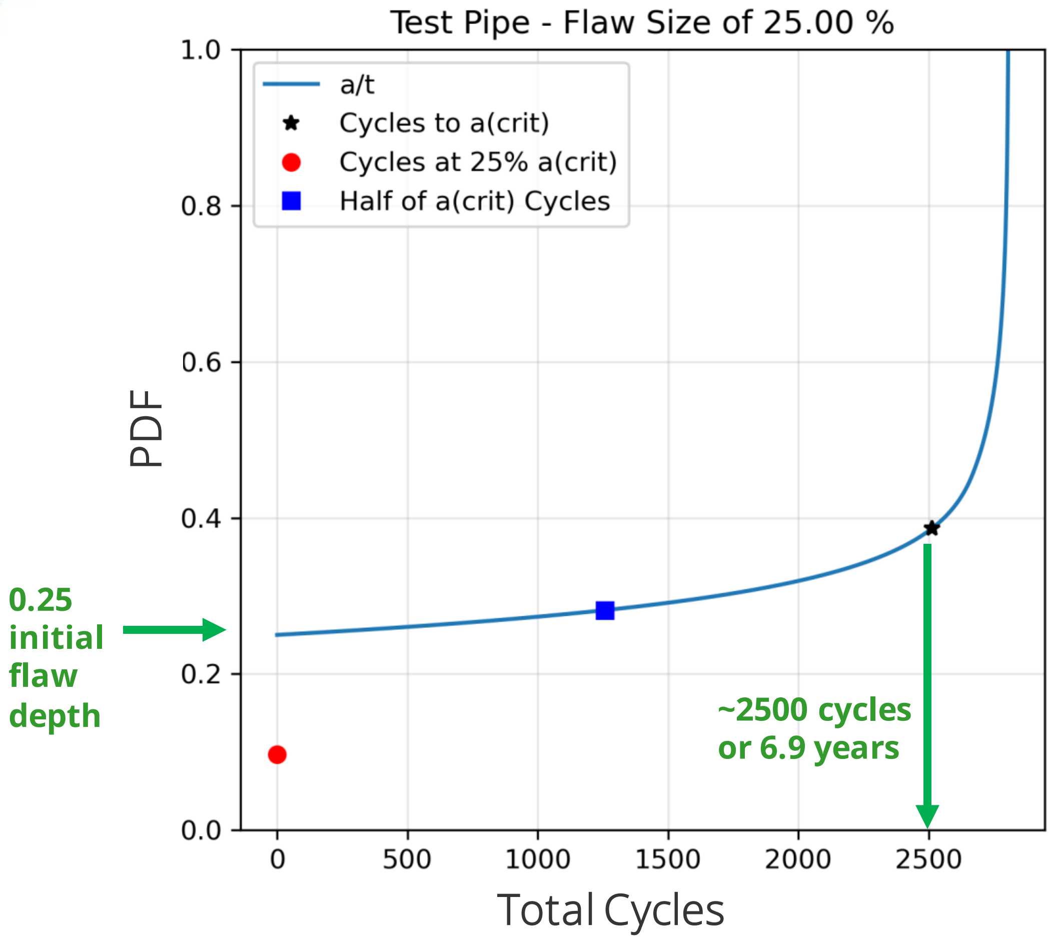


Figure: *Cycle count based QoIs mapped to crack evolution*

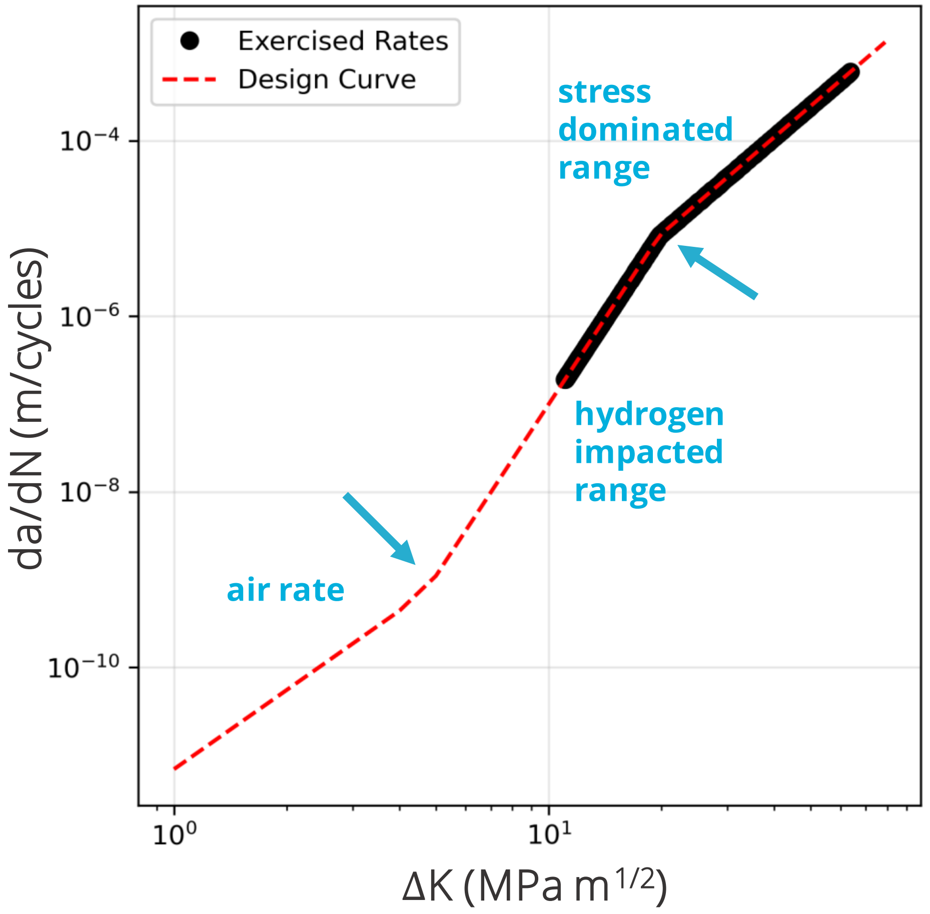


Figure: *Crack growth rates realized during crack evolution compared to underlying design curves*

Probabilistic Problem Specification: Inputs

Uncertain variables represented with uncertainty distributions

Pipe Material

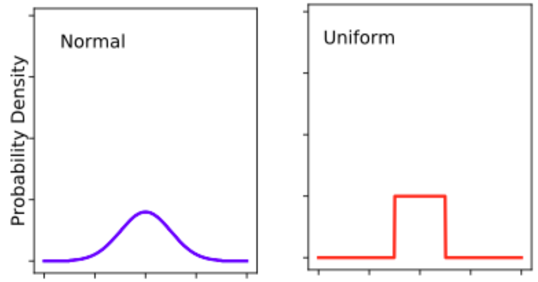
- X52
- 52 ksi yield strength
- 36 in outer pipe diameter
- 0.406 in thick walls
- 55 MPa $m^{1/2}$ fracture resistance (K_{IH})

Gas Environment

- 100% H_2
- variability in maximum pressure
  - ***850 ± 20*** psi ***normally distributed***
- variability in minimum pressure
