Sandia National Laboratories

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UTILIZING PROBABILISTIC ANALYSES TO EXPLORE PERFORMANCE MARGINS OF NATURAL GAS INFRASTRUCTURE FOR THE TRANSPORT AND DELIVERY OF HYDROGEN AND HYDROGEN BLENDS

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MOTIVATION

Transporting hydrogen or blended hydrogen in pipelines is being explored as a potential element of the future energy economy

Utilizing current natural gas pipelines is an attractive option but the impact of hydrogen embrittlement on pipeline structural integrity is not fully understood

Where the natural gas industry previously leveraged significant experience for their technical basis to shape operation and maintenance decisions, this is not yet available for hydrogen/hydrogen blends

Proposal: Utilize probabilistic fatigue and fracture models to assist in understanding hydrogen's impact on pipeline structural integrity
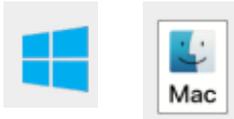
WHAT IS HELPR?

Hydrogen Extremely Low Probability of Rupture (HELPR) is a modular probabilistic fracture mechanics platform developed to assess structural integrity of natural gas infrastructure for transmission and distribution of hydrogen natural gas blends. HELPR contains fatigue and fracture engineering models allowing fast computations, while its probabilistic framework enables exploration and characterization of the sensitivity of predicted outcomes to uncertainties of the pipeline structure and operation.

Publicly available *(current version is v1.1.0)*

GUI Interface

Windows and Mac installers available

- https://helpr.sandia.gov

Open-source distribution

- https://github.com/sandialabs/helpr
- Sphinx documentation of code
  - https://sandialabs.github.io/helpr/

HELPR GUI Interface

Materials and Methods

HELPR's Technical Basis

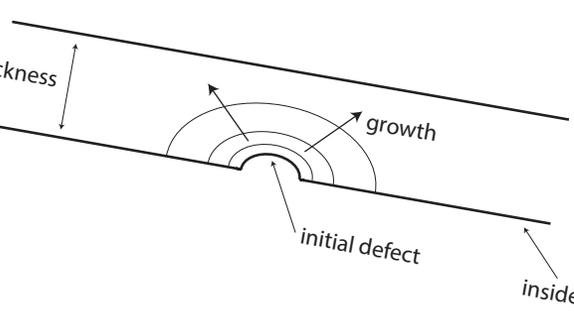Industry Motivated Scenarios

Sensitivity Studies and Probabilistic Analyses

Results

Deterministic Study
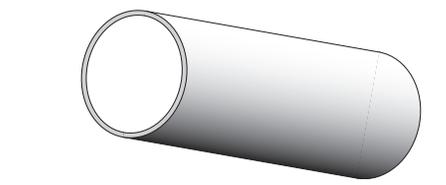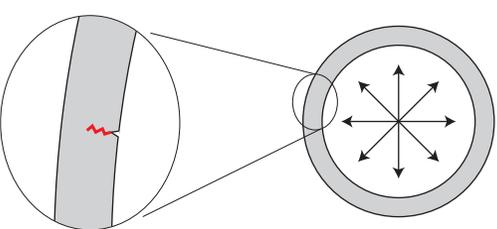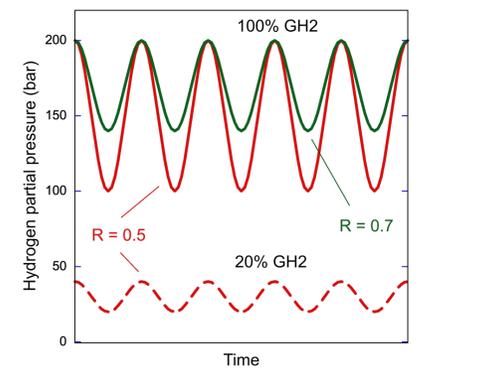
Sensitivity Study

Probabilistic Analysis

Summary

R = 0.5

R = 0.7

100% GH2

20% GH2

Accounts for hoop stress from cyclic internal pressure loading (*evolves in terms of pressure cycles*)

Uses stress intensity factor (K) solution for longitudinally-oriented, semi-elliptical *(thumbnail)* and infinite internal cracks to model stress state at crack tip *(from Anderson textbook v2)*

Fatigue crack growth rates calculated using ASME B31.12 Code Case 220 *(with additional term accounting for hydrogen partial pressure)*

