Uncertainty Propagation by Nested and Non-Nested Sampling in Probabilistic Fitness-For-Service Evaluations of Pressure Tubes in CANDU Reactors

Chris Manu and Leonid Gutkin

Kinectrics Inc.
Toronto, Ontario, Canada

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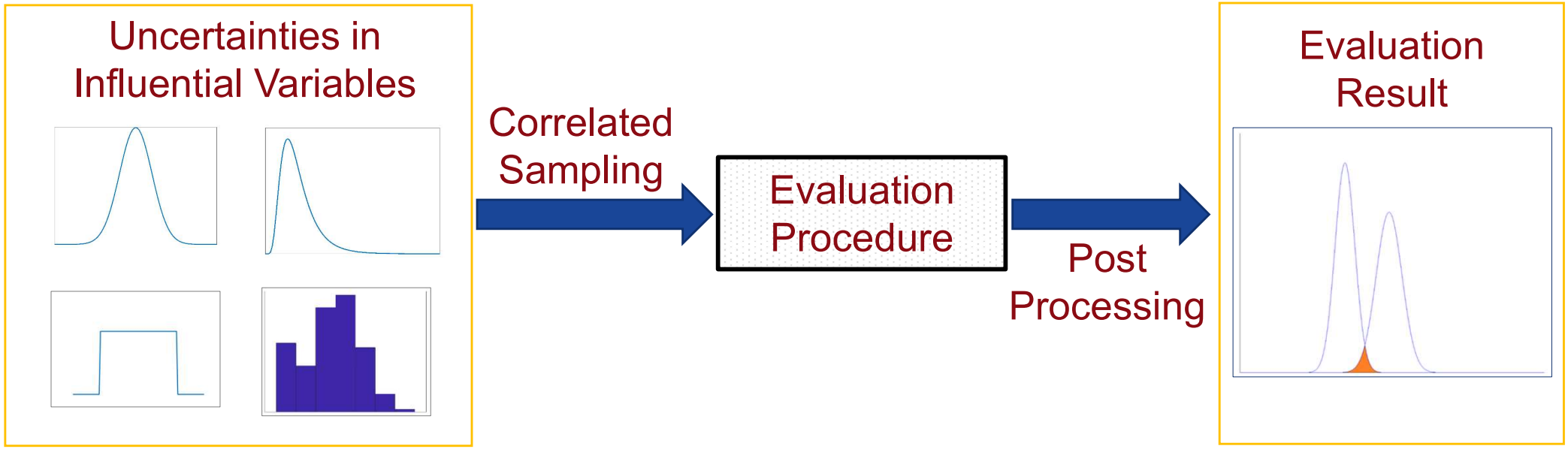
Introduction

- CSA N285.8 is a Canadian nuclear standard that specifies the technical requirements for the owner/operator to evaluate cold-worked Zr-2.5%Nb alloy pressure tubes in CANDU reactors for continued operation.
- An informative Annex to CSA N285.8 was developed to provide guidelines for performing uncertainty analysis in probabilistic evaluations relevant to the scope of the Standard.
- The Annex does not provide guidance regarding use of either nested or non-nested sampling for the propagation of uncertainties.
  - Non-nested sampling has traditionally been used.
- A pilot study on application of nested sampling to uncertainty propagation in pressure tube fitness-for-service evaluations has been performed.

CSA Standard N285.8 Annex on Uncertainty Analysis

- CSA N285.8 methodology for performing uncertainty analysis
  - Identification of influential variables
  - Characterization of uncertainties
  - Characterization of statistical correlations
  - Propagation of uncertainties
  - ➢ No provisions with respect to using nested or non-nested sampling



CSA Standard N285.8 Annex on Uncertainty Analysis

Uncertainty components in model response

Variable type	Best estimate obtained using	Uncertainty component	
Type A	Parametric model *"mechanistic models"*	$U^{(p)}$	Parametric uncertainty
		$U^{(n)}$	Uncertainty in numerical representation
Type B	Statistical model *"empirical models"*	$U^{(r)}$	Residual uncertainty
		$U^{(d)}$	Uncertainty due to limitations in model-basis data sets

No guidance is provided for characterizing model form uncertainty. Research and development work is still on-going to establish approach(es) to characterizing this uncertainty component.