  - ***638 ± 20*** psi ***normally distributed***
    - *R = N(0.751, 0.03)*
- variability in temperature
  - ***285 to 300*** K ***uniformly distributed***

Initial Flaw (crack)

- variability in flaw depth (a/t)
  - ***0.2 to 0.3 uniformly distributed***
- 40 mm flaw length



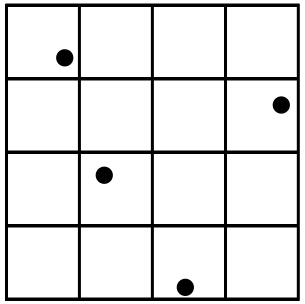
Probability distributions used to characterize uncertainty or variability

Quantities of Interest (QoI)

- critical crack size as well as ASME based criteria
  - *cycles to 25% critical crack size*
  - *cycles to ½ cycles for critical crack size*

Probabilistic Settings

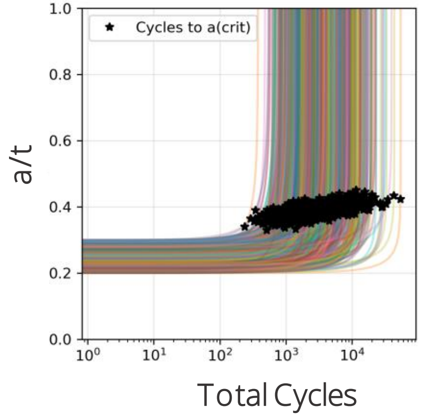
- Latin hypercube sampling (LHS)
- 100 samples



