Excellence through Collaboration

Uncertainty Analysis in Probabilistic Fitness-for-Service Evaluations of Zr-2.5Nb Pressure Tubes

Christopher Manu, *Amec Foster Wheeler*

Leonid Gutkin, *Kinectrics*

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Outline

- Introduction
- Background
  - Uncertainties in parametric models
  - Uncertainties in statistical models
- Annex on Uncertainty Analysis for CSA Standard N285.8
  - Objective and scope
  - Identification of influential variables
  - Uncertainty characterization for influential variables
  - Incorporation of uncertainty characterization results into probabilistic evaluation
- Summary

Introduction

- In fitness-for-service evaluations, both deterministic and probabilistic approaches may be used to address uncertainties in loading conditions as well as material resistance to degradation and failure.
- Deterministic approaches do not allow for quantitative assessment of reliability of component or system of interest and may lead to overly restrictive results due to stack-up of conservatisms.
- Probabilistic approaches provide more representative assessment of reliability of component or system of interest by directly and systematically accounting for uncertainties in relevant non-deterministic variables.

Background

Parametric models

(also referred to as “physics-based” or “mechanistic”)

Example: free diffusion

- Uncertainty in diffusivity $D(T)$ is characterized independently
- Uncertainty in C is characterized by propagating uncertainty in D through the solution of diffusion differential equation

$$C(t,x) = \hat{C}(t,x) + U_C$$

$$\frac{\partial \hat{C}}{\partial t} = \hat{D}(T)\frac{\partial^2 \hat{C}}{\partial x^2}$$

$$U_D$$

C : response variable (concentration as a function of t, x)

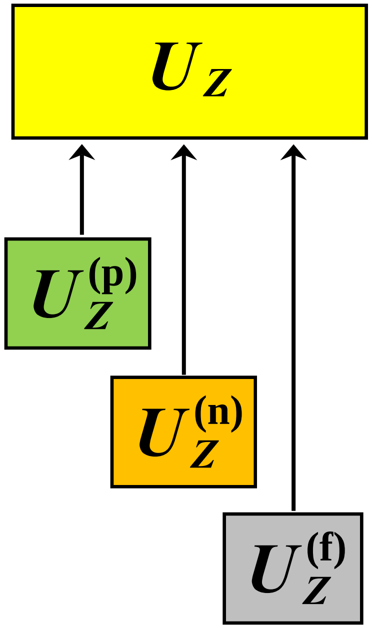
t, x : explanatory variables (time t, location x)

$D(T)$: model parameter (a function of temperature T)

Background

Uncertainties in parametric models

$$Z = \hat{Z} + U_Z$$



- $U_Z^{(p)}$ — **Parametric uncertainty due to uncertainties in non-deterministic parameters involved in the model**
- $U_Z^{(n)}$ — **Uncertainty due to finite precision of computations and finite level of convergence involved in numerical representation of mathematical formulation used in the model**
- $U_Z^{(f)}$ — **Uncertainty due to assumptions and approximations made when physical phenomenon of interest is represented by mathematical formulation used in the model**

Background

Statistical models

(also referred to as "data-driven" or "empirical")

Example: diffusivity

- Uncertainty in diffusivity D is characterized directly without propagating uncertainties in Q_D and E_D
- Uncertainties in Q_D and E_D may be inferred from uncertainty in D

$$\ln(D) = \ln(\hat{D}) + U_{\ln D}$$

$$\hat{D} = \hat{Q}_D \exp\left(\frac{\hat{E}_D}{RT}\right)$$

D : response variable (diffusivity)

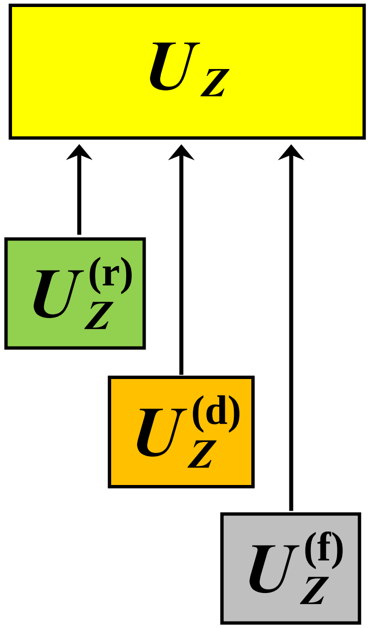
T : explanatory variable (temperature)