Pre-existing cracks are assumed *(not initiated)* and depth/length ratio is assumed constant (a/2c)

Yield strength and fracture resistance are user inputs

thickness

growth

initial defect

inside surface

Crack Growth Rate Curves

Varying χ_{H_2}; R=0.75; P_{max}=850psi

- Exercised Rates (χ_{H_2}=0.1)
- χ_{H_2}=0
- χ_{H_2}=0.01
- χ_{H_2}=0.1
- χ_{H_2}=1

Air
8.5 psi H_2
85 psi H_2
850 psi H_2

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

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

g(P) is hydrogen partial pressure dependent term

Ref: San Marchi, SAND2023-00924O

MATERIALS AND METHODS: INDUSTRY MOTIVATED SCENARIOS

INDUSTRY MOTIVATED PIPELINE SECTIONS

Pipe Grade	Wall thickness, t (mm / inches)	MOP (MPa / psi)
X52	7.92 / 0.312	5.38 / 780
X70	8.74 / 0.344	5.38 / 780
X65	9.52 / 0.375	5.38 / 780
Grade B	9.52 / 0.375	4.48 / 650
X60	12.7 / 0.500	5.38 / 780
X52	22.2 / 0.875	5.38 / 780

*Yield strength assumed to be value after X, e.g., 52 ksi for X52, and 35 ksi for Grade B

+Grade B has lower MOP

Natural gas pipelines are composed of a variety pipe grades and wall thicknesses (t)

Pipe grade and wall thickness dictate level of stress in a pipe

Percentage of specified minimum yield strength (%SMYS) is a critical safety margin for a section of pipeline (dictated by governing body)

6 sections of pipeline from 58-mile segment of real world pipeline were selected for this work to illustrate variability within a pipeline

Constant 30" outer diameter (OD) assumed for all pipeline sections

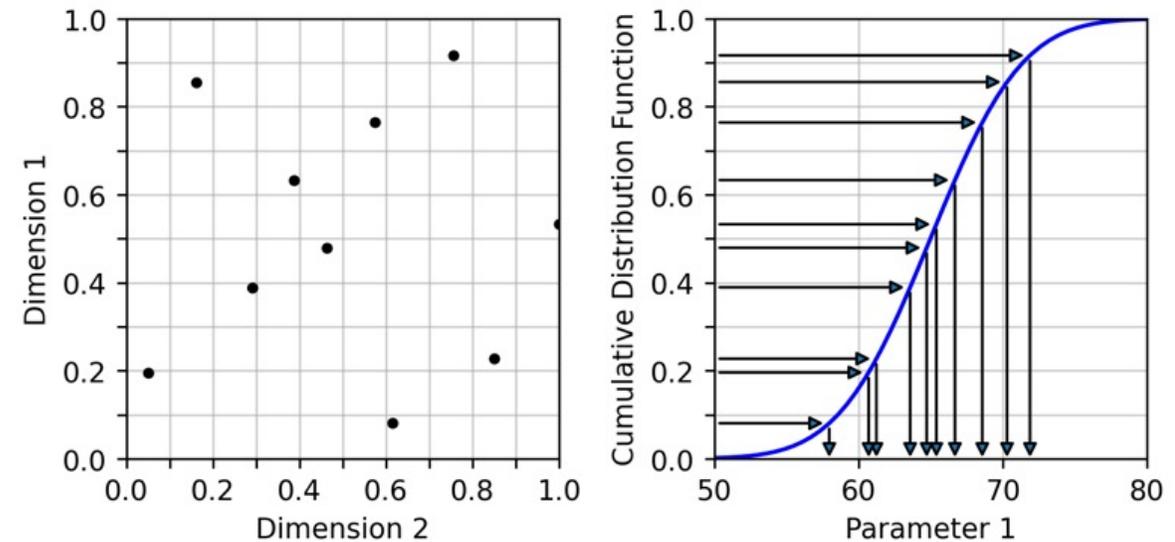# MATERIALS AND METHODS: SENSITIVITY STUDY AND PROBABILISTIC ANALYSES

Sensitivity study are used to understand the impact of individual input parameters when varied within realistic ranges *(varied one at a time)*

- H_2 partial pressure
- Initial flaw depth
- Maximum pressure
- Minimum pressure
- Temperature
- Fracture toughness

Probabilistic analysis will use Latin hypercube sampling (LHS) of input parameter uncertainty distributions, propagated through the deterministic fatigue and fracture calculations

