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APPLICATION OF UNCERTAINTY ANALYSIS IN THE COMPARISON OF VOID FRACTION CALCULATIONS WITH EXPERIMENT

Jason Pascoe
AMEC-NSS
Toronto, Ontario, Canada

Yuksel Parlatan
Ontario Power Generation
Pickering, Ontario, Canada

B. McLaughlin
AMEC-NSS
Toronto, Ontario, Canada

Sophia Fung
AMEC-NSS
Toronto, Ontario, Canada

ABSTRACT

Safety analysis computer codes are designed to simulate phenomena relevant to the assessment of normal and transient behaviour in nuclear power plants. In order to do so, models of relevant phenomena are developed and a set of such models constitutes a computer code. In accident or transient analysis the values of certain output parameters (margin parameters) are used to characterize the severity of the event. The accuracy of the computer code in calculating these margin parameters is usually obtained through validation and variation in the margin parameter is estimated through the propagation of variation in the code input. A method for estimating code uncertainty respect to a specific output parameter has been developed.

The methodology has the following basic elements: (1) specification and ranking of phenomena that govern the behaviour of the output parameter for which an uncertainty range is required; (2) identification of models within the code that represent the relevant phenomena; (3) determination of the governing parameters for the phenomenological models and Identification of uncertainty ranges for the governing model parameters from validation or scientific basis, if available; (4) decomposition of the governing model parameters into related parameters; (5) identification of uncertainty ranges for the modelling parameters for use in Best Estimate Analysis; (6) design and execution of a case matrix; and (7) estimation of the code uncertainty through quantification of the variability in output parameters arising from uncertainty in modelling parameters.

This methodology has been employed using simulations of Large Break Loss of Coolant Accident (LOCA) tests in the RD-14M test facility to calculate the uncertainty in the TUF thermal hydraulics code calculation of the coolant void fraction. The uncertainty has been estimated with and without plant parameters (parameters specific to the RD-14M test loop). The TUF coolant void fraction uncertainty without plant parameters was determined to be 0.08 while the uncertainty with plant parameters included was determined to be 0.11. The uncertainty value without plant parameters included is comparable to the uncertainty in the measurements (0.09). The uncertainty value with plant parameters included is larger than the variation in the bias (0.10) of the TUF calculation of void fraction. From these findings, it can be concluded that the estimated accuracy of the TUF code calculation of void fraction is consistent with the available experimental data.

1.0 INTRODUCTION

The work described in this paper pertains to the issue of establishing the uncertainty in the TUF code calculation of coolant void fraction.

The specific Figure of Merit (FOM) for this work was the void fraction at the location of the neutron scatterometer in RD-14M at a specified point in time. This location corresponds roughly to the centre of the 10^{th} simulated fuel bundle in the heated Section 14 of the RD-14M loop. As the length of the RD-14M heated sections scale one-to-one with CANDU fuel channels, the 10^{th} simulated fuel bundle corresponds to bundle 10 in a CANDU channel.

The modelling parameters and their associated uncertainty ranges used in this work are similar to those for the Pickering 5-second BEAU Analysis [1]. That similarity can be used to provide support for the choice of modelling parameters and their uncertainty ranges used in a BEAU analysis in the following manner.

Consider the circumstance in which a code accuracy value (bias and variability in bias) has been obtained in an Integral Effects Test (IET) such as RD-14M. Assume that the IET is a reasonable representation of a plant application in that:

- Components, geometry and elevations are scaled appropriately,
- Working fluids are similar to those used in the plant application,
- Experimental protocol leads to reasonably similar timing of events, and
- The same dominant phenomena are acting in both the IET and plant application with an acceptable level of distortion.

An uncertainty value in an output parameter for the plant BEAU application can then be obtained through the propagation of modelling uncertainties by varying modelling parameters around their expected uncertainty ranges. If those modelling parameters adequately characterize the relevant models and their uncertainty ranges are reasonable, the output parameter uncertainty should be fairly close to the estimated value for the code accuracy for the same parameter.

A comparison between the RD-14M variation in bias and the Pickering B BEAU integrated uncertainty substantiates both the process of parameter decomposition (PIRT process) and the adequacy of the modelling parameter uncertainty ranges in an overall sense.

In addition, a sensitivity analysis of the influence of the input parameters on the figure of merit allows for the identification of the parameters of significance. Consistency of these parameters both within the tests as well as with the plant application provides additional confidence in the resultant uncertainty estimates.

2.0 Nomenclature

CANDU	Canadian Deuterium-Uranium
CUE	Code Uncertainty Estimation
FES	Fuel Element Simulator
FOM	Figure of Merit
IUA	Integrated Uncertainty Analysis
LOCA	Loss Of Coolant Accident
PIRT	Phenomena Identification and Ranking Table
PKPIRT	Phenomena key Parameter Identification and Ranking Table
Tolerance Interval	A statistical interval within which, with some confidence, a specified proportion of a population falls (i.e., X/Y tolerance interval would specify the X percent of the population is contained within the interval with a confidence level of Y).
TUF	Two Unequal Fluids -- the two phase system thermal hydraulic code used in CANDU analyses.
Uncertainty	The uncertainty of a computer code prediction that arises from the uncertainty in code models. In this report, the uncertainty is taken to be equal to the 95/95 Tolerance Interval divided by 2.