Demonstration LHS from two uniform distributions

Probabilistic Problem: Results

Figure: *Ensemble of crack evolution results*



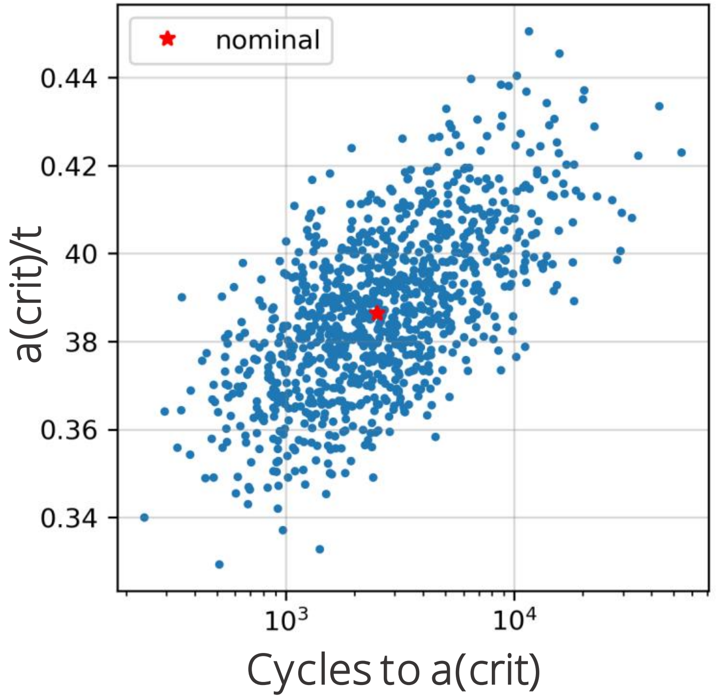


Figure: *Scatter plot of QoI results*

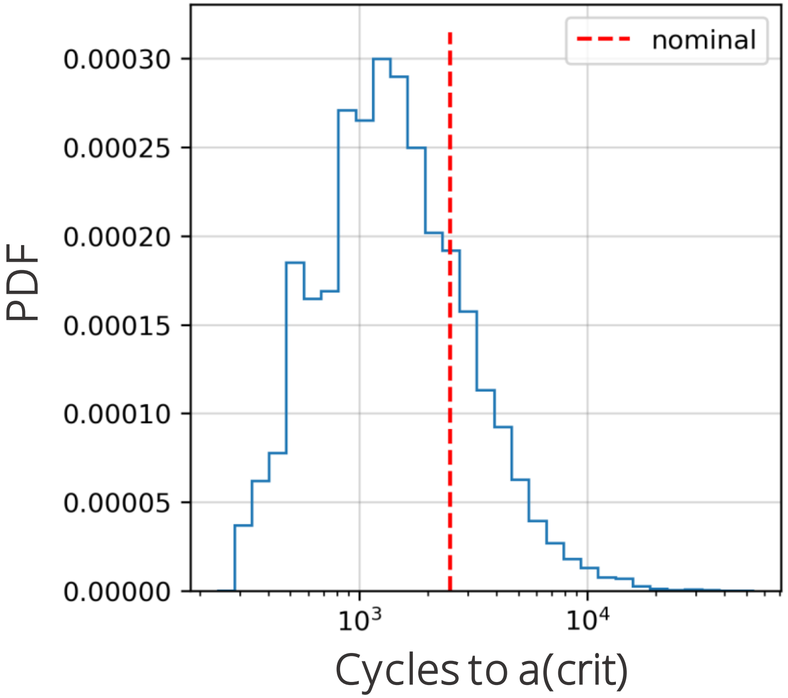


Figure: *Visualizing QoI variability as probability distribution*

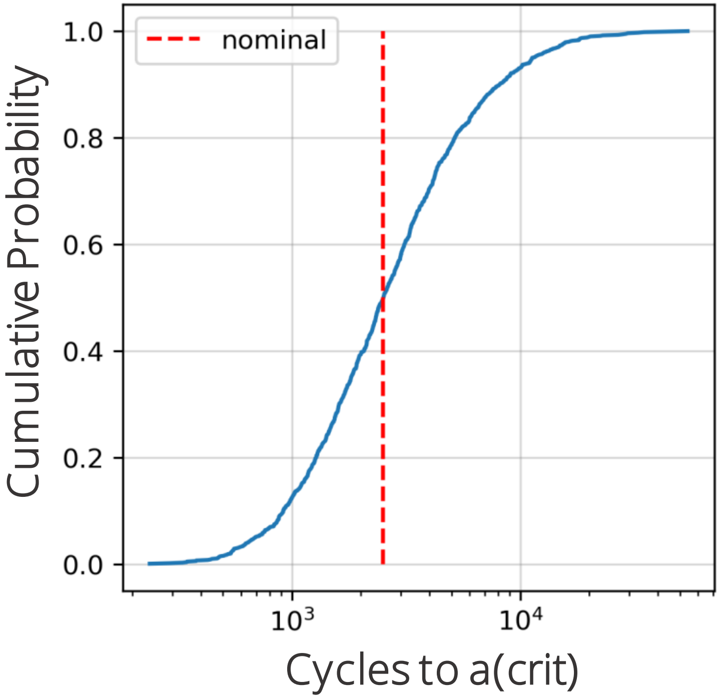


Figure: *Visualizing QoI variability as cumulative probability distribution*

Probabilistic Problem: Sensitivities

Table: Input parameters varied in sensitivity studies

Variable	Uncertainty Dist.	Nominal
Maximum pressure (psi)	N(850, 20)	850
Minimum pressure (psi)	N(638, 20)	638
Temperature (°K)	U(285, 300)	293
Initial flaw depth (a/t)	U(0.2, 0.3)	0.25
H_2 volume fraction*	U(0, 0.2)	0.1