- Stratified Monte Carlo sampling for better coverage of probability space
- Same parameters as explored in sensitivity study

Illustration of Latin hypercube sampling (LHS)

MATERIALS AND METHODS: PARAMETER SUMMARY

Values, Ranges, and Distributions Used in Analyses

Property	Nominal values	Sensitivity studies	Probability analysis	Modified flaw uncertainty	Modified minimum pressure uncertainty
Maximum pressure (MPa)	5.38	3.48, 4.14, 4.48, 4.83, 5.38	5.38	5.38	5.38
Minimum pressure (MPa)	4.44	3.76, 4.30, 4.84, 5.11, 5.27	U(4.11, 4.88)	U(4.11, 4.88)	U(4.58 , 4.88)
Initial flaw depth (%)	25	1, 5, 25, 30, 40	U(5, 30)	U(5, 20)	U(5, 30)
Initial flaw length (mm)	19.8	19.8♦	U(19.8, 198)	U(19.8, 198)	U(19.8, 198)
Volume fraction H_2 (%)	100	0, 1, 5, 20, 100	100	100	100
Temperature (^{o}K)	294	278, 285, 293, 315, 322	U(278, 322)	U(278, 322)	U(278, 322)
Fracture Resistance (MPa m$^{1/2}$)	55	55, 60, 65, 70, 75	U(55, 75)	U(55, 75)	U(55, 75)

* U(min, max)

♦ modified to maintain flaw length / flaw depth ratio = 10 for flaw depth sensitivity study

RESULTS: DETERMINISTIC STUDY

Deterministic evaluations for each pipeline section using nominal input parameter values
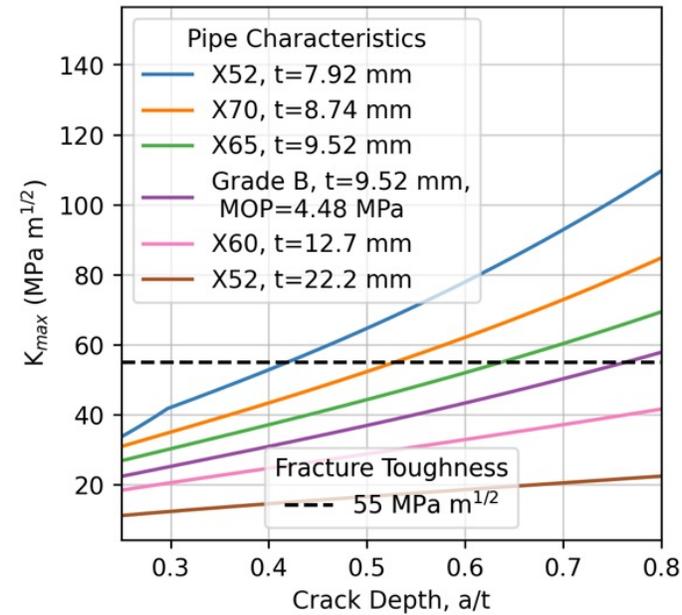
Wide range of stress cycles to failure observed

- *Failure considered when K solution equal to fracture toughness*
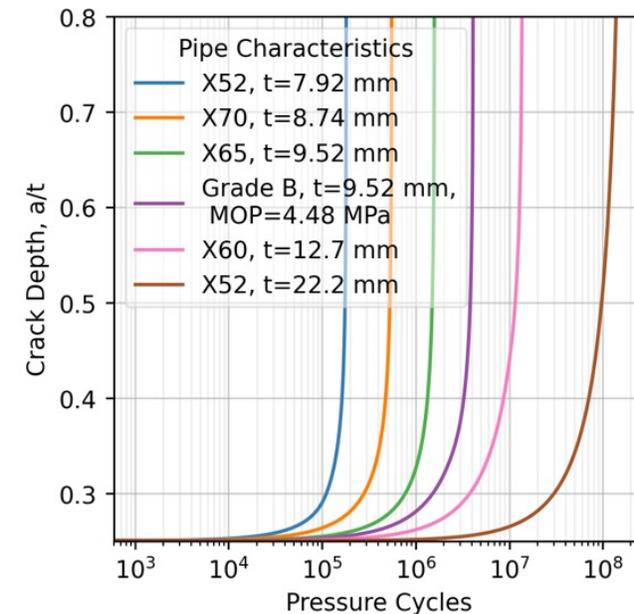- *Critical crack depth a_{crit}*