3.0 Analysis Methodology

3.1 Objectives

The primary objective of the work described in this paper was to calculate the uncertainty for the TUF code calculation of void fraction using RD-14M LOCA tests identified in Reference [2].

The secondary objective of this work is to provide substantiation of:

1. The completeness of the modelling parameters used in the Pickering B 5-second BEAU analysis [1]; and
2. The adequacy of the modelling parameter uncertainty ranges.

3.2 Assessment Methodology

Although the Pickering B 5-second BEAU analysis [1] was focused on obtaining an estimate of the 95th percentile value of hot bundle enthalpy for a 100% RIH break, a number of secondary analyses were also performed. One of those estimated the uncertainty in the TUF calculation for void fraction for a specific channel group (comparable to HS14 in RD-14M in terms of power and elevation). The estimation was executed in a manner similar to that documented in this paper for the TUF calculation of void fraction in RD-14M. Specifically, the Pickering B and RD-14M uncertainty estimations for the void fraction FOM used:

- The same modelling parameters with some exceptions,
- The same uncertainty ranges for the modelling parameters,
- The same number of cases in the case matrix, and used the same method of estimating the uncertainty ranges.

The validity of both the process used to estimate the uncertainty in the TUF calculation of void fraction and the specific estimated value of the uncertainty obtained through a Pickering IUA are assessed through the comparison of the following quantities:

- The RD-14M neutron scatterometer measurement uncertainty,
- The variation in the bias of the TUF calculation of void fraction,

- The uncertainty in the TUF calculation of void fraction estimated from an RD-14M IUA, and
- The uncertainty in the TUF calculation of void fraction estimated from a Pickering B IUA.

Given that the RD-14M loop is representative of a CANDU power plant (in terms of voiding behaviour) and the neutron scatterometer provides accurate measurements of void fraction, the variation in the bias of the TUF calculation of void fraction provides a direct estimate of the expected variability in the TUF calculation of void fraction. If the list of relevant modelling parameters used in the RD-14M IUA is complete, and their uncertainty ranges are reasonable, the estimated uncertainty range of the figure of merit should be greater than or equal to the variation in the calculated void fraction bias. Table 1 lists the RD-14M tests used in this analysis, as well as their characterization as large or small break tests.

If that is not the case, and the uncertainty range is less than the variation in the bias in the calculated void fraction, the following actions are required:

- The PKPIRT process and parameter decomposition process should be reviewed to ensure that all modelling parameters that influence the calculation of the void fraction are accounted for.
- The basis for the modelling parameter uncertainty range should be revisited and, if the basis for the uncertainty range is not well established, the uncertainty range should be increased.
- The amount of the increase in the modelling parameter uncertainty range should be sufficient to ensure that the revised uncertainty range is greater than or equal to the variation in the bias.

Substantiation of the uncertainty in the TUF calculation of void fraction for the Pickering B LBLOCA case is assessed through the use of the comparison of propagated uncertainty and accuracy metric. The comparison of a ‘propagated uncertainty and accuracy metric’ involves comparison of the variation in the bias in the TUF code calculation of void fraction with the Pickering B IUA value for the void fraction FOM. If satisfied, the metric provides quantitative confirmation and justification for the choice of modelling parameters, and their associated uncertainty ranges, as used in a plant IUA.

Further substantiation is provided through the use of confirmatory sensitivity analysis. The Pickering B void fraction IUA examined the sensitivity of the void fraction FOM to the modelling parameters. A similar sensitivity analysis was done using the RD-14M results. Some differences in the parameter rankings are expected (the RD-14M IUA did not vary any physics parameters, for example). However, if the parameter rankings are similar, the adequacy and completeness of the modelling parameters is generally indicated.

The basic elements of the methodology to establish code uncertainty (CUE) consists of:

1. Specification and ranking of phenomena that govern the behaviour of the output parameter for which an uncertainty range is required (PIRT process).
2. Identification of models within the code that represent the relevant phenomena.
3. Determination of the governing parameters for the phenomenological models and identification of uncertainty ranges for the governing model parameters from validation or scientific basis, if available.
4. Decomposition of the governing model parameters into related parameters. The decomposition process stops when a related parameter is obtained for which there is a defensible uncertainty range.
5. Identification of uncertainty ranges for the modelling parameters for use in BEAU.
6. Design and execution of a case matrix.
7. Estimation of the code uncertainty through quantification of the variability in output parameters arising from uncertainty in modelling parameters using the results generated from the case matrix.

The void fraction uncertainty values have been calculated separately for large break tests and all LOCA tests in RD-14M.

Table 2 lists the parameters varied in this analysis in order to perform the uncertainty estimation. Also included in this table is the parameter identifier, and the distribution of the associated uncertainty.

The modelling parameters to be varied during the uncertainty calculation are identical to those used in the Pickering B 5-second BEAU analysis as are their uncertainty ranges with the following exceptions:

- Single-phase break discharge multiplier
- Two-phase break discharge multiplier
- Critical heat flux (CHF) multiplier

The single-phase break discharge multiplier was modified in the RD-14M simulations to account for non-developed flow at the break orifice, while the two-phase break discharge multiplier was modified to account for the use of the Henry-Fauske model to simulate conditions slightly dissimilar from those used to develop the model. The CHF multiplier was modified to reflect the 7-element FES in RD-14M since no 7-pin CHF correlation is available in TUF.