*Added H_2 volume fraction to sensitivity study

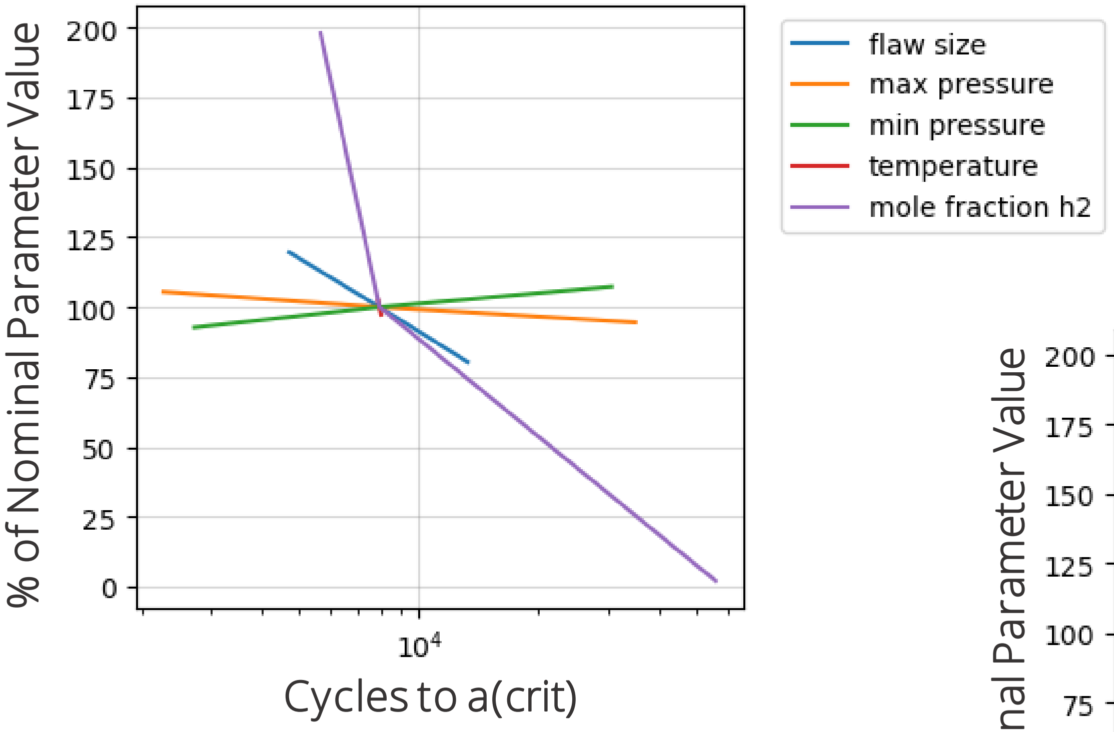


Figure: *Sensitivity study of variable bounds*

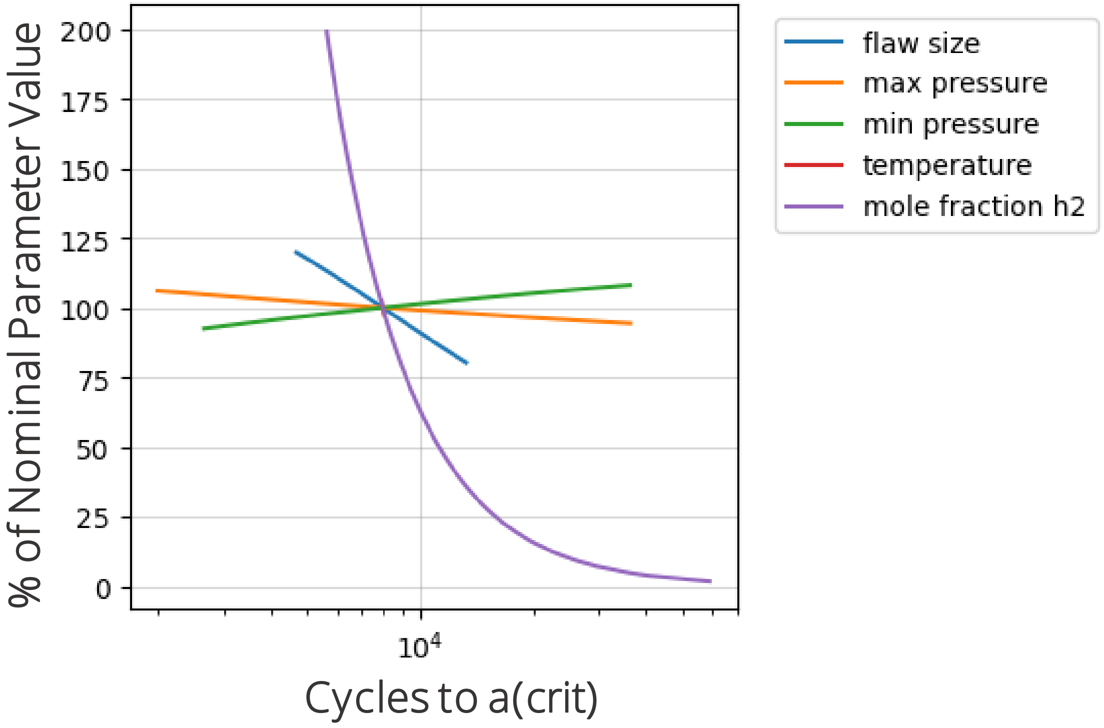


Figure: *Sensitivity study of uncertainty distributions*

Probabilistic Problem: Sensitivities

Table: Input parameters varied in sensitivity studies