Assuming a fracture toughness of 55 MPa m$^{1/2}$ for use with hydrogen based on ASME B31.12

- *100 MPa m$^{1/2}$ assumed otherwise*

Nominal Stress Intensity Factor Values for Pipe Sections

Nominal Crack Growth Evolutions for Pipe Sections

RESULTS: SENSITIVITY STUDY

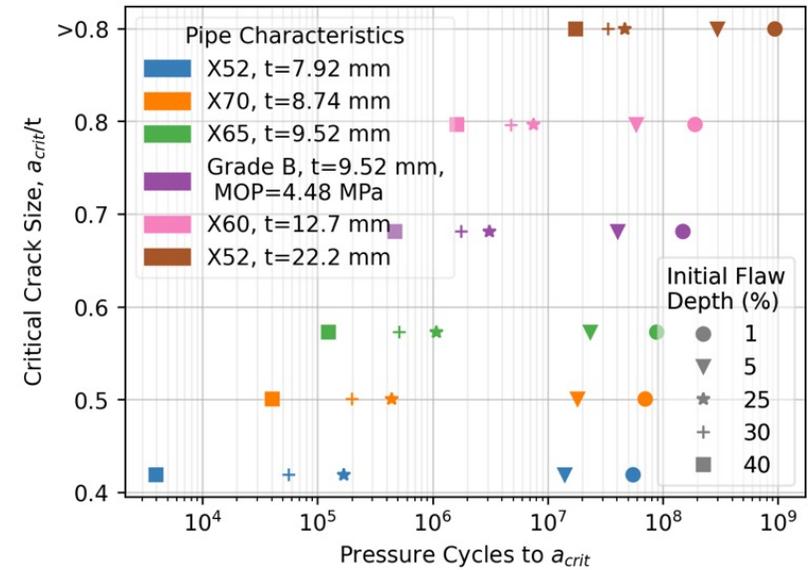Sensitivity studies completed for user input parameters

- *Parameters at nominal values when not varied in study*

Cycles to failure varied over many orders of magnitude for individual pipeline sections
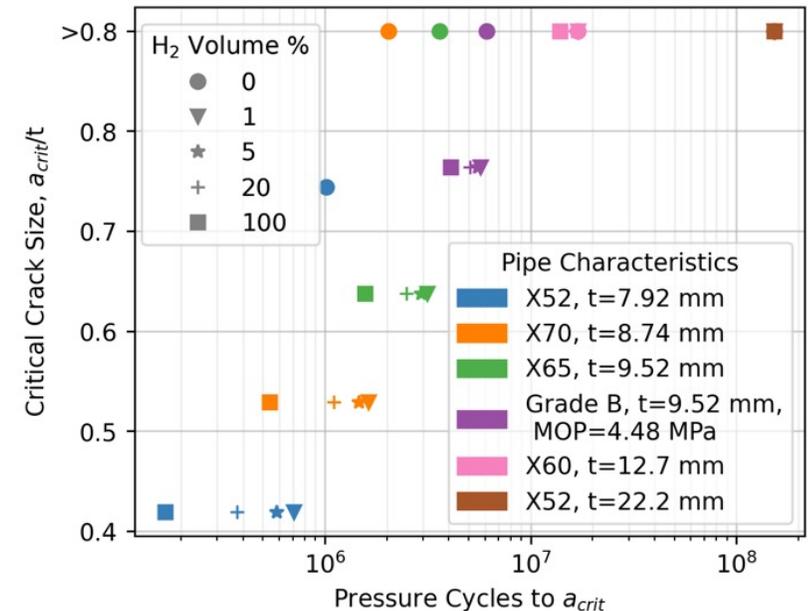
Critical crack size, a_{crit} *(when stress intensity factor = fracture resistance)* varied from ~40% wall thickness to 80% (max considered) across pipeline sections