The thermal hydraulics plant parameters identified in the Pickering B 5 second BEAU analysis are intended to be used for Pickering B and none of them apply to RD-14M. The fuel and sheath properties are not relevant to RD-14M, since it uses Fuel Element Simulators (FES) which has a composition that is different from 28-element fuel used in Pickering B. The form losses are not relevant uncertainty parameters, since these are limit estimate values.

The RD-14M IUA did include a number of additional plant parameters that are listed below:

- time to open the break
- break Area

- fuel element simulator thermal conductivity
- fuel element simulator specific heat capacity
- fuel element simulator power supply
- ASTM 304 stainless steel sheath emissivity

While it is acknowledged that the FES is not a homogenous material, only one uncertainty value is used for the FES thermal conductivity and specific heat capacity since a lumped parameter approach is used by TUF. Given that the FOM for this work is void fraction, it is not necessary to take into account detailed properties and behaviour of the FES and this approach is sufficient to accurately evaluate the contribution to the calculated uncertainty in void fraction arising from heat transfer rate to coolant.

In the Pickering B IUA, a specific figure of merit for coolant voiding is required. The FOM for coolant voiding is the void fraction at a particular point in time and space.

The RD-14M FOM was chosen to be the coolant void fraction at the location of the neutron scatterometer at the time when the coolant void fraction in the best estimate simulation reached 0.4. The value of 0.4 for the FOM was chosen arbitrarily to generally fall within the rapid portion of the voiding transient for each RD-14M experiment.

The void fraction at a specific point in time cannot be used as the FOM in this study, since it is not possible to develop a scaled time that is characteristic to both RD-14M and Pickering B. This statement should not be misconstrued to mean that RD-14M and Pickering B are not scaled for the phenomena relevant for coolant void generation. Rather, it reflects the practicalities associated with scaling analysis.

The RD-14M neutron scatterometer is located near the centre of the 10th of 12 simulated fuel elements from the inlet of Test Section 14.[1] Test Section 14 has the same feeder characteristics and elevation of a low power channel near the bottom of Darlington NGS (Channel X-12) [3].

The determination of a similar channel in Pickering NGS B is problematic as Darlington NGS and Pickering NGS B are not entirely similar. However, while RD-14M was designed to be representative of Darlington NGS, it will likely represent Pickering NGS B as well.

The channel voiding and flow characteristics are expected to be similar between Darlington and Pickering since the same mechanisms for generation of void are applicable to both and in the same relative magnitudes. These mechanisms are void transport, heat transfer and flashing. Upon initiation of a large break at the Reactor Inlet Header, channels in the broken core pass will undergo rapid voiding at the channel outlets. The flows in these channels will then rapidly reverse.

[1] The neutron scatterometer measures coolant void fraction over a 60 cm section of the RD-14M channel, which spans a region larger than the 10th fuel bundle. To accommodate this region of influence a volume weighted average of bundles 9, 10 and 11 from the TUF model is used to represent the void fraction at the neutron scatterometer.

The channel elevation and power were considered to ensure a reasonable comparison for the RD-14M and Pickering NGS B BEAU uncertainty values for void fraction.

To provide further substantiation for the selection of the Pickering B channel, use was made of the calculated voiding transients obtained in the base case of the Pickering IUA. The voiding transients were obtained for fuel bundle location 10.

From the comparison of the RD-14M measured void transients and simulated Pickering NGS B void transients, the void fraction in channel group 9 (middle elevation, high power), at fuel bundle locations 9, 10 and 11, was chosen for the Pickering NGS B FOM[2].

The selection of another channel group (other than group 9) could possibly result in a slight change in results but would not alter the conclusions reached in this paper.

An order statistics approach [4] to identification of the uncertainty range was used in this analysis. Steps 6 and 7 of the CUE methodology describe the method of creation and execution of the cases. A case in the context of uncertainty analysis refers to a complete set of code input parameters that will produce a code output value (i.e., FOM). A case matrix is a set of ‘n’ cases. A case is defined by randomly sampling each input parameter distribution.

The number of cases, n, used for the case matrix was determined using the following inequality [5], determined by order statistics of a sample from a population with a continuous but unknown distribution function:

$$\gamma \le I_{1-P}\left(m, n-m+1\right)$$

There γ is the confidence level, I is the incomplete Beta function, P is the fraction of the population that lies between r^{th} smallest and s^{th} largest of the sample, and m = r + s. The inequality is applicable to any particular choice of r and s. For one-sided confidence intervals, either r = 0 or s = 0. For a double sided interval, r and s are greater than 0.

The uncertainty quantification in this paper uses 215 cases. With a confidence level of approximately 96%, it can be stated that 95% of the population is between the 3rd minimum and the 3rd maximum obtained from the 215 cases.

The case matrix was executed using TUF for all 215 cases for each RD-14M experiment to produce 215 values for the FOM for each RD-14M experiment.

The FOM values are sorted from smallest to largest and the 3rd and 213th largest values are selected. The difference between these cases represents the extents of the 95/95 tolerance interval of the FOM distribution.

All cases in the case matrix begin from the same steady state analysis. To ensure consistency with the Pickering B IUA, the uncertainties on input parameters are only applied when the

[2] To facilitate comparison with the RD-14M calculations, the calculated Pickering B void fractions at bundle locations 9, 10 and 11 were averaged in an analogous manner to the calculated RD-14M void fractions at simulated bundle locations 9, 10 and 11.

transient portion of the analysis begins (i.e., the time when the break opens).