Q_D, E_D : non-deterministic model parameters

Background

Uncertainties in statistical models

$$Z = \hat{Z} + U_Z$$



$U_Z^{(r)}$ — Residual uncertainty representing observed variation that is not attributable to any of the explanatory variables used in the model

$U_Z^{(d)}$ — Uncertainty due to limitations in model-basis data set (in terms of balance, coverage, measurement uncertainties)

$U_Z^{(f)}$ — Uncertainty due to assumptions and approximations made when physical phenomenon of interest is represented by mathematical formulation used in the model

Canadian Standards Association Standard N285.8

Overview

- **Canadian Standards Association (CSA) Standard N285.8:**
  "Technical requirements for in-service evaluation of zirconium alloy pressure tubes in CANDU reactors"

- **Structure of CSA Standard N285.8:**
  - **Clauses 1, 2, 3:** Scope, references, definitions, nomenclature
  - **Clause 4:** General requirements
  - **Clause 5:** Evaluation of pressure tube flaws
  - **Clause 6:** Evaluation of pressure tube to calandria tube contact
  - **Clause 7:** Assessment of reactor core
    - Deterministic approach
    - Probabilistic approach
  - **Clause 8:** Evaluation of material surveillance measurements

Annex on Uncertainty Analysis for CSA Standard N285.8

Objective and definition

- **Informative Annex G to CSA Standard N285.8 has been developed by CSA N285.8 Technical Subcommittee to provide guidelines for performing uncertainty analysis in probabilistic evaluations relevant to scope of CSA Standard N285.8.**
- **Annex G defines uncertainty analysis as: *the process of identifying and characterizing the influential sources of uncertainty in the probabilistic evaluation, assessing the impact of uncertainties on the probabilistic evaluation results, and developing, to the extent practicable, a quantitative measure of this impact*.**

Annex on Uncertainty Analysis for CSA Standard N285.8

Scope

- Annex G applies to the following evaluations:
  - Protection against fracture (Clause 7.2.3)
  - Pressure tube failure due to degradation mechanisms related to flaws (Clause 7.3.2.3)
  - Pressure tube failure due to pressure tube to calandria tube contact (Clause 7.3.3.3)
  - Leak-before-break (Clause 7.4.3)

Annex on Uncertainty Analysis for CSA Standard N285.8

Methodology (I)

Objective of uncertainty analysis:
Review probabilistic evaluation using bottom-up approach focussing on characterization of uncertainties for influential non-deterministic variables

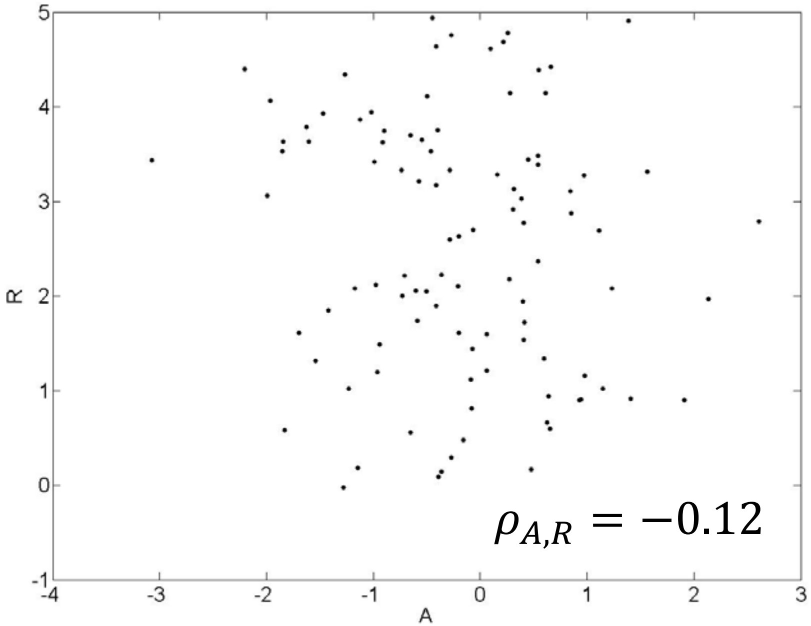
- **Stage I:** Identification of influential variables
  - Analysis of probabilistic evaluation outputs
  - Sensitivity analysis
  - Expert judgment

