Incorporation of Global Sensitivity Analysis into Probabilistic Evaluations of Pressure Tube Leak-Before-Break in CANDU Reactors

Christopher Manu, Leonid Gutkin
Kinectrics Inc.
Toronto, Ontario, Canada

Fifth International Symposium on Probabilistic Methodologies for Nuclear Applications

Tokyo, Japan
October 7 to 9, 2024

CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

Outline

- Introduction
- Probabilistic evaluations of leak-before-break
  - Brief description of evaluation
  - Input and output variables
- Method of global sensitivity analysis
  - Variance-based methods
  - Method of Sobol’
- Global sensitivity analysis for the evaluation of pressure tube leak-before-break
  - Matrix of evaluation cases
  - Results
- Summary

CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

Introduction

- A work program is underway to establish the inputs and to develop the tools required to perform enhanced uncertainty analysis for probabilistic evaluations related to pressure tube flaws

- Global sensitivity analysis is a key infrastructure tool for enhanced uncertainty analysis
  - Identification of influential variables allows directing greater effort towards characterization of uncertainties in non-deterministic variables having greater effect on evaluation outcome
  - Overview of incorporation of global sensitivity analysis into probabilistic evaluations of leak-before-break (LBB) is provided in this presentation

CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

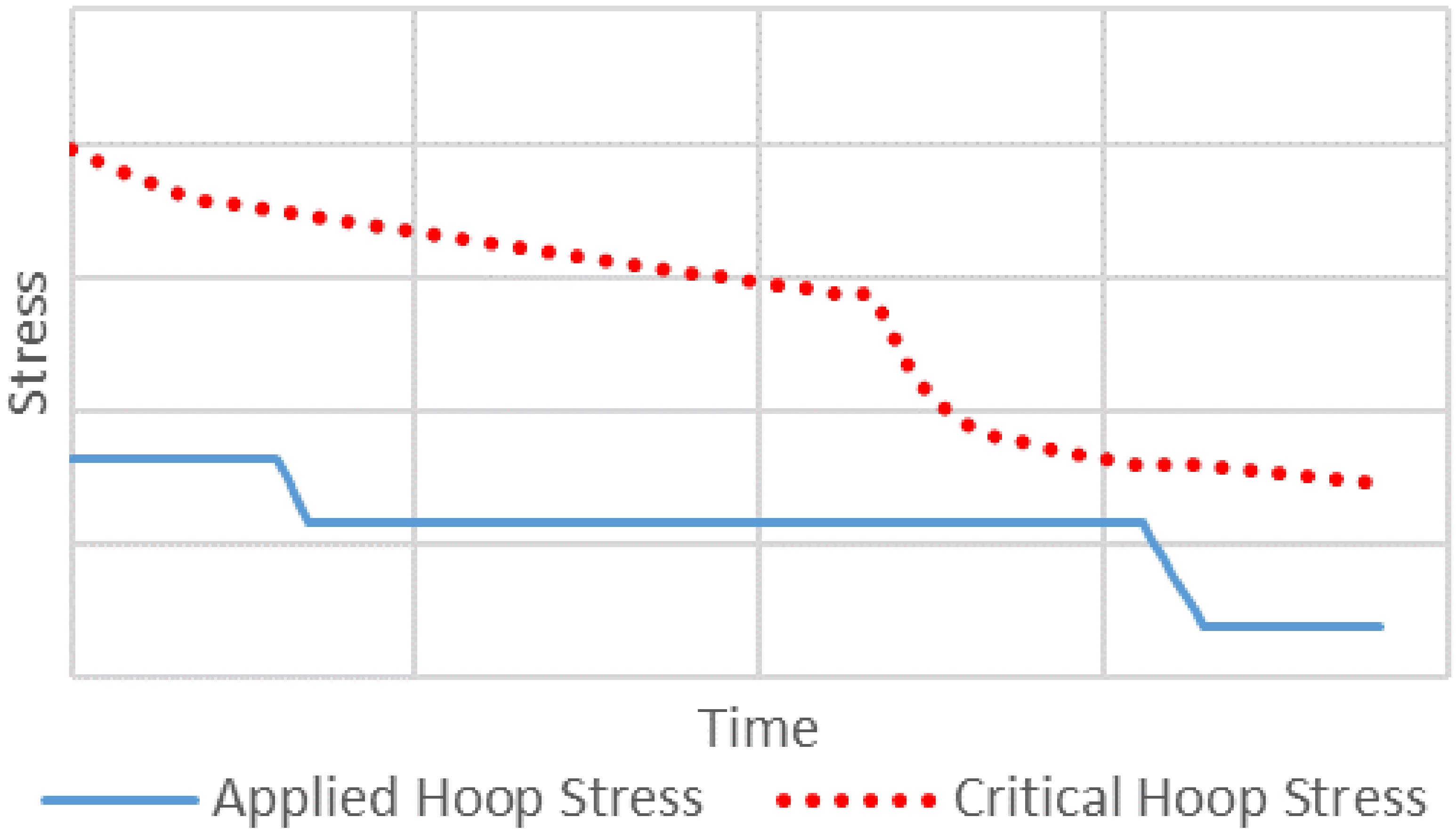
Probabilistic Evaluations of Leak-Before-Break