It is expected that this approach will have a negligible impact on the calculated uncertainty values and the findings contained in this paper for the following reasons:

- The following parameters are not relevant during the steady state since they are not active: the break valve is not open during the steady state, and the RD-14M loop has zero void on the primary side during steady state conditions:

  CHF Multiplier (penalty factor)

  Post CHF HTC

  Single Phase break discharge mass flux

  Two phase mass flux

  Bubble Diameter

  Interfacial Heat Transfer Coefficient

  Interfacial Drag Coefficient

  Virtual Mass Coefficient

  ‘Boiling parameter

  Φ^2 (two-phase multiplier)

  Break Opening Time Initiation

  Break Area
  Sheath Emissivity (304 Stainless Steel)

- Any uncertainty in the pre CHF Heat Transfer Coefficient (HTC), Initial Fuel/Sheath Heat Transfer Coefficient, Fuel Element Simulator Thermal Conductivity, Fuel Specific Heat Capacity or Fuel Element Simulator Thermal Conductivity would be manifested in the fuel element simulator temperatures which are measured accurately to within 1°C.
- Uncertainty in the friction factor would be manifested in the loop and channel flows. The steady state RD-14M flow is liquid and can be accurately measured by the RD-14M turbine flow meters.
- Uncertainty in the Pump Head would be manifested in the RD-14M loop flows which have a small measurement uncertainty.
- The power (Power Supply) was accurately measured during the RD-14M steady state and any variability within the measurement uncertainty can be reasonably expected to have a negligible impact on the calculated uncertainty values.

It was also found that the steady state for test B0302 was inherently unstable. To correct this problem the steady state setup for B0304 (a counterpart test) were used. All cases were executed without failures in all experiments; hence 215 FOM values exist for each experiment.

Table 1: RD-14M Tests Used

Test Number	Break Size [mm]	Single/Multi-Channel?	Channel Power
B0101	30	Multi-Channel	Full/decay
B0102	30	Multi-Channel	No Power
B0103	30	Multi-Channel	No Power
B0105	25	Multi-Channel	Full/decay
B0106	44	Multi-Channel	Full/decay
B0107	35	Multi-Channel	Full/decay
B0108	48	Multi-Channel	Full/decay
B0109	48	Multi-Channel	No Power
B0110	30	Multi-Channel	No Power
B0111	15	Single Channel	Power pulse
B0112	18	Single Channel	Power pulse
B0113	18	Single Channel	Power pulse
B0114	18	Single Channel	Full/decay
B0115	18	Single Channel	Full/decay
B0116	18	Single Channel	No Power
B0117	18	Single Channel	Power pulse
B0118	25	Single Channel	Power pulse
B0301	18	Single Channel	Full/decay
B0302	18	Single Channel	Power pulse
B0303	18	Single Channel	Full/decay
B0304	18	Single Channel	Power pulse
B0305	15	Single Channel	Power pulse
B0306	25	Single Channel	Power pulse
B0307	48	Single Channel	Power pulse
B0308	48	Single Channel	Full/decay
B0309	25	Multi-Channel	Full/decay
B0310	30	Multi-Channel	Full/decay
B0311	48	Multi-Channel	No Power
B0312	48	Multi-Channel	Full/decay

Table 2: Parameter and Distributions

ID	Parameter	Distribution	Type
S01	Pre CHF Heat Transfer Coefficient	Normal	Modelling
S02	CHF Multiplier	Normal	Modelling
S03	Post CHF HTC	Normal	Modelling
S04	Single Phase break discharge mass flux	Uniform	Modelling
S05	Two phase mass flux	Normal	Modelling
S06	Bubble Diameter	Beta	Modelling
S07	Interfacial Heat Transfer Coefficient	Triangular	Modelling
S08	Interfacial Drag Coefficient	Truncated normal	Modelling
S09	Virtual Mass Coefficient	Uniform	Modelling
S10	Boiling parameter	Uniform	Modelling
S11	2 phase multiplier	Normal	Modelling
S12	Friction factor	Normal	Modelling
S13	Initial Fuel/Sheath Heat Transfer Coefficient	Normal	Modelling
S14	Break Opening Time Initiation	Uniform	Plant
S15	Break Area	Half-Normal	Plant
S16	Fuel Element Simulator Thermal Conductivity	Normal	Plant
S17	Pump Head	Normal	Plant
S18	Power Supply	Normal	Plant
S19	Sheath Emissivity	Uniform	Plant
S20	Fuel Specific Heat Capacity	Normal	Plant

4.0 Results

4.1 Uncertainty in the Void Fraction

As part of the FOM selection, case matrix plots are generated. A case matrix plot is a graph of the void fraction at the neutron scatterometer for a given cases for each experiment. The case matrix plots for experiment B106 is shown in Figure 1 for the uncertainty cases. The red line on the plot indicates the best estimate case and the grey lines represent all the cases in the case matrix.

The 95/95 tolerance interval for the FOM of each experiment is listed in Table 3 for all experiments. The LBLOCA tests are shaded, and a separate average is provided for those tests.

The mean and standard deviation of the FOM were averaged over all experiments. The averaged values are listed in Table 4. This table shows that the average value of the FOM from the TUF simulations is slightly lower than 0.4 which corresponds to the best-estimate value.