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Maximum pressure (psi)	N(850, 20)	850
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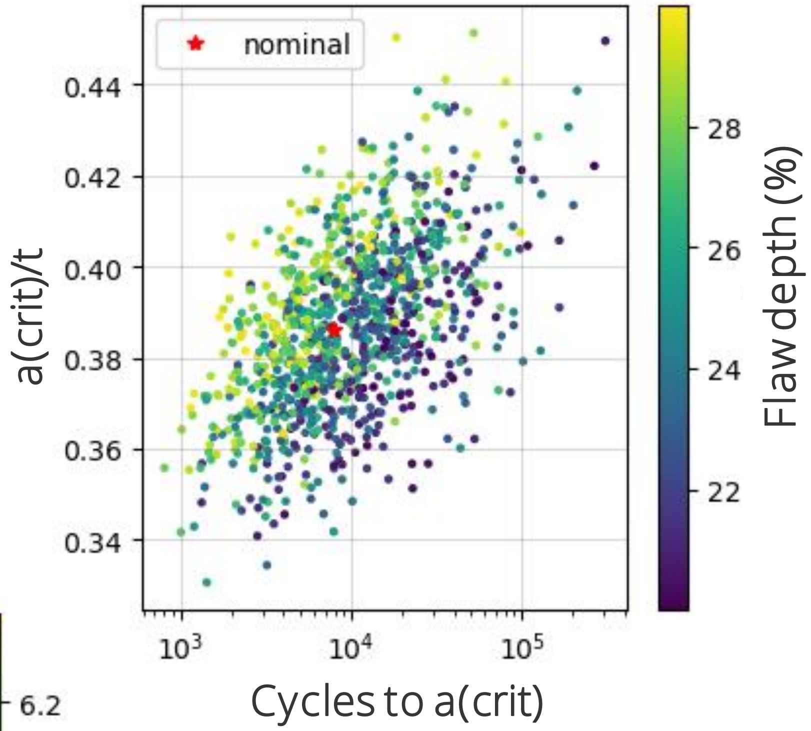


Figure: *QoI correlation to flaw depth*

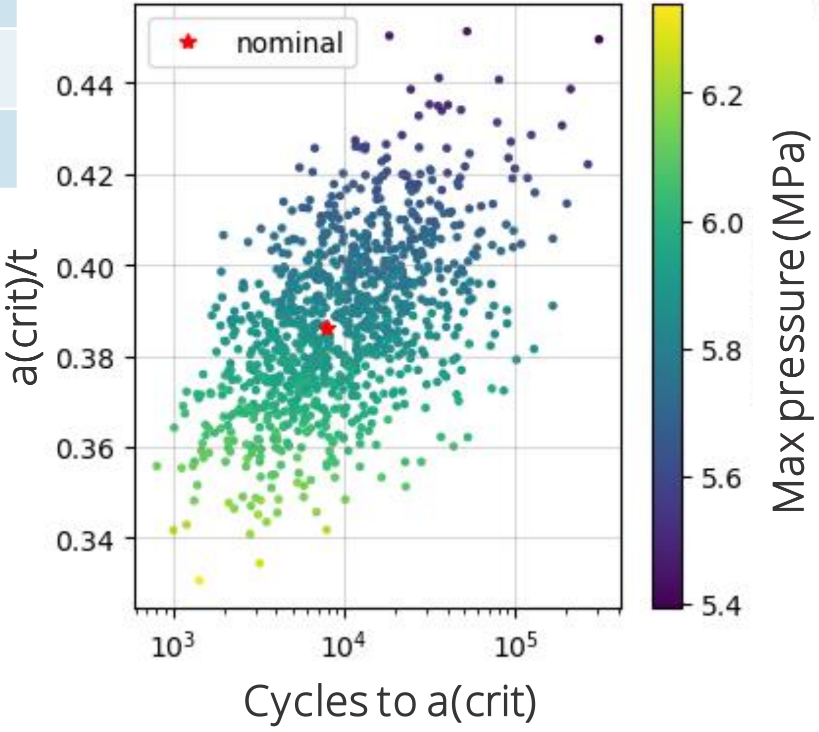
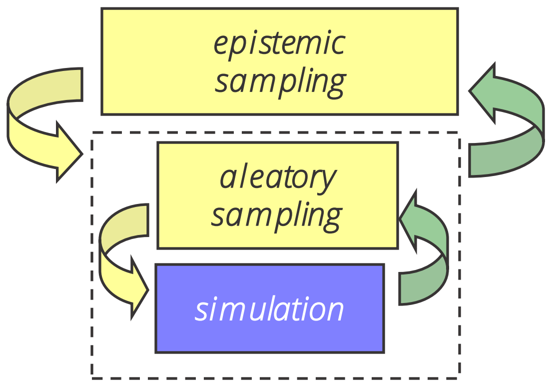