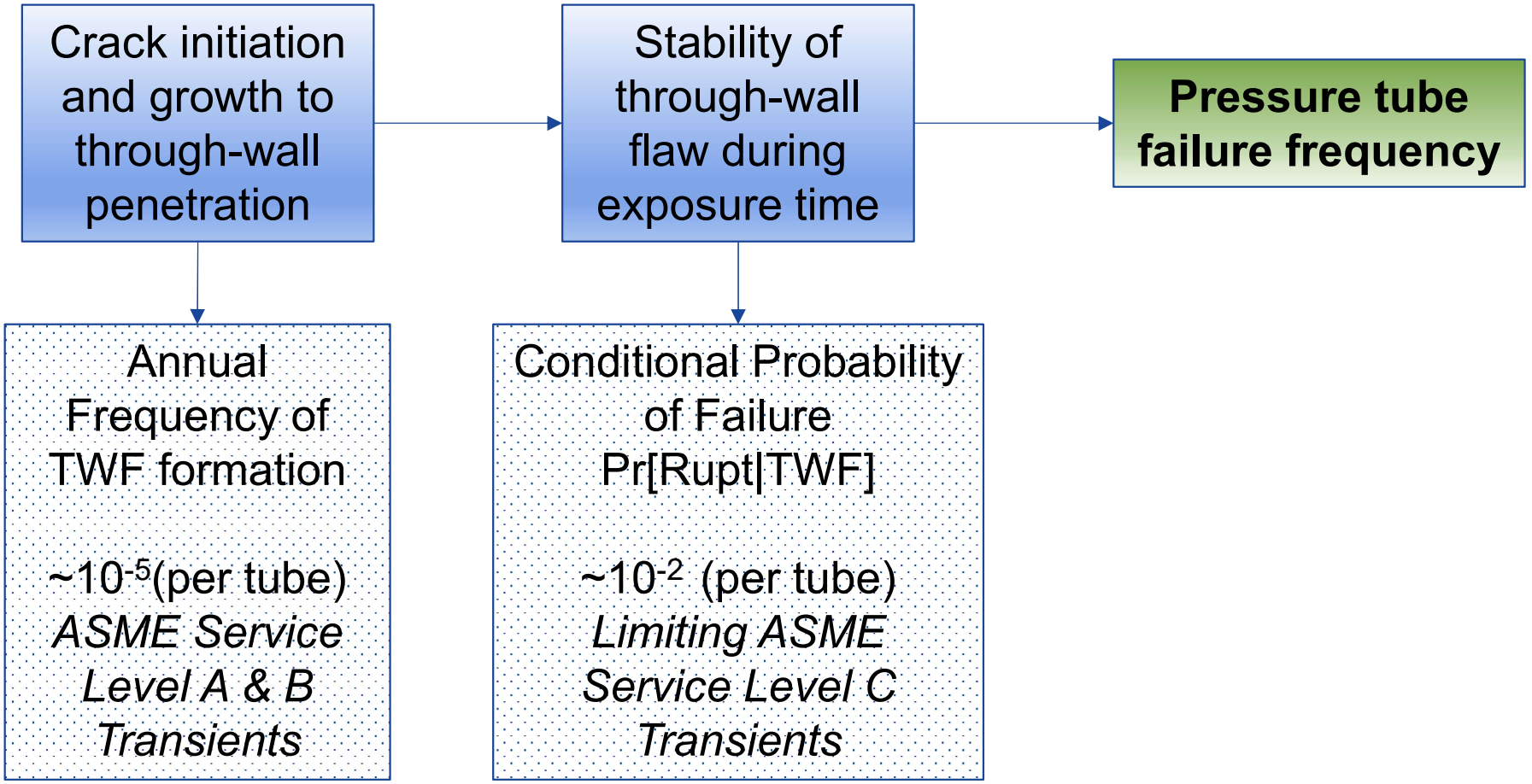
Pilot Study on Nested Sampling Uncertainty Propagation

Scope & Objectives

- Pilot study on application of nested sampling to uncertainty propagation
  - Portion of probabilistic evaluation of pressure tube fracture protection where a through-wall flaw is postulated to exist
  - The result of this portion of the evaluation is the conditional probability of failure given the existence of a through-wall flaw
- The objectives were:
  - Investigate impact of nested sampling on computer code performance
  - Investigate impact of nested sampling on evaluation outcome

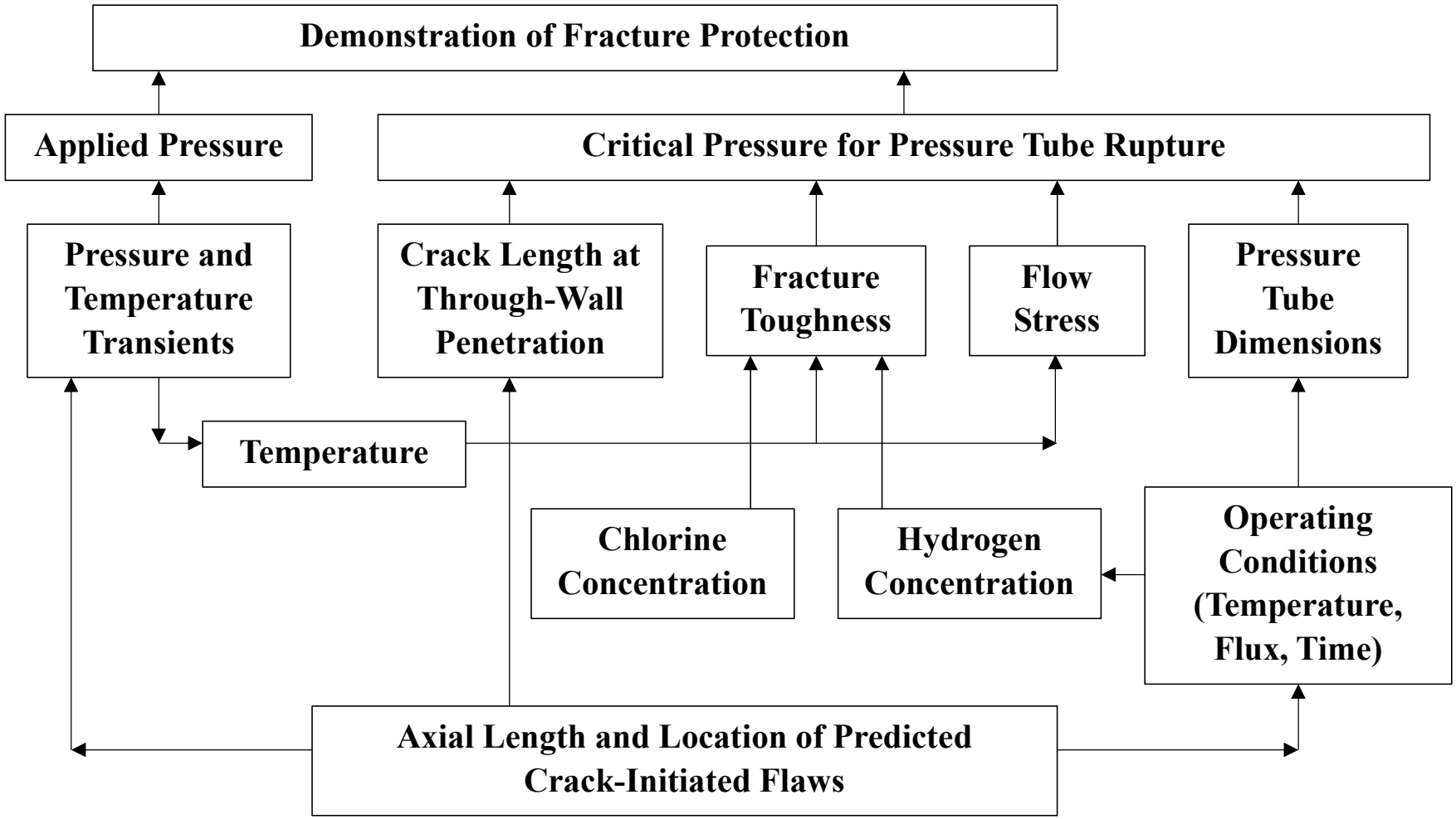
Pilot Study on Nested Sampling Uncertainty Propagation