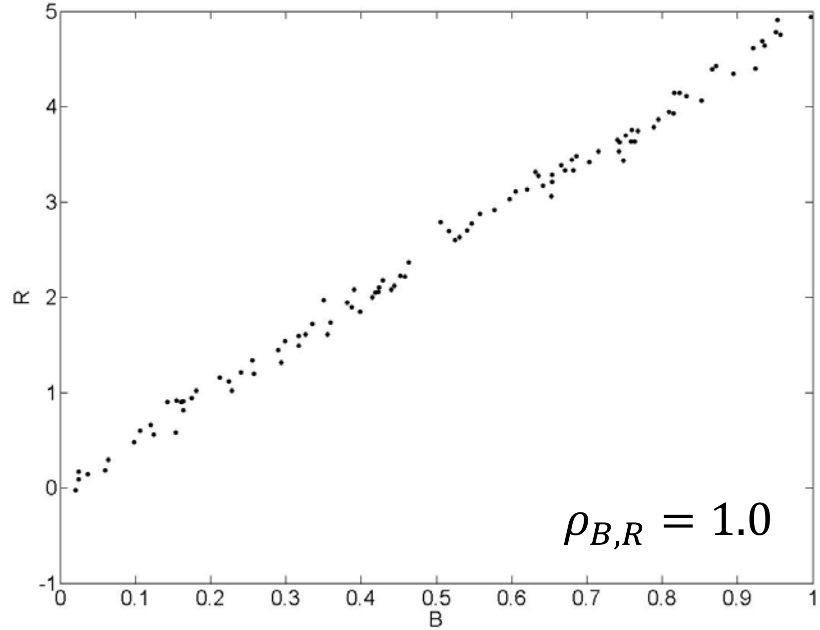
Identification of influential variables allows to direct greater effort towards the **uncertainty characterization** of variables having greater effect on the probabilistic evaluation outcome

Annex on Uncertainty Analysis for CSA Standard N285.8

Analysis of probabilistic evaluation outputs

Input Random Variables: A, B **Output Random Variable: R**





Scatter plots showing ρ, the correlation coefficient

$$\rho_{i,j} = \frac{C_{i,j}}{\sqrt{C_{i,i}C_{j,j}}}$$

C is covariance

Annex on Uncertainty Analysis for CSA Standard N285.8

Sensitivity analysis

Sensitivity coefficient S_j

$$S_j = \frac{X_j^{(0)}}{R^{(0)}} \left(\frac{\partial R}{\partial X_j} \Bigg|_{X^{(0)}} \right) \quad \text{where} \quad \begin{array}{l} X_j \text{ is input variable} \\ R \text{ is output variable} \\ R^{(0)} \text{ is reference value of } R \\ X_j^{(0)} \text{ is reference value of } X_j \end{array}$$

Example: Output variable in evaluation of leak-before-break (LBB)

$$R = \min \left(\frac{\sigma_h^{(cr)}(t)}{\sigma_h(t)} \right) \quad \text{where} \quad \begin{array}{l} \sigma_h^{(cr)}(t) \text{ is critical hoop stress} \\ \sigma_h(t) \text{ is applied hoop stress} \\ t \text{ is time in LBB sequence of events} \end{array}$$

Annex on Uncertainty Analysis for CSA Standard N285.8

Methodology (II)

Uncertainty components in model response:
Originate from different sources in calibrated parametric models and in statistical models

- **Stage II:** Characterization of uncertainties for influential variables
  - Statistical assessment
  - Expert judgment