- Pressure tube leak-before-break (LBB)
  - A through-wall flaw is postulated to grow axially by delayed hydride cracking mechanism as the reactor transitions from normal operating conditions to a cold and depressurized state
  - Leak-before-break is demonstrated (pressure tube is not considered to rupture) if the applied hoop stress remains below the critical hoop stress at all times during LBB sequence of events
- Probabilistic evaluations of LBB
  - Performed in accordance with CSA Standard N285.8
  - LBB evaluation procedure is applied to a large number of realizations of relevant influential non-deterministic variables that are simulated from their representative distributions
- Output of probabilistic evaluations of LBB:
  - Obtained using Monte Carlo method (random sampling), typically with 100,000 simulations
  - Single-valued output: Probability of pressure tube rupture conditional upon existence of a through-wall flaw
  - Distributed output: Ratio of critical hoop stress to applied hoop stress, minimized over time in LBB sequence of events
  - Distributed output variable is used in global sensitivity analysis

CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

Probabilistic Evaluations of Leak-Before-Break



Output variable

$$R = \min_t \left(\frac{\sigma_c(t)}{\sigma_a(t)} \right)$$

σ_c = critical hoop stress

σ_a = applied hoop stress

t = time with respect to start of pressure tube leak in LBB sequence of events

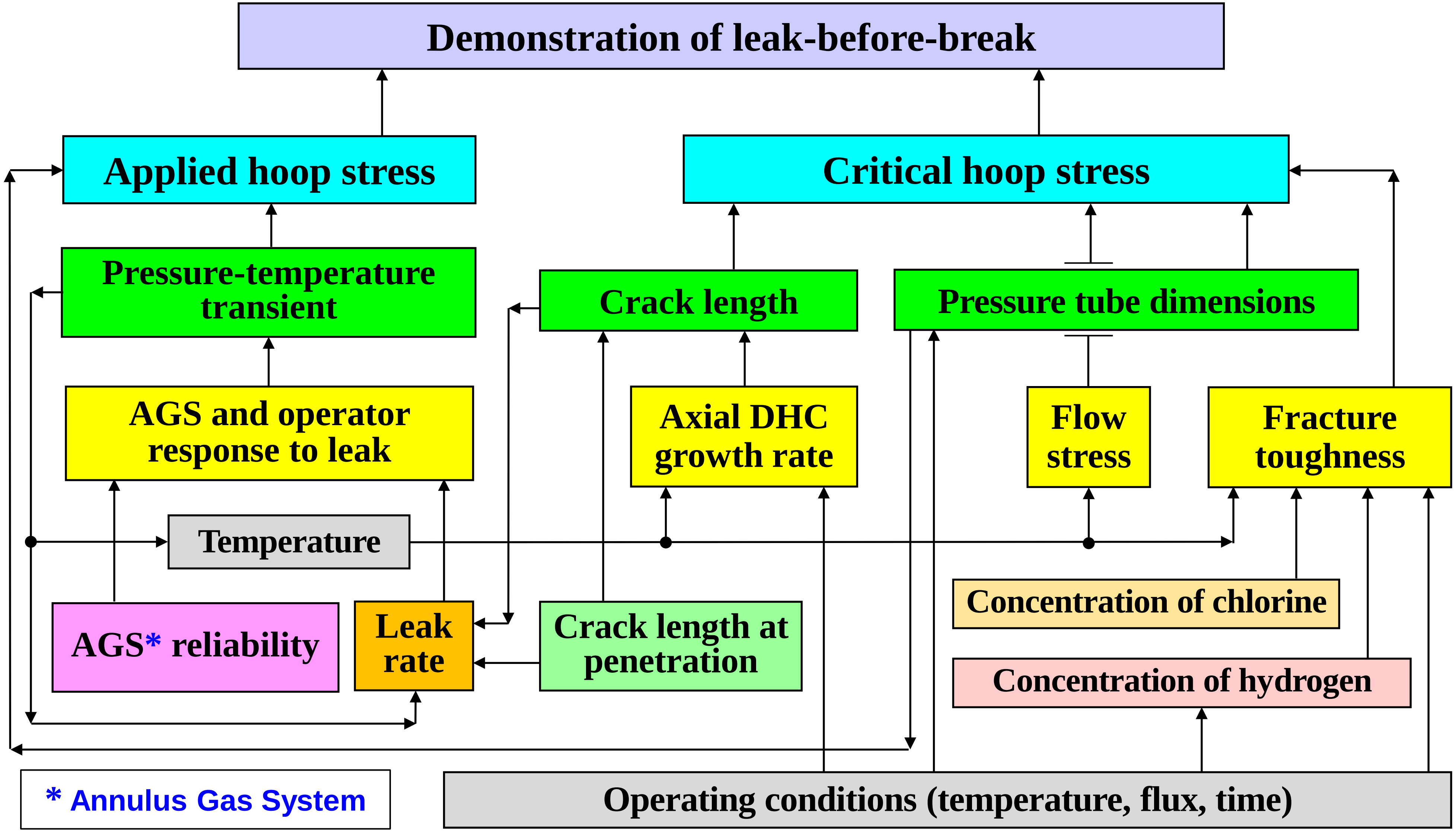
$R > 1$: LBB is demonstrated

$R \leq 1$: LBB is not demonstrated (break-before-leak)

CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

Probabilistic Evaluations of Leak-Before-Break



CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

Distributed Input Variables in LBB Evaluations

- Fracture toughness (K_c)
- Axial DHC growth rate (V_a)
- Transverse yield stress (S_y)
- Transverse ultimate tensile stress (S_{ut})

Inputs Representing Mechanical Properties

- Hydrogen equivalent concentration (H_{eq})
- Chlorine concentration ($[Cl]$)

Inputs Representing Material Chemistry

Dimensional Inputs

- Axial flaw length at first through-wall penetration (L_p)
- Wall thickness of pressure tube (W_{PT})
- Inner diameter of pressure tube (D_{PT})

Inputs Related to Annulus Gas System

- Delay in operator response to dew point alarm (OD_{DPA})
- Delay in operator response to beetle alarm (OD_{BA})
- Availability of dew point alarm (AV_{DPA})
- Availability of beetle alarm (AV_{BA})

CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

Method of Global Sensitivity Analysis

- Variance-based methods of global sensitivity analysis were given preference
  - Variance-based methods aim to apportion the variability in a model's output variable to the different sources of variability in the model's input variables
  - Good applicability in different analysis settings, such as ranking of influential input variables and screening of non-influential ones
  - Reliable use with models of various complexity, including non-linear and non-monotonic
  - Computationally viable for moderate number of input variables involved in evaluations of interest

CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

Method of Global Sensitivity Analysis

❑ Variance-based methods of global sensitivity analysis

- First-order sensitivity index: Fraction of variance in output variable directly attributed to input variable of interest

$$S_i = \frac{V\big(E(y|x_i)\big)}{V(y)}$$

- Higher-order sensitivity indices: Capture effects of interactions between input variables
- Sensitivity indices of all orders sum to 1

$$\sum_i S_i + \sum_i \sum_{j>i} S_{ij} + \sum_i \sum_{j>i} \sum_{l>j} S_{ijl} + \cdots + S_{123\ldots k} = 1$$

- Total sensitivity index: Fraction of variance in output variable attributed to input variable of interest both directly and due to its interactions with other variables

$$S_i^T = \frac{V(y) - V\big(E(y|x_{\sim i})\big)}{V(y)}$$

S_i = First-order sensitivity index

S_{ij} = Second-order sensitivity index

S_{ijl} = Third-order sensitivity index

S_i^T = Total sensitivity index

y = Output variable

x_i = Input variable

$x_{\sim i}$ = All input variables except x_i

CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

Method of Global Sensitivity Analysis

- The sensitivity indices were estimated using the method of Sobol', a numerical procedure involving Monte Carlo simulations with prescribed sampling structures

- Method of Sobol' is a particularly widely used variance-based method
  - Excellent computational efficiency
  - Robustness of sensitivity metrics

- Method of Sobol' judged to be applicable to all three probabilistic evaluations related to pressure tube flaws

- Sobol' sensitivity indices used in current work
  - First-order sensitivity index
  - Total sensitivity index
  - Second-order sensitivity index calculated but not used/documented/presented

CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

Matrix of Evaluation Cases for Global Sensitivity Analysis

Reactor Unit	Fuel Channel	Evaluation Time, EFPH	Flaw Axial Location
Unit A or Unit B	Channel X1	150,000	Inlet rolled joint
			Middle of channel
			Outlet rolled joint
		300,000	Inlet rolled joint
			Middle of channel
			Outlet rolled joint
	Channel X2	150,000	Inlet rolled joint
			Middle of channel
			Outlet rolled joint
		300,000	Inlet rolled joint
			Middle of channel
			Outlet rolled joint

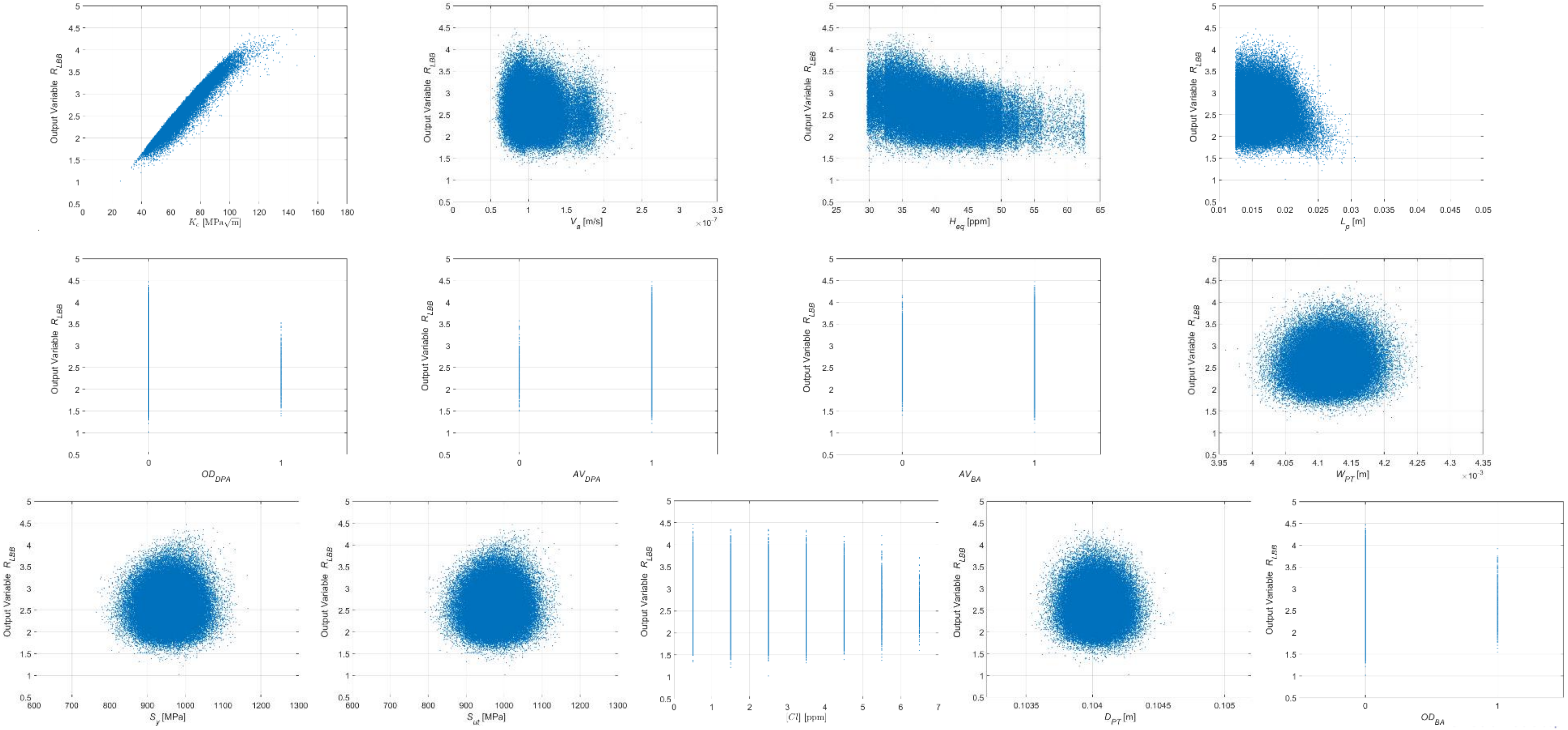
Each condition is considered with two variants of AGS-related variables:

- OD_{DPA}, OD_{BA}, AV_{DPA} and AV_{BA} are simulated from distributions
- No delay in operator response and perfect availability of both alarms

CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

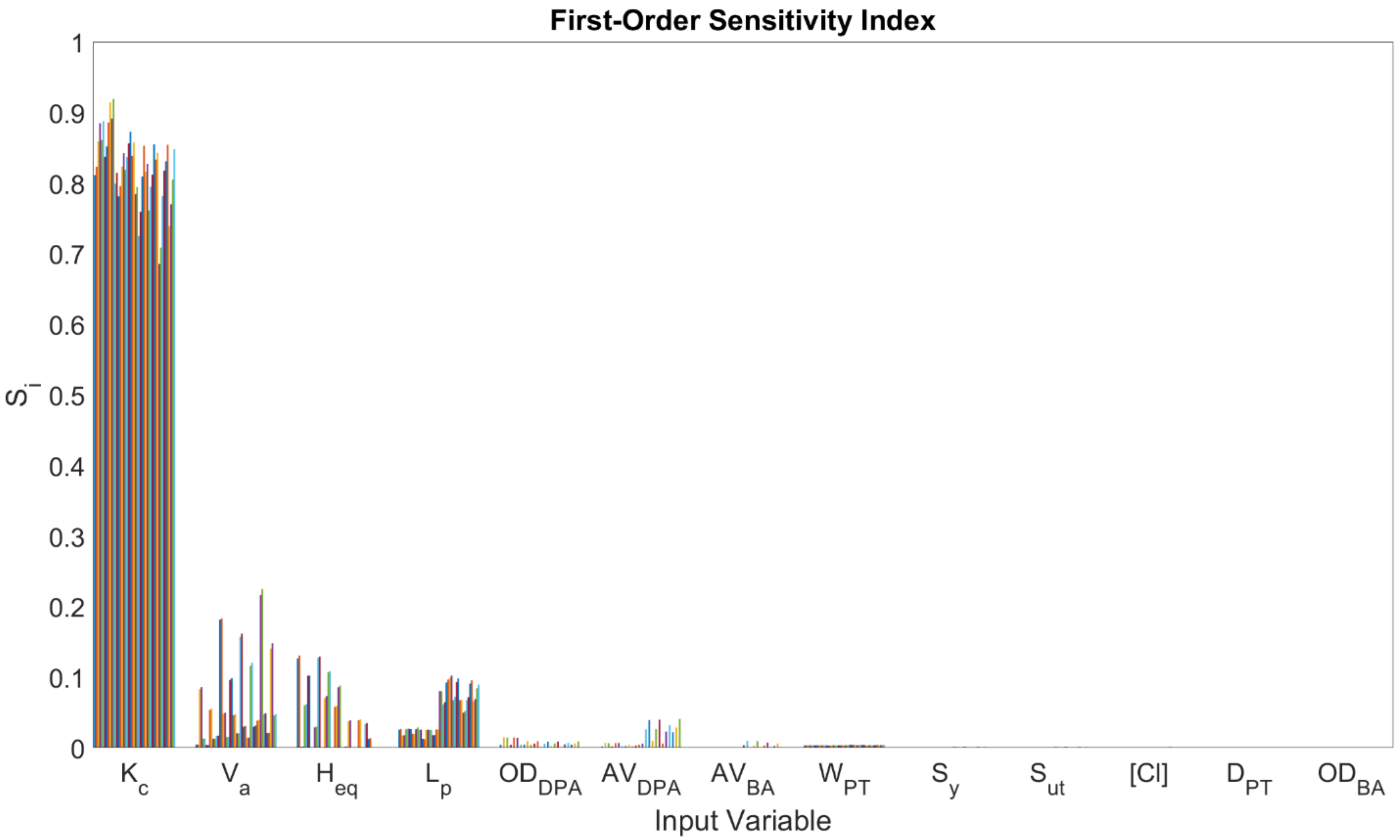
Exploratory Correlation Analysis: Inlet rolled joint, late life



CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

"Excellence Through Collaboration"

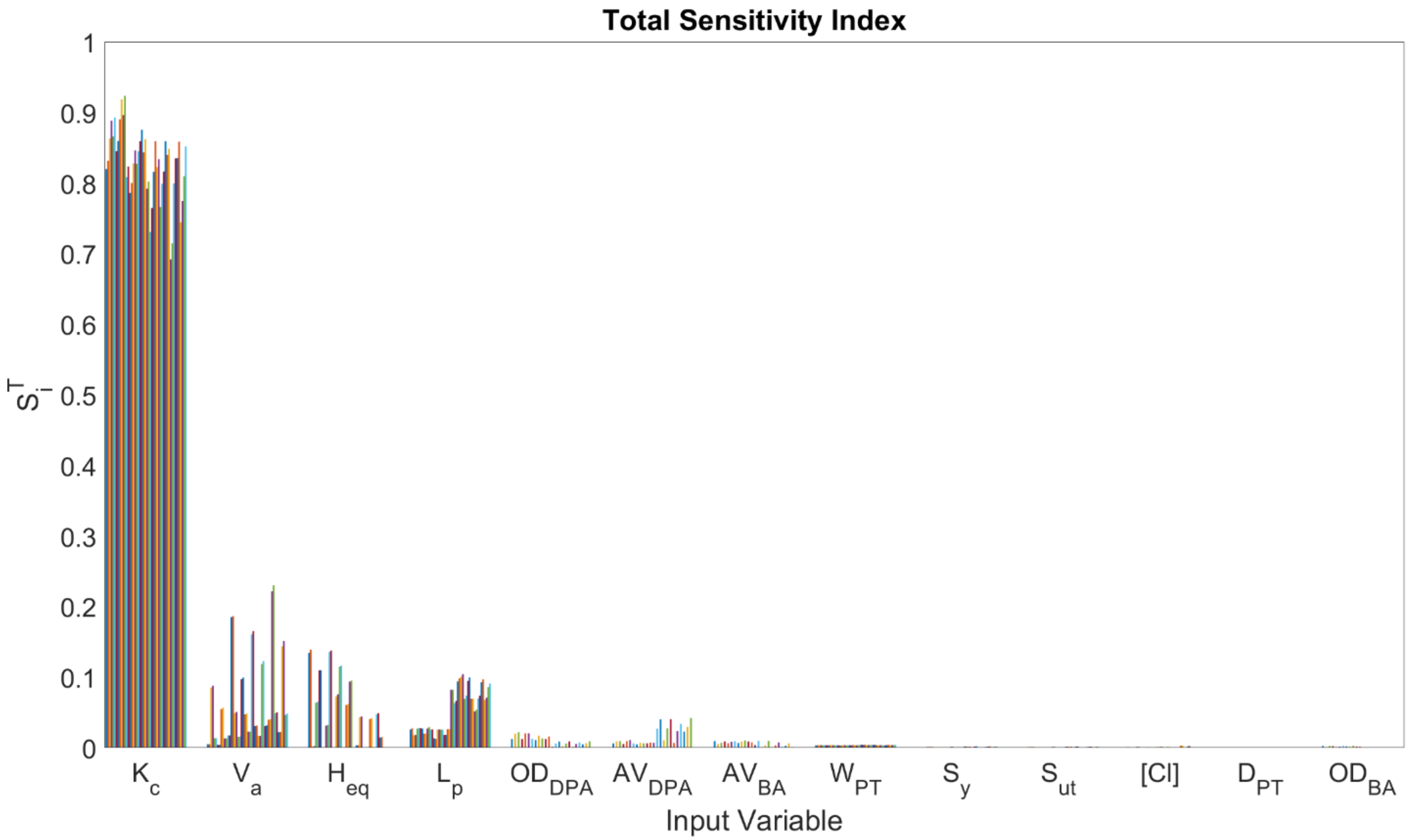
Results of Global Sensitivity Analysis



CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

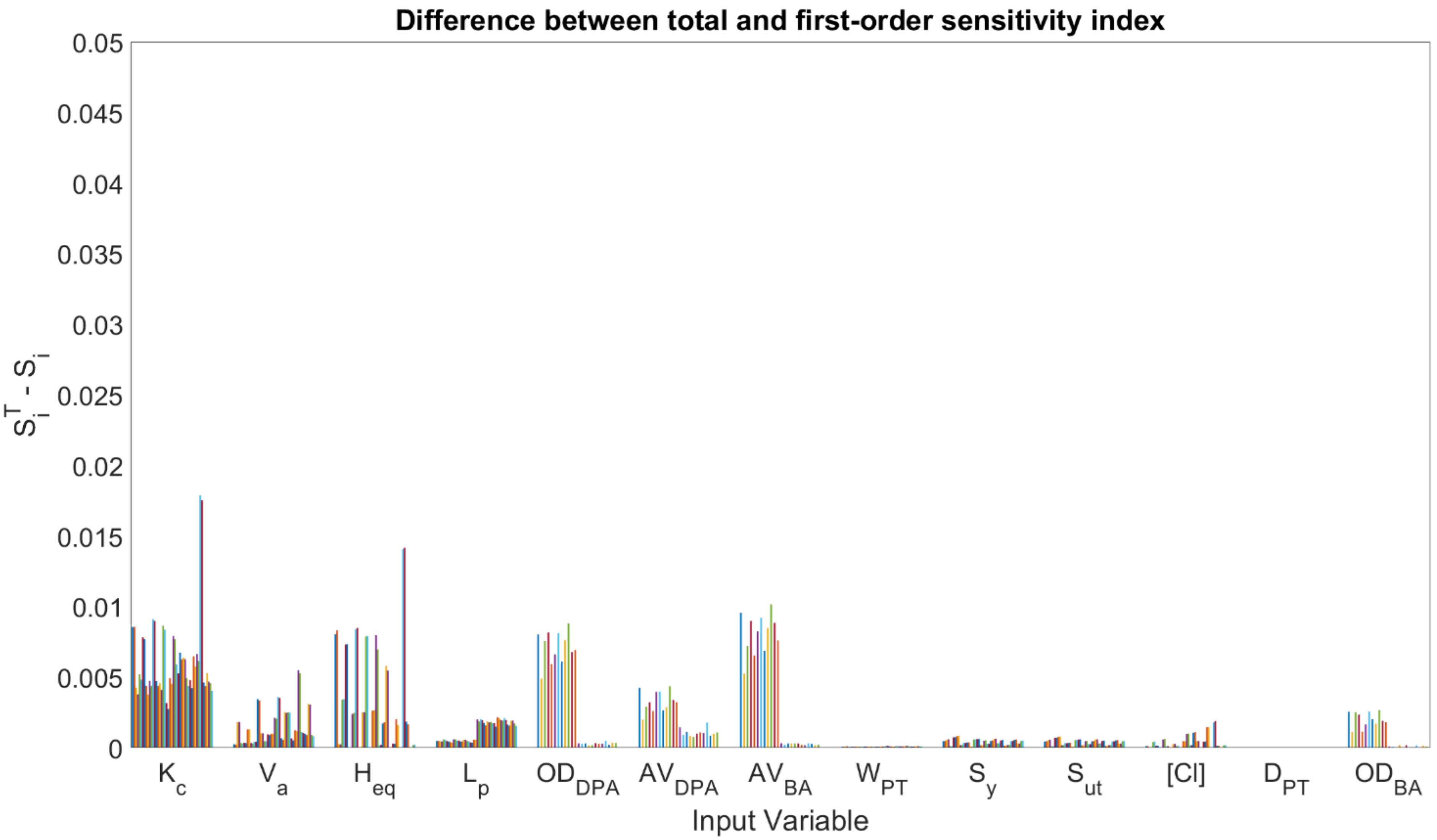
Results of Global Sensitivity Analysis



CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

Results of Global Sensitivity Analysis



CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

Summary

- Infrastructure for enhanced uncertainty analysis in probabilistic evaluations strongly relies on global sensitivity analysis
  - A reliable and efficient method of global sensitivity analysis – method of Sobol’ – has been selected for probabilistic evaluations of leak-before-break
  - Selected method is a variance-based method that is adequate for performing global sensitivity analysis in conjunction with all three probabilistic evaluations related to pressure tube flaws
  - Implementation of selected method of global sensitivity analysis that is compatible with computer code P-LBB V1.1 has been created