The uncertainty in the TUF calculation of void fraction for RD-14M large break tests was found to be equal to 0.08 and 0.11 (Table 4) without and with plant parameters, respectively.

The mean standard deviation of the RD-14M figure of merit values for the large break tests (i.e., 0.04 and 0.05 without and with plant parameters, respectively, (Table 4) compares well with the neutron scatterometer measurement uncertainty (0.04[3]). Similarly, the mean standard deviation of the RD-14M figure of merit values for all of the RD-14M LOCA tests (i.e., 0.06 and 0.08 without and with plant parameters, respectively, (Table 4)) is somewhat higher than the overall neutron scatterometer measurement uncertainty (0.04 for large break tests and 0.03 for all other tests). The mean standard deviations above for void are expressed as fractions.

From these findings it can be interpreted that the uncertainty in the TUF calculation of void fraction is sufficiently small to consider the TUF code fit-for-purpose.

In the Pickering B 5-second IUA, the uncertainty in the coolant void fraction was calculated at each point in time[4]. The case matrix plot for Pickering B is shown in Figure 2.

Despite the fact that an estimate of computer code uncertainty cannot be directly obtained from code accuracy values, a comparison of an IUA value and code accuracy can be useful to provide justification for the adequacy of the magnitude of the propagated uncertainty ranges in an overall sense to increase confidence in code predictions for BEAU applications. Consider the circumstance in which a code accuracy value (bias and variability in bias) has been obtained in an Integral Effects Test (IET). Assume that the IET is a reasonable representation of a plant application.

An uncertainty value in an output parameter for the plant application can then be obtained through the propagation of modelling uncertainties by varying modelling parameters around their expected uncertainty ranges. If those modelling parameters adequately characterize the relevant models and their uncertainty ranges are reasonable, the output parameter uncertainty should be fairly close to the estimated value for the variation in code bias for the same parameter.

[3] The 2 standard deviation uncertainty value for the neutron scatterometer used on large break experiments is 0.085 [6]. The 2 standard deviation uncertainty value for the neutron scatterometer used on small break experiments is 0.065 [6].

[4] The Pickering B uncertainty analysis uses 215 cases in its case matrix, similar to the uncertainty analysis documented in this paper. In addition, only the modelling parameters were propagated in the Pickering 5-second BEAU analysis.

Comparison of the estimate of the IUA value and code accuracy is predicated on the code calculation being reasonably accurate – i.e., the bias is zero or close to zero. The code accuracy will therefore be characterized by the variability in the bias. Therefore, the metric for 'propagation of uncertainty and accuracy' is defined as follows[5]:

$$U_{DS} \geq \sqrt{2} \cdot \sigma_B$$

Where U_{DS} is the uncertainty from the Pickering B 5-second BEAU analysis (95/95 tolerance interval),

σ_B is the variability in the bias reported for each RD-14M experiment.

This metric is evaluated graphically by comparing the uncertainty from each point in time from the Pickering B 5-second BEAU analysis to the accuracy reported for RD-14M large break experiment B106 in Figure 3. As the time period over which the variation in bias was calculated is one to two seconds, that time period is over which the comparison of uncertainty and variation is bias is performed.

From the results, the identified input parameters/boundary conditions and their propagated uncertainty ranges, and the representation of the power plant are adequate.

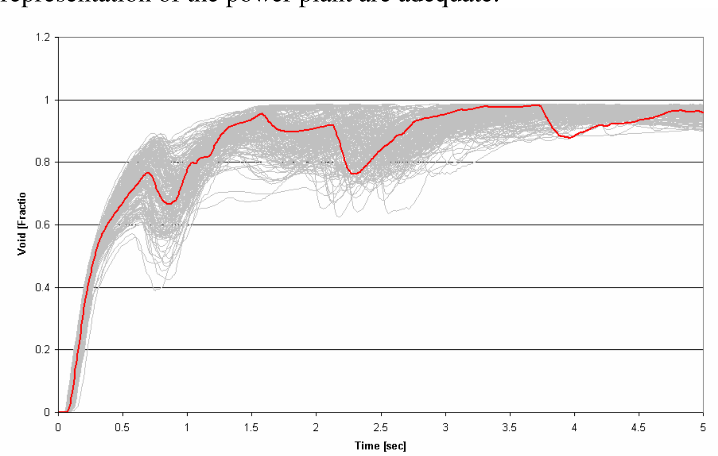

Figure 1: B0106 Void Fraction Transient

Table 3: All Test 95/95 Tolerance Intervals

	Plant Parameters	
Case	**Without**	**With**
B0101	0.29	0.37
B0102	0.46	0.41
B0103	0.31	0.17
B0105	0.24	0.32
B0106	0.08	0.17
B0107	0.43	0.45
B0108	0.09	0.14
B0109	0.19	0.16
B0110	0.42	0.47
B0111	0.14	0.28
B0112	0.35	0.45
B0113	0.33	0.43
B0114	0.31	0.43
B0115	0.35	0.35
B0116	0.62	0.77
B0117	0.34	0.47
B0118	0.11	0.33
B0301	0.31	0.37
B0302	0.14	0.36
B0303	0.20	0.36
B0304	0.15	0.33
B0305	0.13	0.27
B0306	0.14	0.29
B0307	0.07	0.19
B0308	0.07	0.16
B0309	0.25	0.34
B0310	0.32	0.39
B0311	0.24	0.24
B0312	0.09	0.13
Averages		
All	0.25	0.33
LBLOCA	0.15	0.22

[5] It should also be noted that the specific numerical value used in this equation will dependant on the number of data points used to estimate U_{DS} and σ_B and will likely between 1 and $\sqrt{2}$.