Deeper initial flaws or higher H_2 volume % results in fewer cycles to failure

Sensitivity Study of Initial Flaw Depth

Sensitivity Study of H2 Volume %

* 0% H2 uses fracture resistance of 100 MPa $m^{1/2}$

Can distill sensitivity results for each pipeline section

- Showing results for X52, t=7.92 mm which nominally had fewest cycles to failure
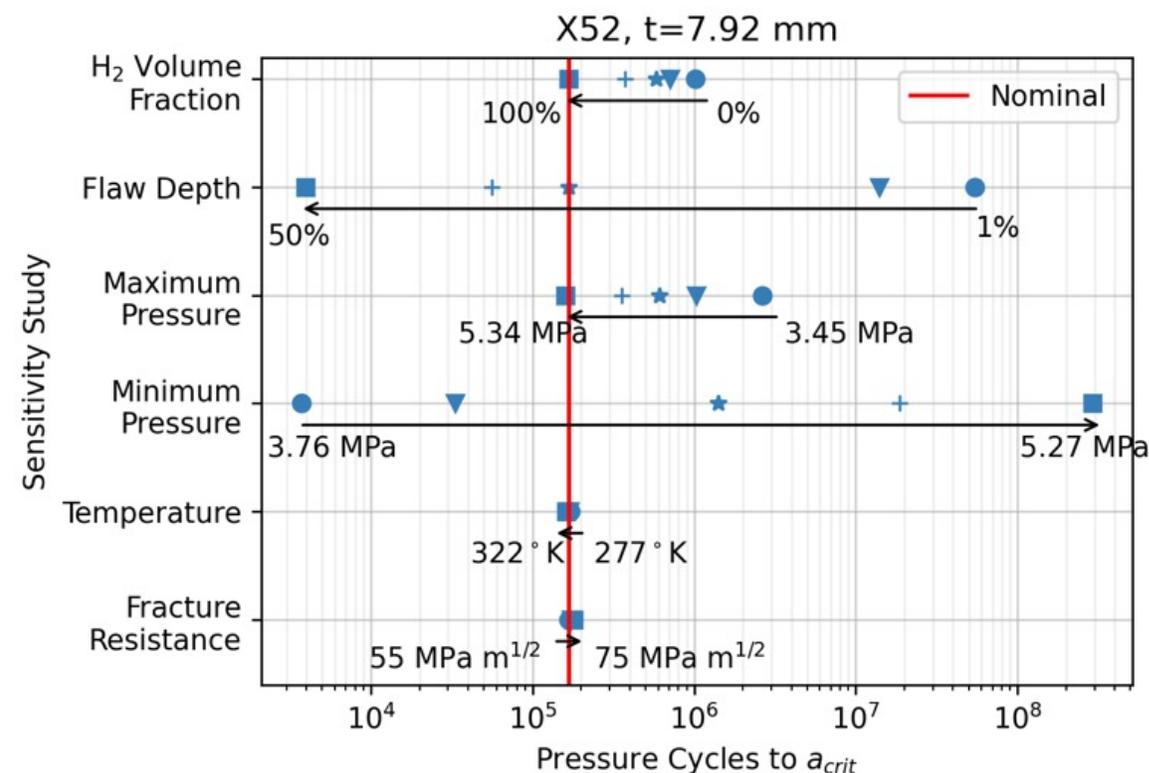
Varying minimum pressure and initial flaw depth *(within ranges considered)* resulted in widest variability in terms of pressure cycles to failure

Temperature had negligible impact *(only impacts hydrogen partial pressure)*

Fracture resistance impacts critical crack size, but this does not translate to a significant impact on cycles to failure

- Exponential nature of crack growth

Summation of Sensitivity Study for X52, t=7.92 mm

*Arrows show correlation direction
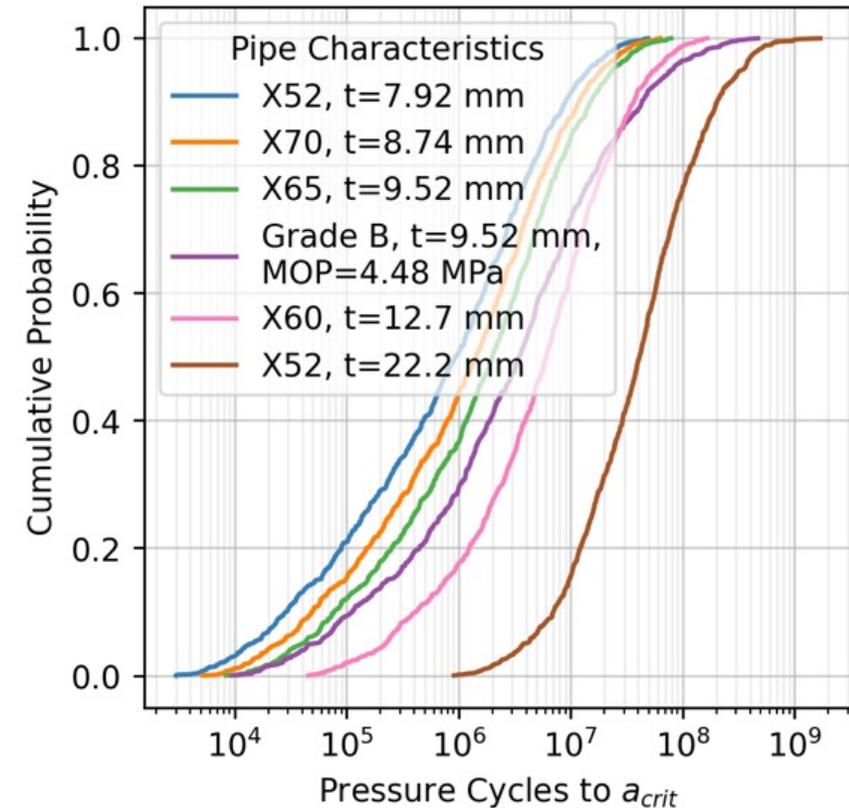
RESULTS: PROBABILISTIC ANALYSIS