Statistical assessment and expert judgment are recognized as complementary approaches, and either one may be used as the primary approach, on a case-by-case basis

Expert judgment as primary approach:
Formal process for elicitation and aggregation of expert opinions

Annex on Uncertainty Analysis for CSA Standard N285.8

Uncertainty components in model response

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

Annex on Uncertainty Analysis for CSA Standard N285.8

Approaches to uncertainty characterization

Variable type	Uncertainty component	Approach to uncertainty characterization	
		Primary	Supplementary
Type A	$U^{(p)}$	Statistical assessment or expert judgment	Expert judgment or statistical assessment
	$U^{(n)}$	Expert judgment	Statistical assessment
Type B	$U^{(r)}$	Statistical assessment	Expert judgment
	$U^{(d)}$	Expert judgment	Statistical assessment

Uncertainty due to model form is currently not included in uncertainty analysis. Research and development work is still on-going to establish approach(es) to characterizing this uncertainty component.

Annex on Uncertainty Analysis for CSA Standard N285.8

Methodology (III)

Results of uncertainty analysis:
Both additional and re-estimated uncertainties affect the outcome of probabilistic evaluation

- **Stage III:** **Incorporation of uncertainty characterization results into probabilistic evaluation**
  - **Monte Carlo simulation method**
  - **Other appropriate methods of uncertainty propagation**

Correlations among uncertainties are to be investigated and appropriately accounted for in the probabilistic evaluation

Summary

An informative Annex G to CSA Standard N285.8 has been developed by CSA N285.8 Technical Subcommittee to provide guidelines for performing uncertainty analysis in probabilistic evaluations specified in Clause 7 of CSA Standard N285.8

Uncertainty analysis as per Annex G involves:

- **Identification of influential variables**
- **Characterization of uncertainties for influential variables**
- **Incorporation of uncertainty characterization results into probabilistic evaluation**
- **Reporting uncertainty analysis results**

Summary

A pilot study is under way to exercise Annex G through its application to probabilistic evaluation of leak-before-break performed on the basis of postulated through-wall crack

Acknowledgments

- **Valuable contributions from members of Task Group of CSA N285.8 Technical Subcommittee responsible for the development of Annex G**
  - **The Task Group was comprised of volunteers from utilities, suppliers and the regulator.**
- **Guidance from CSA N285.8 Technical Subcommittee and N285B Technical Committee**
- **Support provided by CANDU Owners Group**

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Backup Slides

Pilot Study on Uncertainty Analysis for Probabilistic Leak-Before-Break

Objective, scope and computer code

- **Objective**
  - **Exercise Annex G through its application to an example probabilistic evaluation relevant to scope of CSA N285.8**
- **Scope**
  - **Probabilistic leak-before-break evaluation performed on the basis of postulated through-wall crack (Method 1)**
  - **Darlington Unit 3: a representative reactor core often used for impact assessments on probabilistic evaluations**
- **Computer code**
  - **Computer code P-LBB V1.0 by Amec Foster Wheeler**
  - **Complying with requirements of CSA Standard N286.7-99 (Quality Assurance of Analytical, Scientific, and Design Computer Programs for Nuclear Power Plants)**

Pilot Study on Uncertainty Analysis for Probabilistic Leak-Before-Break

Evaluation approach

- A leaking through-wall flaw is postulated to grow axially by delayed hydride cracking (DHC) as the reactor transitions from its sustained operating conditions to a cold and depressurized state
- Leak-before-break is demonstrated if actual crack length remains below critical crack length at any time during this transient
  - Equivalently, if applied stress remains below critical stress for flaw instability at any time during this transient