Figure: *QoI correlation to maximum pressure*

Probabilistic Problem Specification: Epistemic and Aleatory Variables

Table: Input parameters varied in sensitivity studies

Variable	Uncertainty Dist.	Nominal	Uncertainty Type
Maximum pressure (psi)	N(850, 20)	0.85	Aleatoric
Minimum pressure (psi)	N(638, 20)	0.638	Aleatoric
Temperature (K)	U(285, 300)	293	Aleatoric
Initial crack depth (a/t)	U(0.2, 0.3)	0.25	Aleatoric
Pipe outer diameter (in)	N(36, 0.005)	36	Epistemic
Pipe inner diameter (in)	N(35.188, 0.005)	35.118	Epistemic



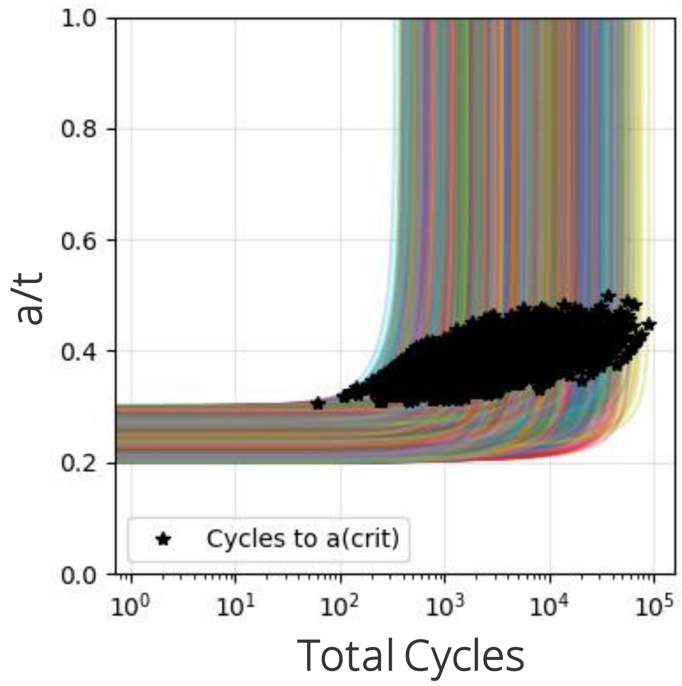


Figure: *Full ensemble QoI results*

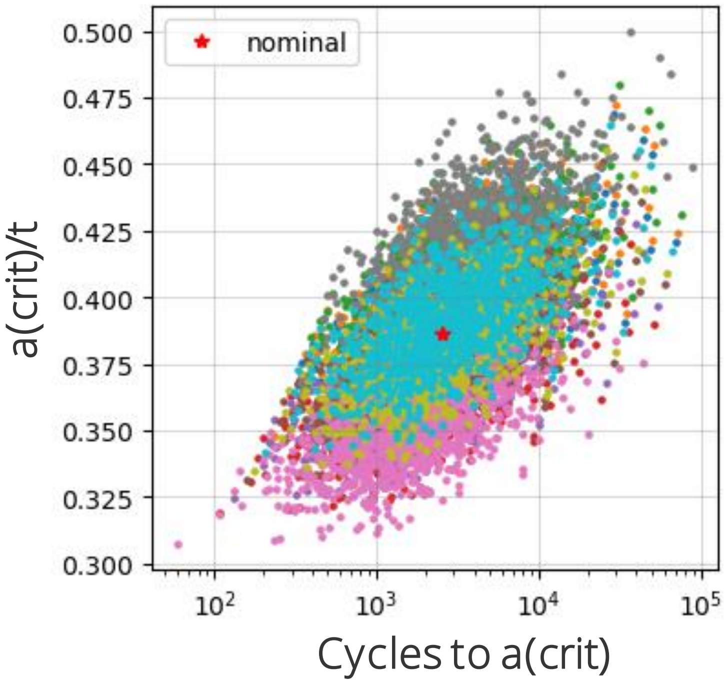


Figure: *QoI results colored by epistemic uncertain sample*

Probabilistic Problem Specification: Epistemic and Aleatory Variables

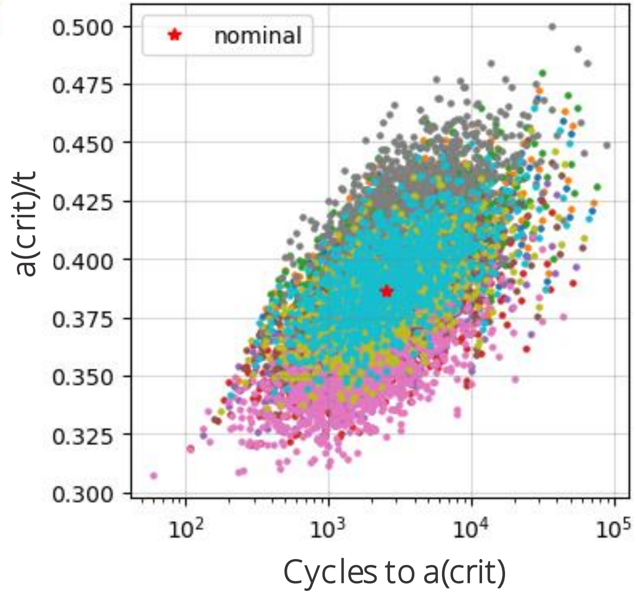


Figure: *QoI ensemble results colored by epistemic sample*

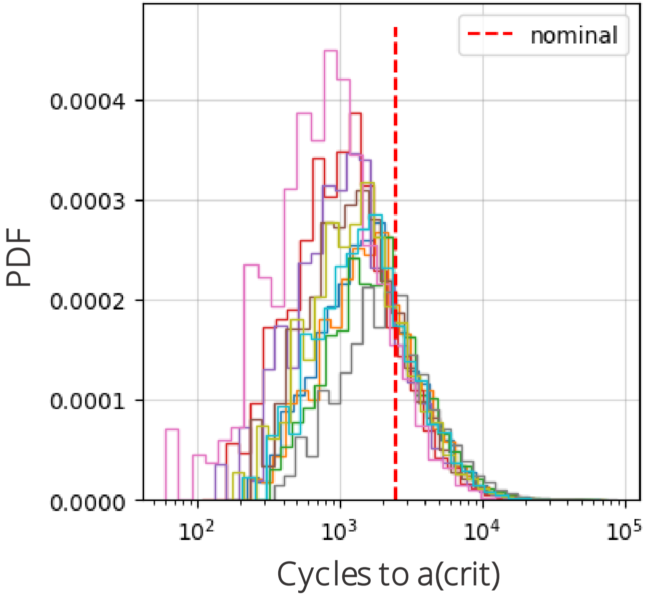


Figure: *QoI PDFs for each epistemic sample*

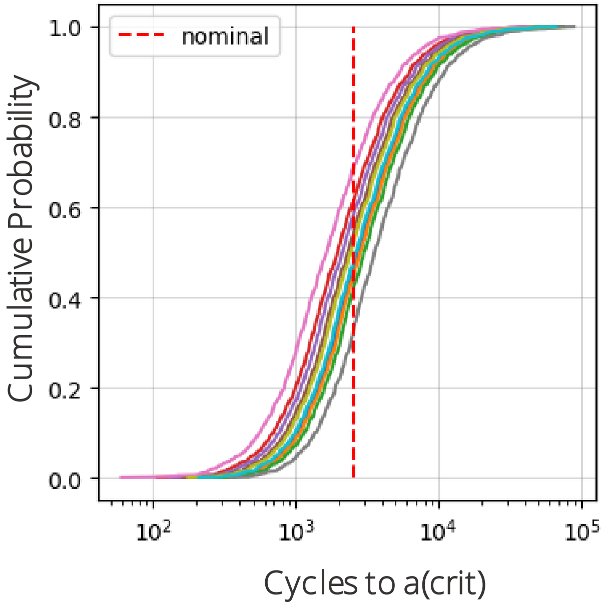