Table 4: All Tests FOM Results

	Without Plant Parameters		With Plant Parameters	
Case	Mean	Standard Deviation	Mean	Standard Deviation
B0101	0.41±0.01	0.08	0.40±0.01	0.09
B0102	0.42±0.01	0.10	0.40±0.01	0.10
B0103	0.37±0.01	0.05	0.36±0.01	0.04
B0105	0.41±0.01	0.06	0.40±0.01	0.07
B0106	0.38±0.00	0.02	0.37±0.01	0.04
B0107	0.42±0.01	0.10	0.43±0.01	0.11
B0108	0.38±0.00	0.02	0.38±0.00	0.03
B0109	0.37±0.01	0.04	0.38±0.00	0.03
B0110	0.52±0.02	0.13	0.50±0.02	0.12
B0111	0.39±0.00	0.03	0.38±0.01	0.06
B0112	0.39±0.01	0.07	0.36±0.01	0.10
B0113	0.38±0.01	0.07	0.37±0.01	0.09
B0114	0.36±0.01	0.08	0.34±0.01	0.10
B0115	0.43±0.01	0.06	0.42±0.01	0.08
B0116	0.48±0.02	0.15	0.44±0.02	0.19
B0117	0.38±0.01	0.06	0.36±0.01	0.10
B0118	0.38±0.00	0.02	0.36±0.01	0.08
B0301	0.36±0.01	0.06	0.34±0.01	0.08
B0302	0.39±0.00	0.04	0.37±0.01	0.07
B0303	0.40±0.01	0.04	0.37±0.01	0.07
B0304	0.39±0.00	0.03	0.40±0.01	0.09
B0305	0.39±0.00	0.04	0.38±0.01	0.06
B0306	0.39±0.00	0.03	0.38±0.01	0.06
B0307	0.38±0.00	0.02	0.37±0.01	0.04
B0308	0.39±0.00	0.02	0.38±0.00	0.03
B0309	0.40±0.01	0.06	0.39±0.01	0.07
B0310	0.41±0.01	0.09	0.40±0.01	0.09
B0311	0.35±0.01	0.06	0.35±0.01	0.06
B0312	0.38±0.00	0.02	0.37±0.00	0.03
Averages				
All	0.40	0.06	0.38	0.08
LBLOCA	0.38	0.04	0.378	0.05

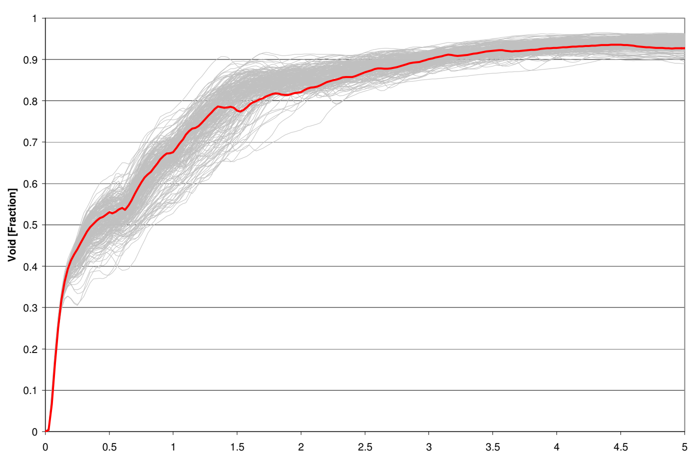

Figure 2: Pickering B Void Fraction Transient

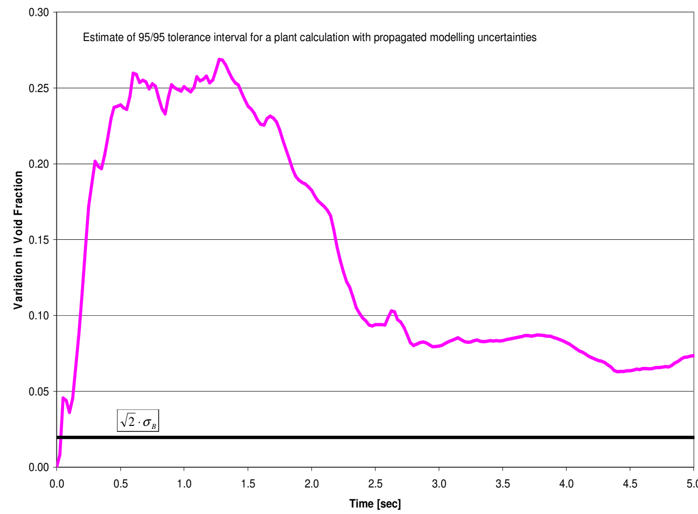

Figure 3: B0106 Comparison of TUF and Plant

4.2 Sensitivity Analysis

A Morris [7] sensitivity plot for a typical RD-14M large break test is given in Figure 4.

A Sobol [8] sensitivity plot for the same test is given in Figure 5.