Probabilistic Fracture Protection Evaluation



Pilot Study on Nested Sampling Uncertainty Propagation

Probabilistic Fracture Protection Evaluation



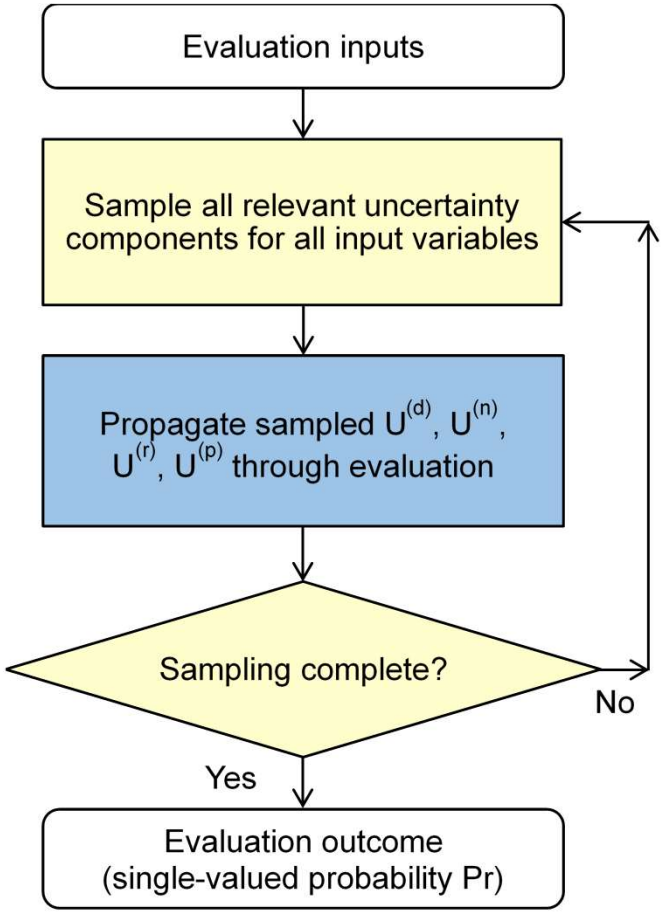
Pilot Study on Nested Sampling Uncertainty Propagation

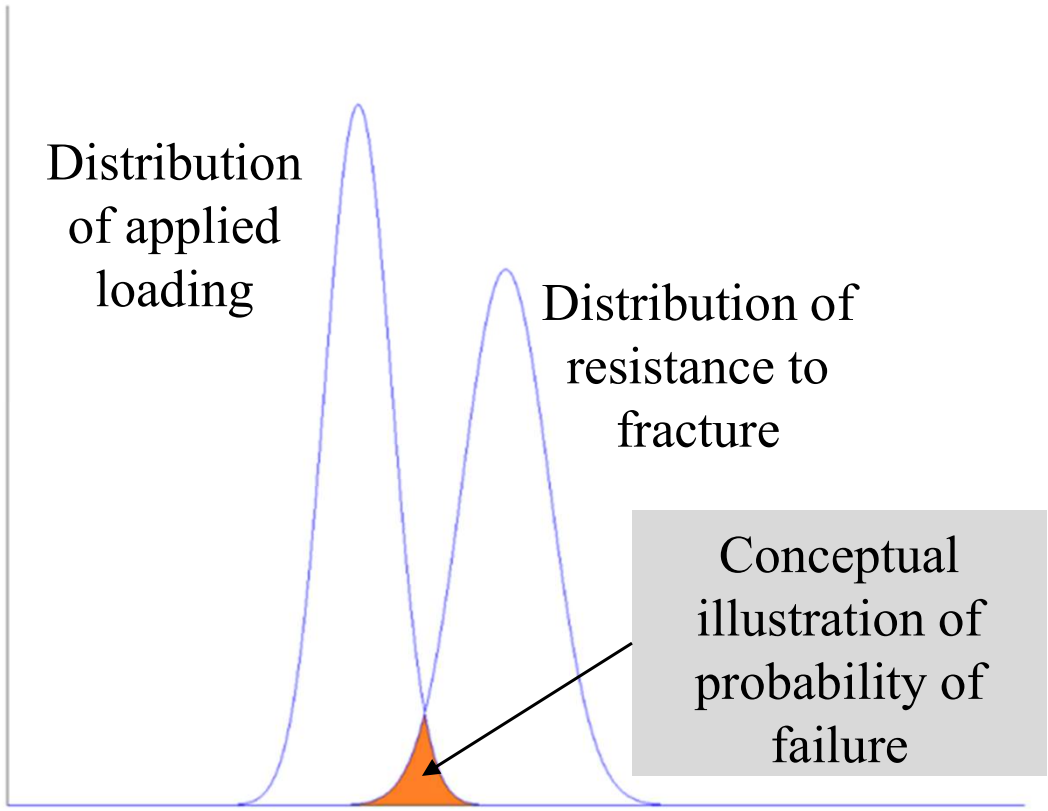
Methodology

- Uncertainties in input variables were first propagated using non-nested sampling (traditional approach)
  - All uncertainty components were propagated together in a single loop
  - Conditional probability of pressure tube rupture obtained as a single-valued quantity
  - Approximately 55,000 simulations were performed using random sampling