1,000 LHS samples of parameter uncertainties propagated through model for each pipeline section

Similar shaped distributions between pipeline sections except for Grade B section with lower MOP

Variability prescribed to input parameters results in almost 4 orders of magnitude variability in the number of pressure cycles to failure
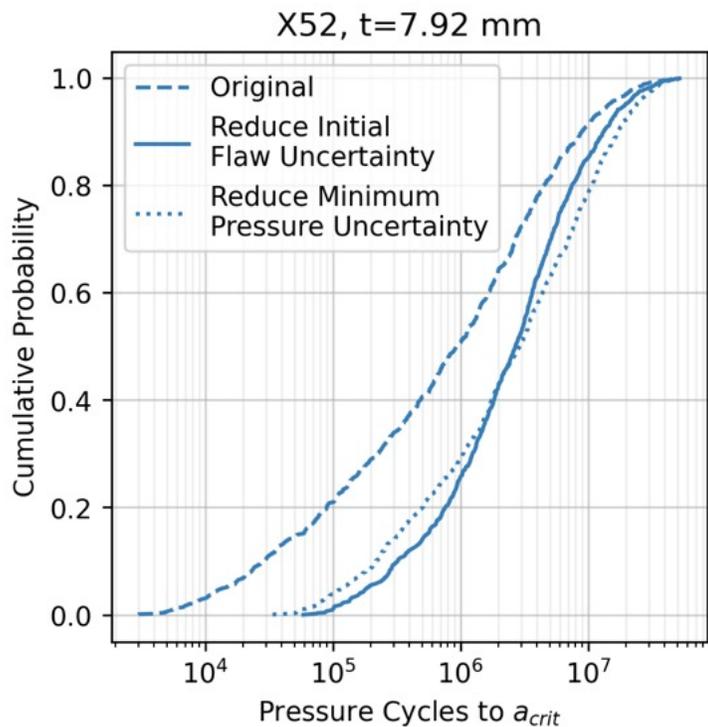
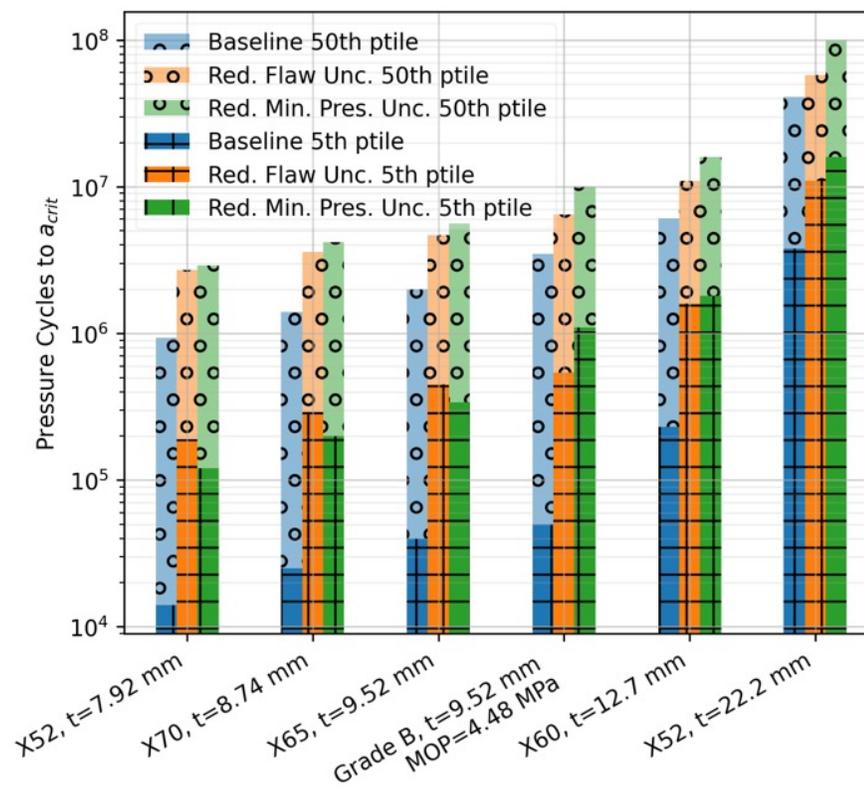Probabilistic Predictions of Pipeline Lifetime