A typical comparison plot for the Morris and Sobol sensitivity rankings is given in Figure 6. This plot compares the relative normalized Morris and Sobol rankings. If the values of both rankings are comparable (i.e., on the same order of magnitude), this indicates that both the Morris and Sobol analysis gave the same importance/weight to the parameter. However, if the rankings are not comparable, then the one with the highest ranking was deemed to be more important in that analysis (i.e., if the Sobol ranking is greater than the Morris ranking, then the parameter was more important in the Sobol analysis than the Morris analysis).

Note that there is a one-to-one correspondence between the parameter numbers in Table 2 and the ones in the Morris, Sobol and comparison plots.

In the Morris plots, parameters which have a relatively large mean are those whose contributions are linear, while those with high standard deviations are more non-linear. In other words, parameters with high means are important contributors to the overall variability on their own, while those with high standard deviation are important in conjunction with other terms.

The Sobol measure is a measure of the amount of the total variance in the FOM due to each parameter, including all combinations with other parameters.

The single most important parameter in the TUF simulation of the RD-14M large break LOCA tests is the single-phase break discharge mass flux. Two-phase break discharge flow does not appear as a sensitive parameter, since the break discharge flow is primarily a single-phase liquid during the time period considered. The break opening time (break opening characteristic) is also an important parameter.

This finding is not surprising as the break characteristics control both the initial rate of depressurization and bulk motion of fluid.

Other findings arising from the Morris and Sobol sensitivity analysis include the following:

- The heated section power is consistently an important parameter second only to the single-phase break discharge mass flux.
- Interfacial shear stress (interfacial drag coefficient) and bubble diameter are consistently important parameters.
- The void fraction shows a non-linear sensitivity to pump head and heated section power.
- The RD-14M tests in the single channel configuration (B0306, B0307 and B0308) show a high degree of sensitivity to break opening time, heated section power, pump head and single-phase break discharge flow.

The sensitivity of the Pickering B IUA TUF results to variations in the modelling parameters was assessed in a similar manner to the RD-14M cases discussed in the previous section. Some of the modelling parameters, such as power supply and break opening time, are not relevant to the Pickering IUA simulations and were not included in the assessment.

The highest ranked parameter in the Pickering IUA was the fuel sheath heat transfer coefficient (gap conductance). The next two highly ranked parameters were bubble diameter and interfacial heat transfer coefficient. The boiling parameter and interfacial drag coefficient are also relatively high ranked. Modelling parameters related to fuel and fuel-to-coolant heat transfer (fuel thermal conductivity and post CHF heat transfer coefficient) also show a moderate degree of influence.

A comparison of the RD-14M and Pickering IUA modelling parameter rankings indicate a high degree of consistency:

- The highest ranking RD-14M modelling parameters are related to the impact of the break: single-phase break discharge mass flux and break opening time. These parameters are not expected to have a large impact on the Pickering IUA as the break size is large enough that any variations will have negligible effect and the break is assumed to open instantaneously. Modelling parameters characterizing voiding effects related to break flow and depressurization (bubble diameter, interfacial heat transfer and boiling parameter), however, are highly ranked in both the RD-14M and Pickering IUAs, as were parameters important to void transport such as interfacial drag.
- The RD-14M power supply was also highly ranked. As discussed previously, the analogous Pickering IUA parameter (reactor power) was not included in the sensitivity assessment. However, the parameter that limits the transfer of power from the fuel to the coolant (gap conductance) is highly ranked in the Pickering B IUA. That finding indicates that heat transfer from the fuel (FES in the case of RD-14M) is an important mechanism for vapour generation in both RD-14M and Pickering B.