Pilot Study on Nested Sampling Uncertainty Propagation

Methodology





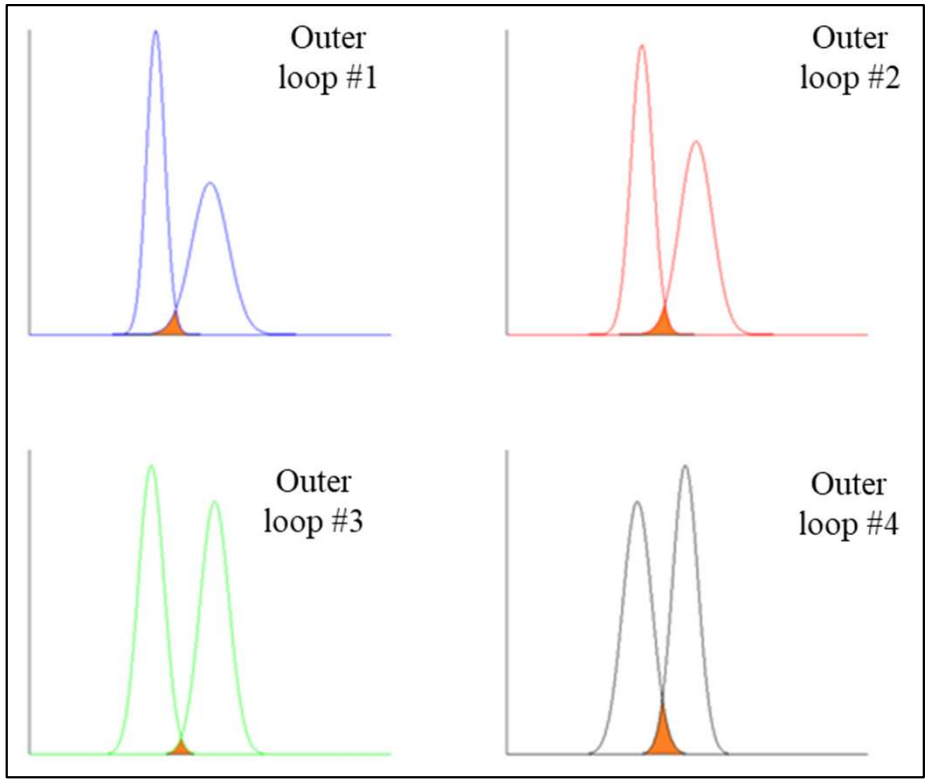
Pilot Study on Nested Sampling Uncertainty Propagation

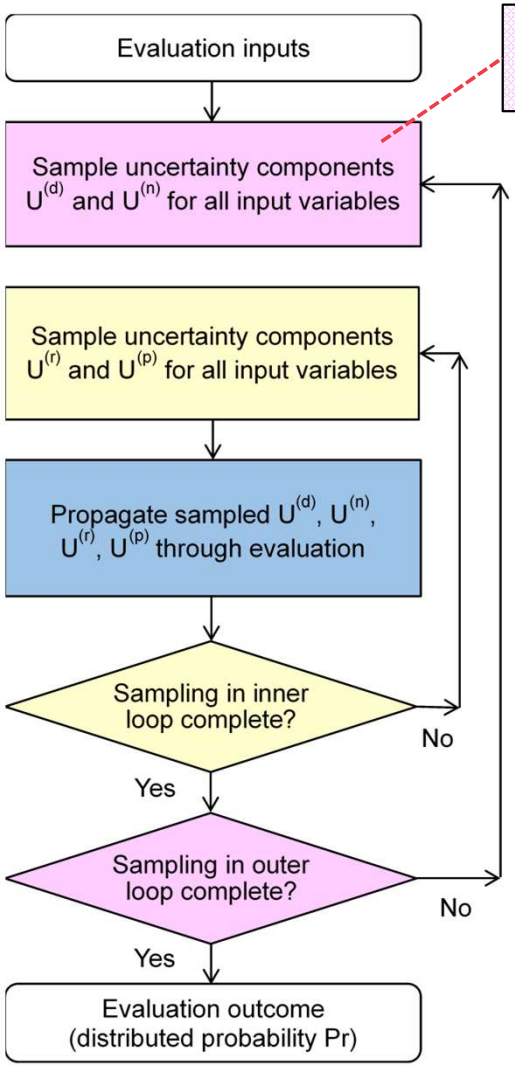
Methodology

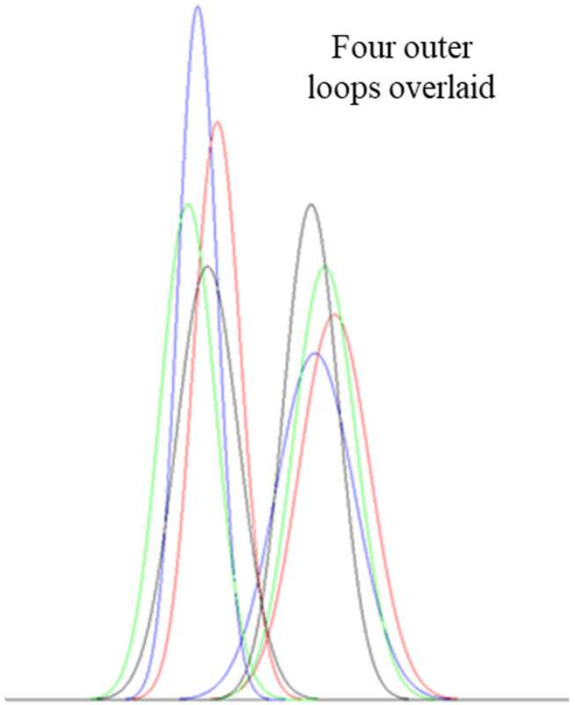
- Uncertainties in input variables were next propagated using nested sampling
  - Uncertainty components were segregated between an inner loop and an outer loop
  - Uncertainty components that are predominantly epistemic in nature were placed in the outer loop (as is commonly done in nested sampling).
  - Conditional probability of pressure tube rupture obtained as a distributed quantity
  - Approximately 55,000 simulations were performed using random sampling for the inner loop
  - 1,000 simulations were performed using random sampling for the outer loop