  - Implementation is capable of calculating first-order sensitivity indices, second-order sensitivity indices as well as total sensitivity indices by method of Sobol’

CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

Summary

- Global sensitivity analyses with baseline inputs have been performed in conjunction with probabilistic evaluations of leak-before-break
  - Matrix of 48 evaluation cases was used in sensitivity analyses to cover different spatial locations and points in time

- In all cases, the total sensitivity indices have been found to be very similar to the first-order sensitivity indices, thereby indicating that the second-order indices and the higher-order indices would not provide additional information
  - Sum of all first-order sensitivity indices was found to be very close to 1.0 for all cases

- Thirteen (13) input variables have been assigned to three different groups by degree of their influence on outcome of probabilistic evaluations of leak-before-break
  - Group 1, with high degree of influence: fracture toughness
  - Group 2, with moderate degree of influence: axial DHC growth rate, axial flaw length at first through-wall penetration, hydrogen equivalent concentration
  - Group 3, with low to very low degree of influence: all other input variables

- Results of this work are intended to be used to guide the process of establishing and refining set of inputs for application of enhanced uncertainty analysis to probabilistic evaluations of leak-before-break

CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

Acknowledgements

- Valuable discussions with:
  - D. Cho of Bruce Power
  - M. Baghbanan, T. Carneiro, J. Lam and M. Poloni of Ontario Power Generation
  - T. Hunt, C. Liu, K. Huang, S. Datla and D.H.B. Mok of Kinectrics

- Support from CANDU Owners Group is appreciated

CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.

CANDU Owners Group Inc.
"Excellence Through Collaboration"

Thank you

CONFIDENTIALITY NOTICE: This presentation contains information that cannot be shared without permission from CANDU Owners Group.