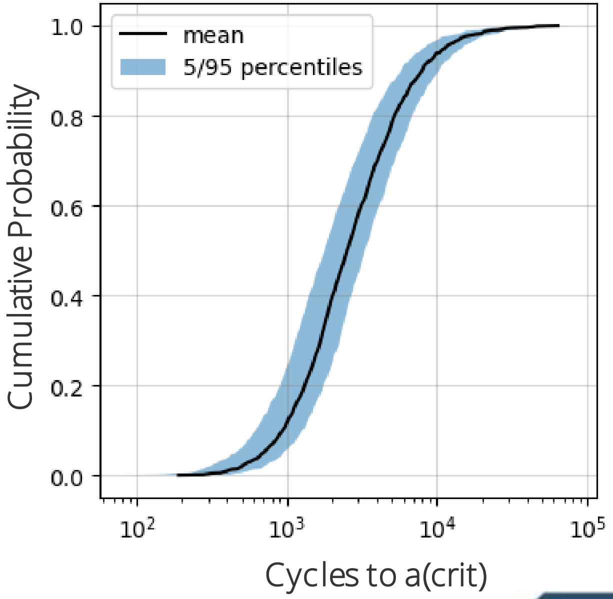


Figure: *QoI CDFs for each epistemic sample*

Figure: *Quantifying epistemic uncertainty as uncertainty range for CDF*



HELPR Credibility

Software Quality Practices

Test Based Development

Utilizing **unit tests** to monitor impact of developments on previously added capabilities

- Ensure all functionality produces expected type of output given type of input

Verification tests with specified error metrics to monitor performance during development

- Direct comparisons to "gold standard" calculations completed externally
- Error due to time stepping algorithm to be quantified

Validation tests (direct comparisons to experimental data) once data available

- Test validity of implemented physics models

Version Controlled Development

Developed using **Gitlab** repository

Continuous integration **(CI)** pipelines run **Pytest** of test database for every commit

Documentation

Automatic code documentation generation, **technical reference manual**, and **user guide** coming soon . . .