Pilot Study on Nested Sampling Uncertainty Propagation

Methodology







Pilot Study on Nested Sampling Uncertainty Propagation

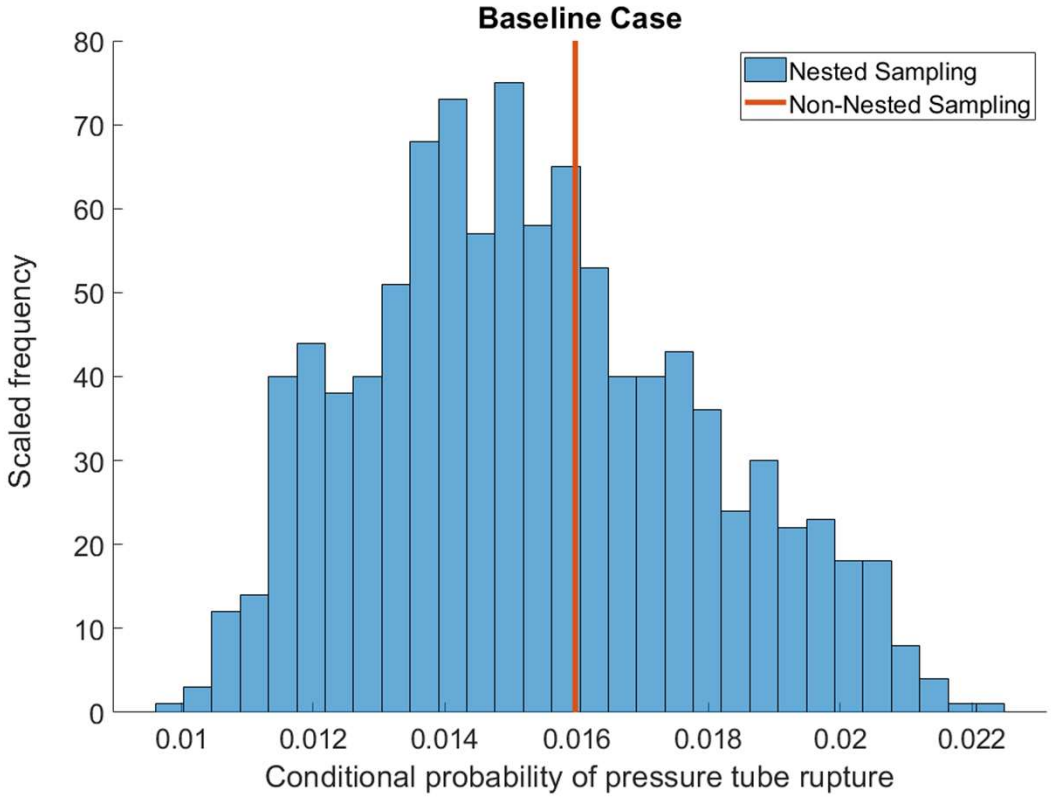
Methodology

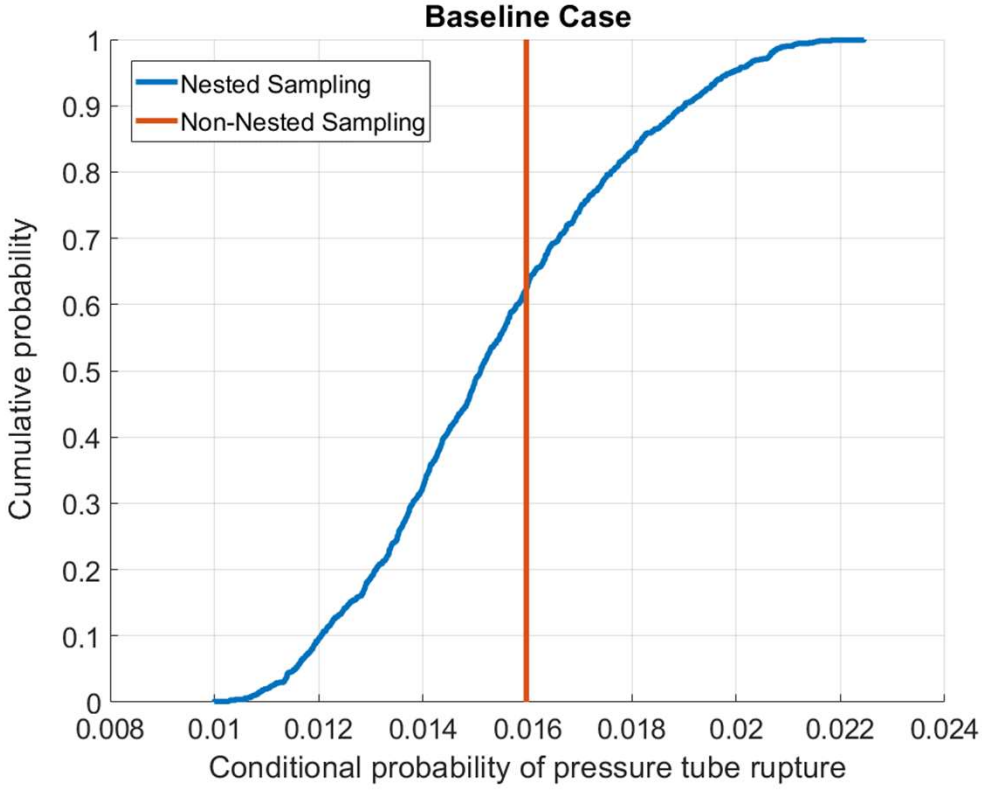
- Two evaluation streams were considered, baseline and extended
- In the baseline evaluation case, uncertainty components were adopted from relevant predictive models and previous work on uncertainty characterization
- In the extended evaluation cases:
  - Uncertainty components in the inner loop were the same as in baseline case
  - Uncertainty components in the outer loop were postulated such that results of the pilot study would be applicable to a range of possible uncertainty characterizations