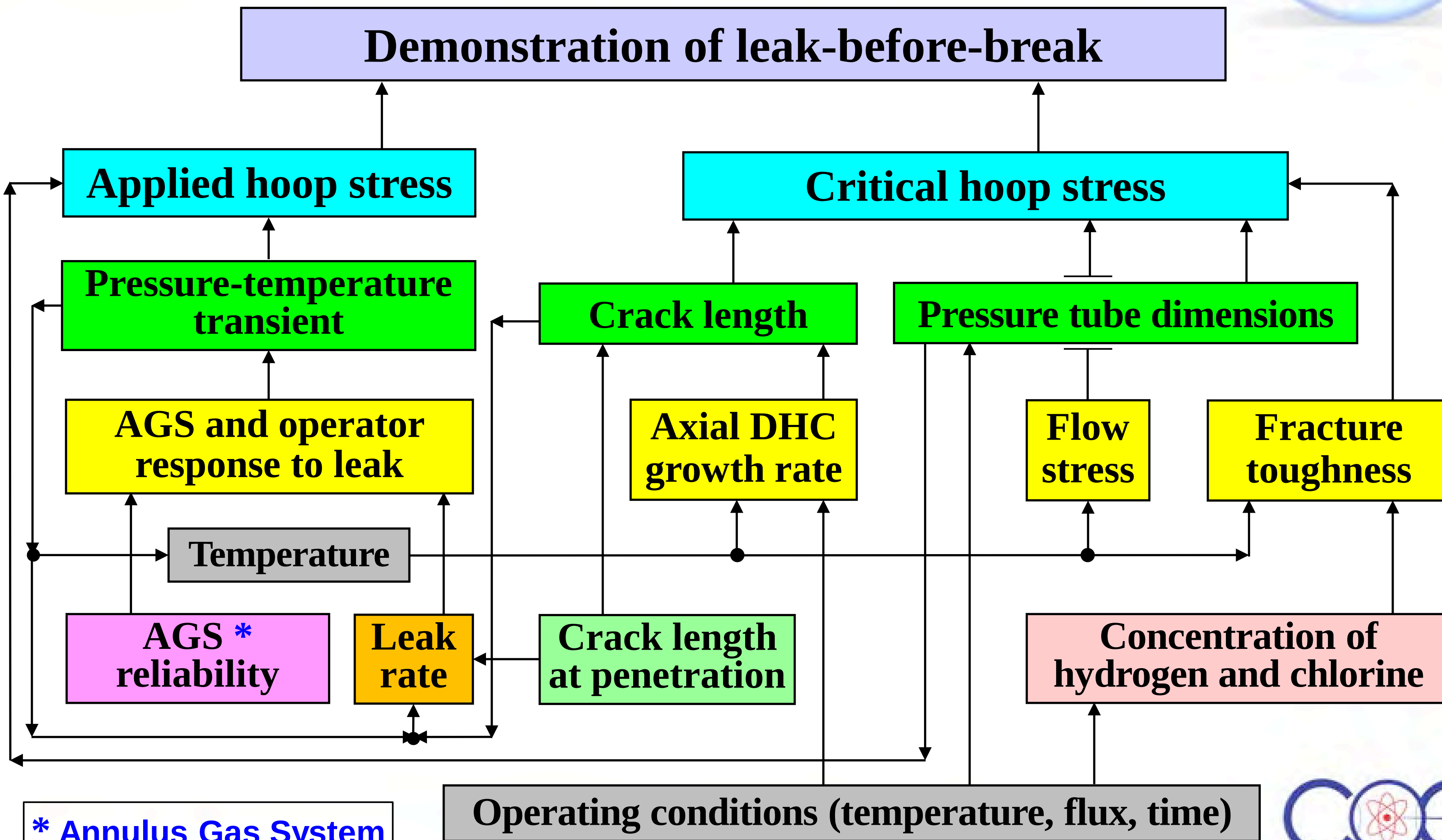
critical hoop stress | fracture toughness | axial DHC growth rate

$$\sigma_h^{(cr)} = \frac{2\sigma_f}{\pi M} \mathrm{acos}\left[\exp\left(-\frac{\pi K_c^2}{4\sigma_f^2 L}\right)\right] \quad \text{where } L = L_p + \int V_a dt$$

bulging factor | flow stress | axial crack length

Pilot Study on Uncertainty Analysis for Probabilistic Leak-Before-Break

Evaluation hierarchy



* Annulus Gas System