Given significant variability in lifetime predictions, can considering impact of reducing uncertainty sources

- Upper bound of initial flaw uncertainty reduced from 30% wall thickness to 20% (*improved inspection*)

- Lower bound of minimum pressure uncertainty increased from 4.11 MPa to 4.58 MPa (*change in operation*)

Can quantify impact of uncertainty reductions through comparing 5th (*rare*) and 50th (*mean*) percentiles of distributions

Which change has the largest impact depends on the pipeline section and percentile considered

RESULTS: PROBABILISTIC ANALYSIS

Probabilistic results can be used for margin assessments when compared to a requirement
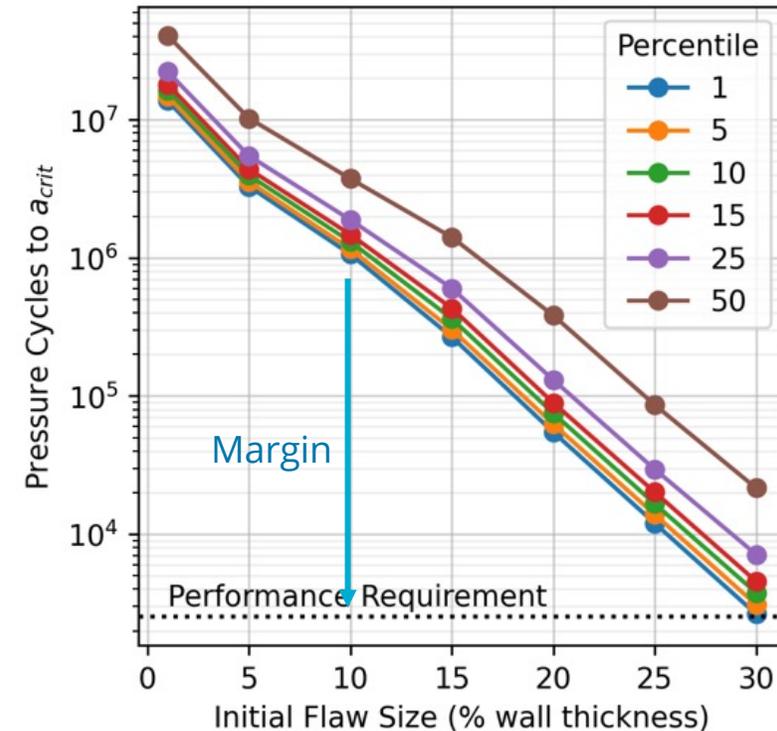
- 7 year inspection requirement is assumed

Percentiles for probabilistic study using X52, t=7.92 shown

- Same as previous study except repeated over a range of fixed initial flaw sizes

For smaller initial flaw sizes significant margin exists for all percentiles consider

For larger flaw sizes margin there is minimal margin for most conservative percentiles 1st and 5th

Performance Margin Estimates for X52, t=7.92

CONCLUSIONS

Deterministic and probabilistic capabilities can aid in developing an understanding of the structural integrity impacts of blending hydrogen into natural gas pipelines

Sensitivity studies can be used to determine the relative impact of uncertainty sources on pipeline lifetime predictions

Probabilistic analyses can help quantify uncertain in performance margin predictions

Such additional information can be leveraged for decision making when lacking historical experience for technical basis

QUESTIONS?

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