Pilot Study on Nested Sampling Uncertainty Propagation

Results

Limiting Channel, Service Level C Loadings



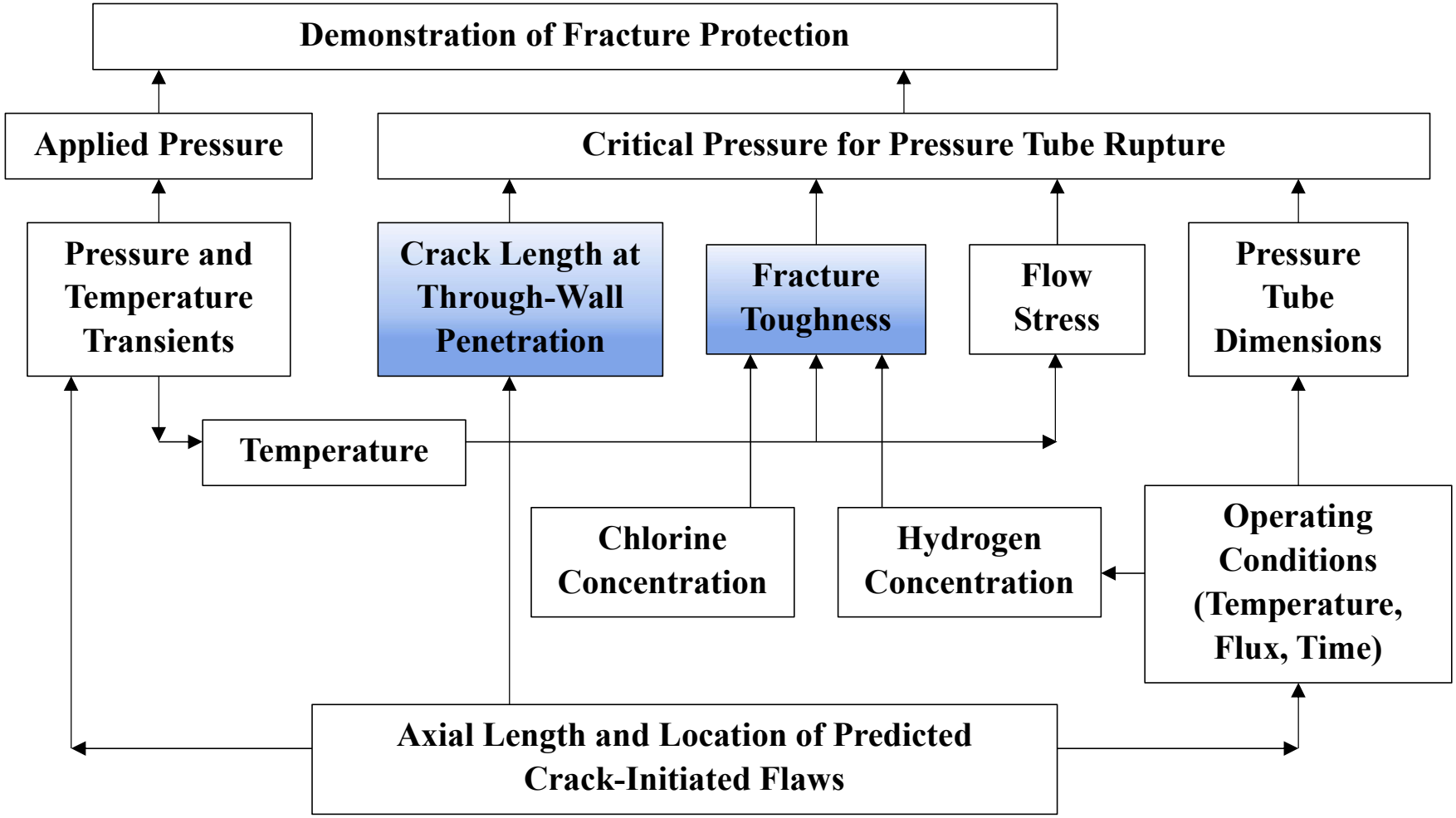


Pr_{NN}	$Pr_{IO}(50\%)$	$Pr_{IO}(95\%)$	$Pr_{IO}(97.5\%)$	Q_{NN}	$\frac{Pr_{IO}(50\%)}{Pr_{NN}}$	$\frac{Pr_{IO}(95\%)}{Pr_{NN}}$	$\frac{Pr_{IO}(97.5\%)}{Pr_{NN}}$
0.01598	0.01510	0.01989	0.02064	61%	0.95	1.24	1.29