Next Steps & Summary

Next Steps

- Release HELPR with **GUI** compatible with **PC** and **Mac**
- Refine failure assessment (**FAD**) capability
  - **Fracture** aspect of the problem
- Support **temporally** varying pressure cycling
- Integrate **materials database** for specifying property defaults
- User guide, technical reference manual, and code **documentation**
- Expand K solution space

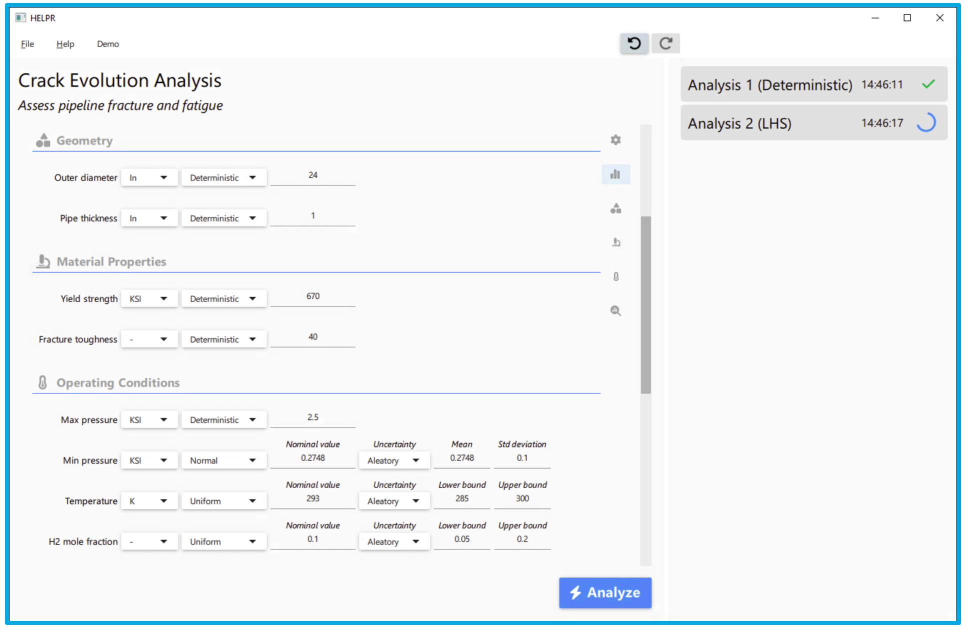


Figure: *Alpha development version of HELPR GUI*

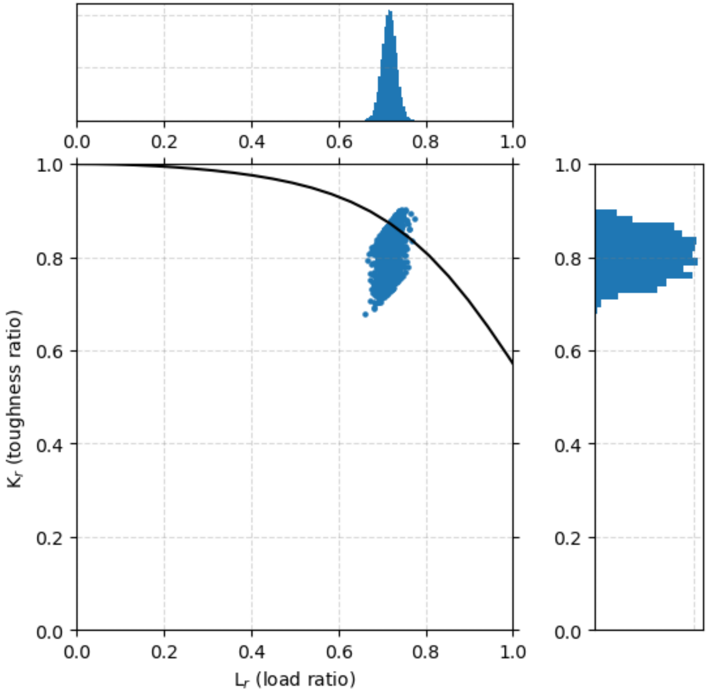


Figure: *Probabilistic failure assessment diagram results*

Summary

HELPR is a modular probabilistic fracture mechanics platform to assess structural integrity of natural gas infrastructure for transmission and distribution of hydrogen natural gas blends

- Fatigue calculations based on pressure-corrected ASME CC2938 design curves
- Probabilistic foundation quantifies variability and uncertainty, enabling informed decision making
- Establishing credibility foundation inherent part of development process
- PC and Mac compatible GUI in development to ensure accessibility

Questions / Comments

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