Pilot Study on Nested Sampling Uncertainty Propagation

Results

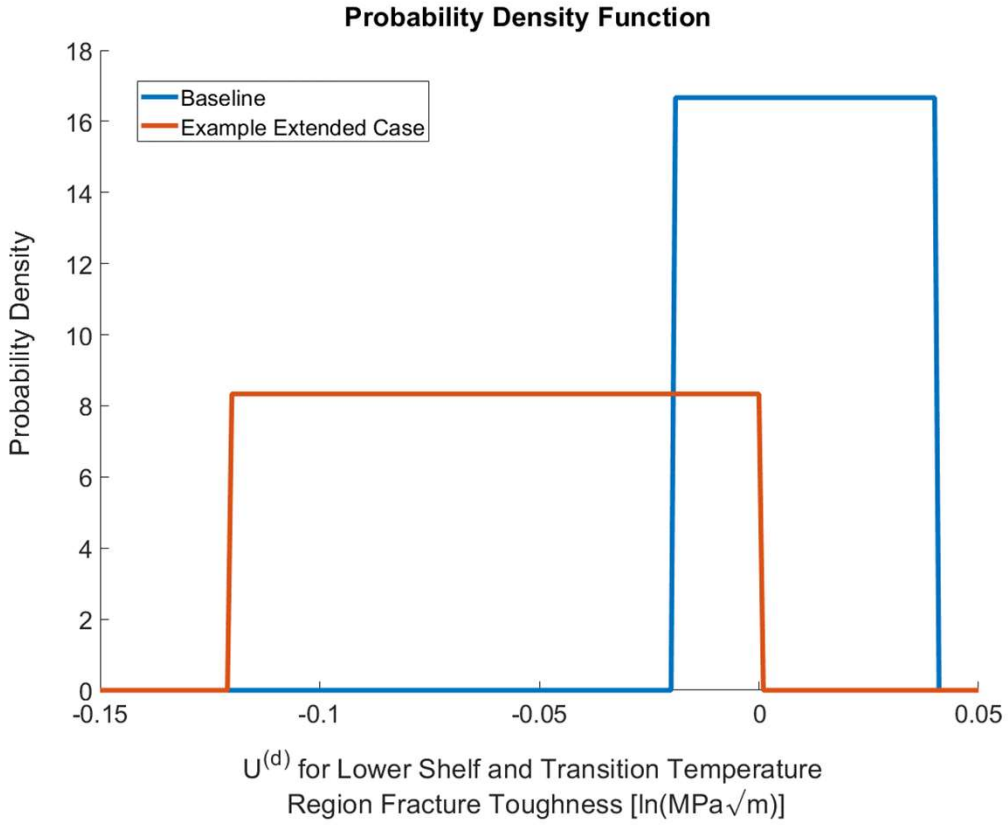
Defining the Example Extended Case

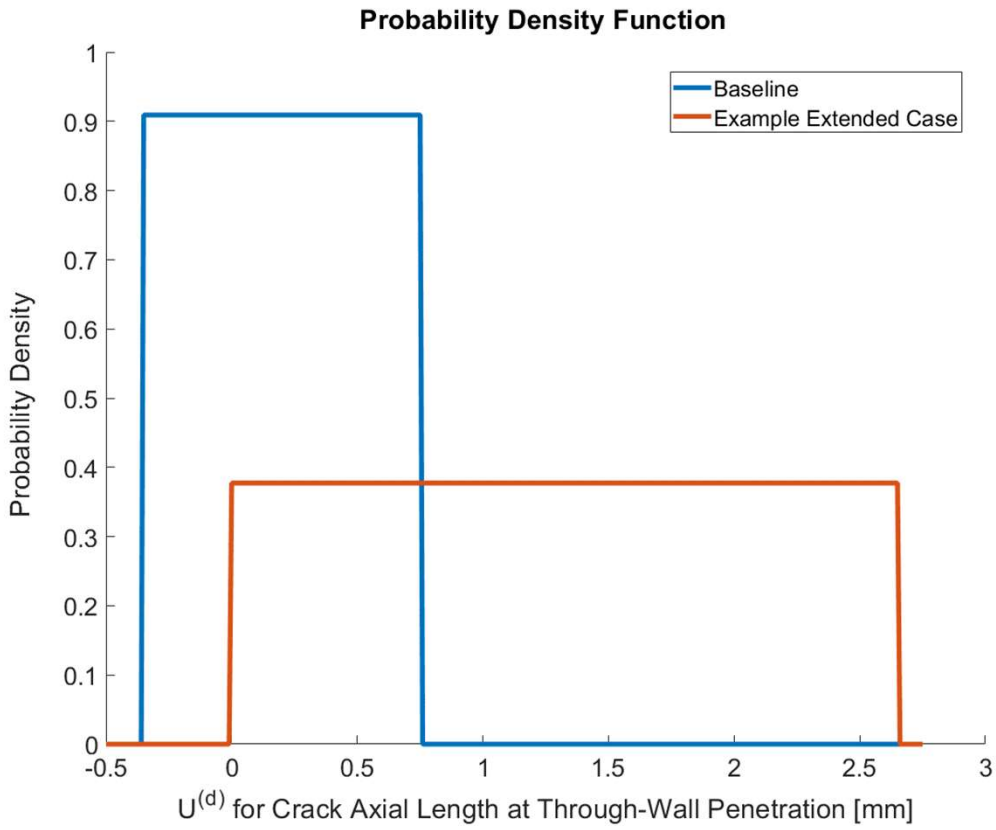


Pilot Study on Nested Sampling Uncertainty Propagation

Results

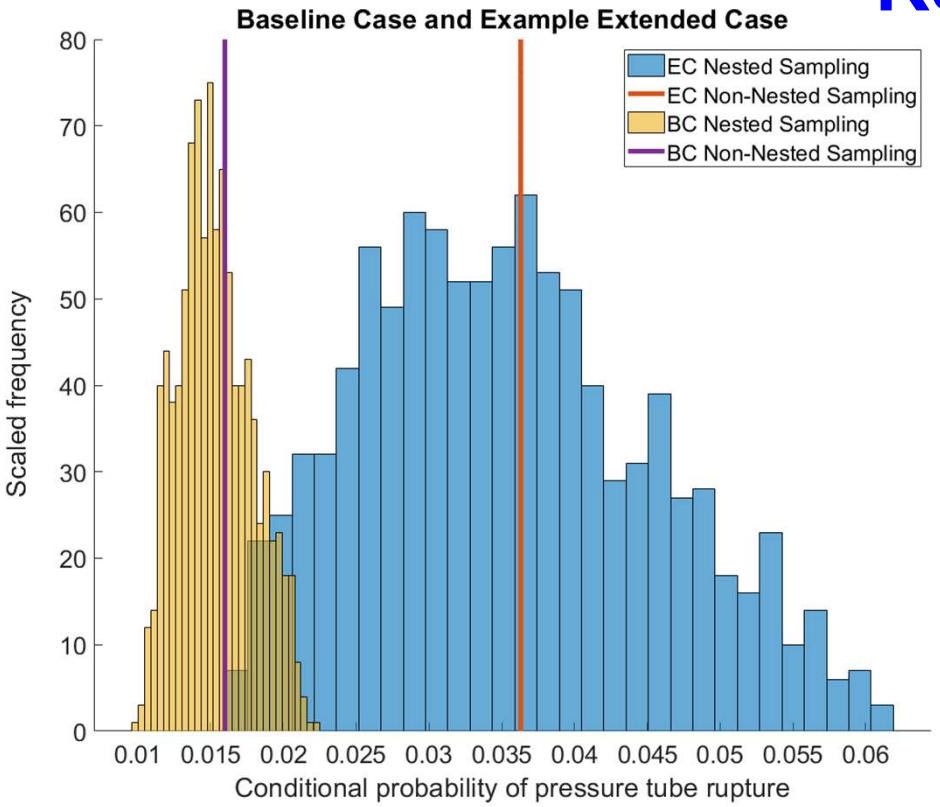
Defining the Example Extended Case

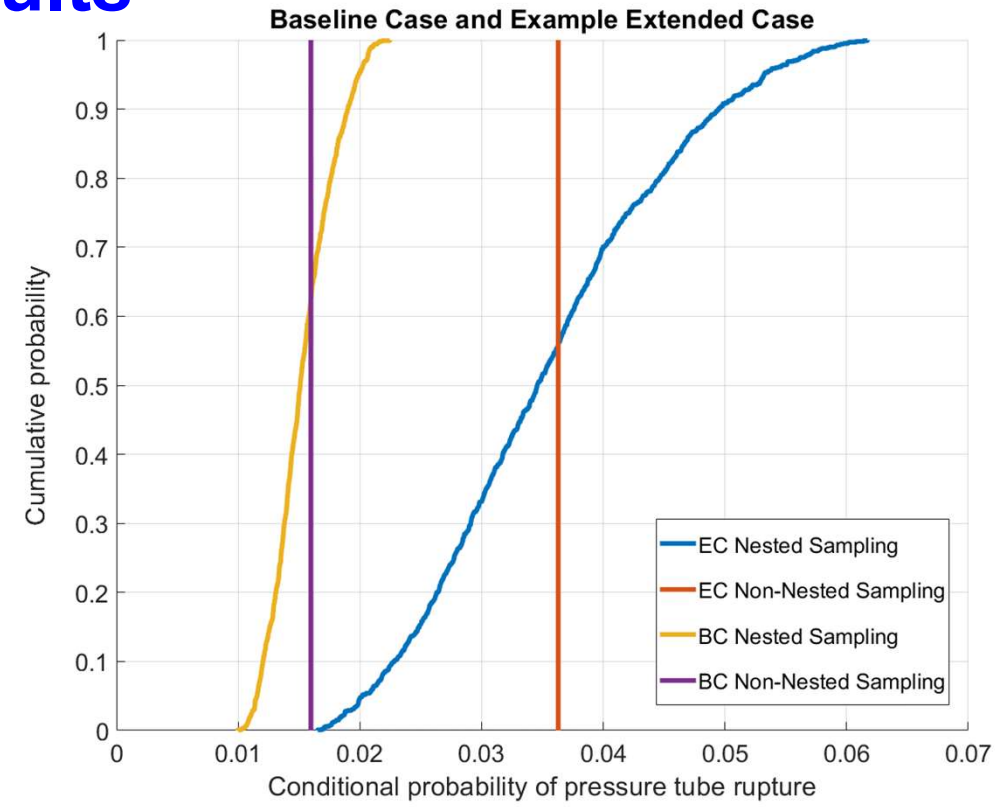




Pilot Study on Nested Sampling Uncertainty Propagation

Results





Case	Pr_{NN}	$Pr_{IO}(50\%)$	$Pr_{IO}(95\%)$	$Pr_{IO}(97.5\%)$	Q_{NN}	$\frac{Pr_{IO}(50\%)}{Pr_{NN}}$	$\frac{Pr_{IO}(95\%)}{Pr_{NN}}$	$\frac{Pr_{IO}(97.5\%)}{Pr_{NN}}$
Baseline	0.01598	0.01510	0.01989	0.02064	61%	0.95	1.24	1.29
Example Extended	0.03625	0.03456	0.05320	0.05617	56%	0.95	1.47	1.55

Conclusions

- Incorporation of nested sampling into probabilistic computer code for evaluation of fracture protection, SCEFPR, allowed the evaluation outcome (conditional probability of pressure tube rupture) to be treated as a distributed variable
  - Segregation of uncertainty components between inner loop and outer loop
  - Distributions of conditional probability of pressure tube rupture are well-behaved and unimodal
- The nested sampling approach, based on the nature of uncertainties, that was applied in the pilot study organically incorporated the framework for enhanced uncertainty analysis defined in CSA Standard N285.8

Conclusions

- Evaluation of most limiting fuel channel, baseline case:
  - Median of distributed conditional probability was found to be about 5% lower than single-valued conditional probability
  - 97.5-th percentile of distributed conditional probability was ~1.3 times higher than single-valued conditional probability
- Evaluations of most limiting fuel channel, extended cases:
  - Median of distributed conditional probability was found to be within − 10% to + 5% of single-valued conditional probability
  - Upper-tail percentiles of distributed conditional probability with respect to single-valued conditional probability varied substantially with the magnitude of outer-loop uncertainties and their locations

Conclusions

- Incorporation of nested sampling into computer code SCEFPR resulted in a large increase in computational time required to perform the PFP evaluation
- Improved characterization of the uncertainties associated with input variables will produce evaluation results that better reflect reality
  - Conclusion is applicable to both non-nested and nested sampling
- Nested sampling could be used for identifying areas of future research and development work
  - Distribution of evaluation outcome depends on uncertainty components that are primarily epistemic in nature