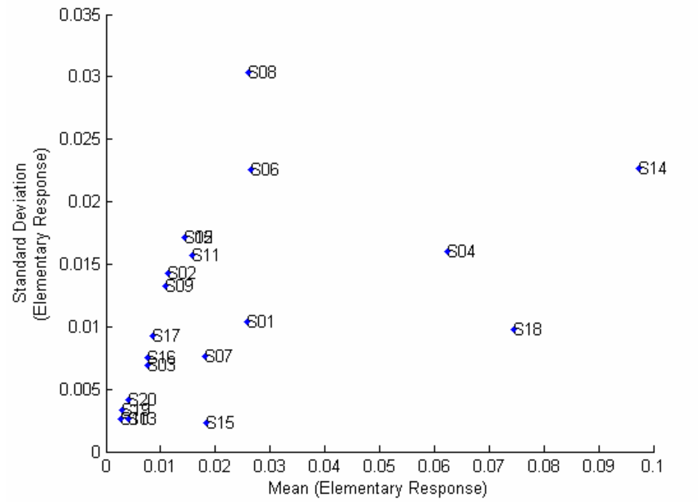

Figure 4: B0106 Morris Sensitivity Plot

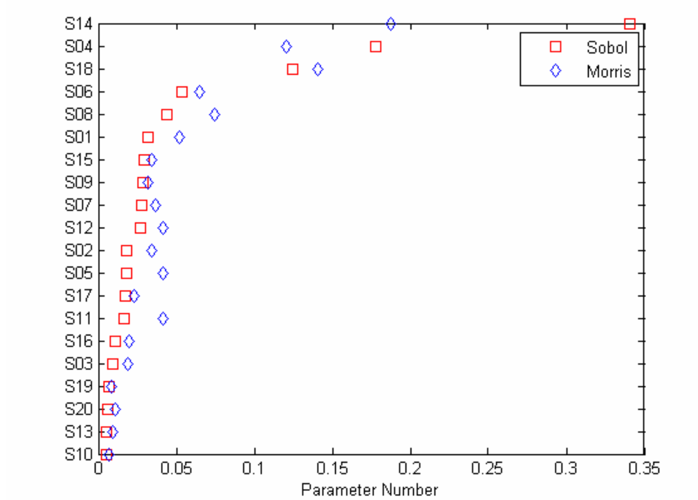

Figure 5: B0106 Comparison of Morris and Sobol' Sensitivity

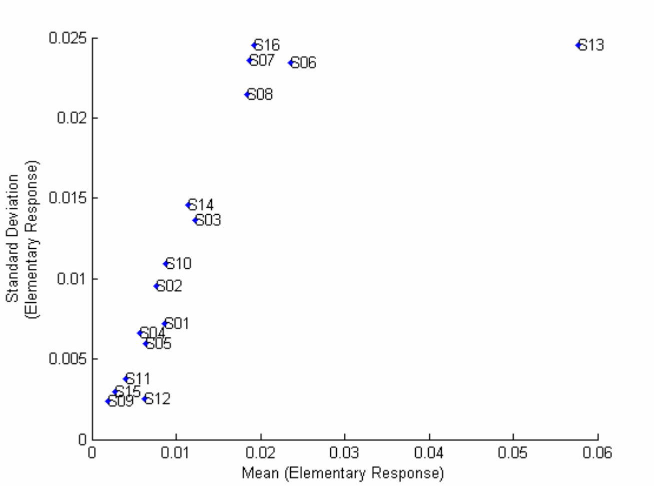

Figure 6: Pickering B Morris Sensitivity Plot

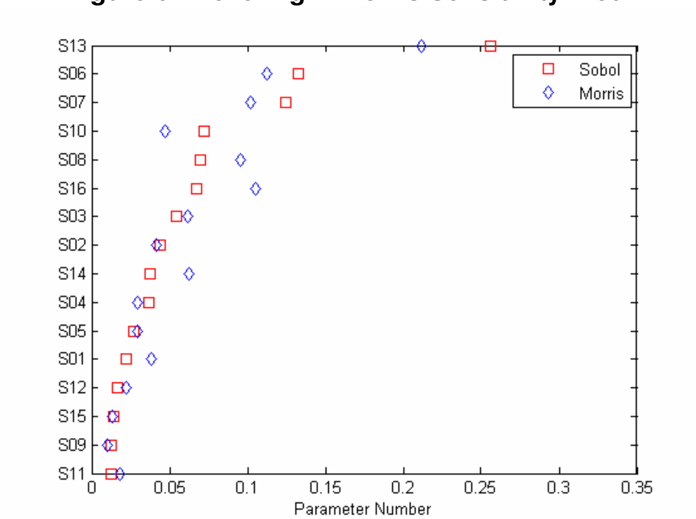

Figure 7: Pickering B Comparison between Morris and Sobol' Sensitivity

5.0 Summary and Conclusions

The CUE methodology has been employed using simulations of large break LOCA tests in RD-14M to calculate the uncertainty in the TUF calculation of coolant void fraction. The uncertainty has been estimated with and without plant parameters (parameters specific to the RD-14M test loop). The TUF coolant void fraction uncertainty without plant parameters was determined to be 0.08, while the uncertainty with plant parameters included was determined to be 0.11[6].

The uncertainty value without plant parameters included is comparable to the uncertainty in the neutron scatterometer measurements (0.09). The uncertainty value with plant parameters included is larger than the variation in the bias (0.10) of the TUF calculation of void fraction. From these findings, it can be concluded that the estimated validity of the TUF code calculation of void fraction is consistent with the available experimental data.

Sensitivity assessments performed for the RD-14M and Pickering IUAs have shown consistency in the parameter rankings, thus confirming the applicability of RD-14M for use in a comparison of an integral effects test with a plant calculation.

The uncertainty in the TUF calculation of void fraction obtained from the Pickering B IUA results using only propagated modelling uncertainties was found to be larger than the variability in the TUF code bias as determined from simulation of large break LOCA tests in RD-14M. This finding indicates that the Comparison of Propagated Uncertainty and Accuracy metric is satisfied.

From the above findings, it can be concluded that the adequacy and completeness of the LBLOCA modelling parameters, and their associated uncertainty ranges as used in the Pickering B BEAU analysis has been further substantiated by extensive comparisons against a correctly scaled integral test facility.

[6] The uncertainty value for the case with plant parameters included is quoted to facilitate comparison with the variation in bias. The influence of plant parameters (boundary conditions) cannot be removed from the calculation of code accuracy.

6.0 References

1. L. Blake, et. al., "Best Estimate Plus Uncertainty Analysis of LBLOCA for a Pickering B CANDU Reactor," Proceedings FEDSM2010-ICNMM2010, Montreal, August 2010.
2. J.R. Buell, P.J. Ingham, and R.S. Swartz, "RD-14M LOCA Tests with Channel Void Measurement: Phase II Tests, B0111-B0118", CANDU Owners Group Document No. COG-01-169, April 2002.
3. "Intercomparison and Validation of Computer Codes for Thermalhydraulic Safety Analysis of Heavy Water Reactors," IAEA-TECDOC-1395, August 2004.
4. H. Glaeser, "Uncertainty Evaluation of Thermal-Hydraulic Code Results", International Meeting on "Best Estimate" Methods in Nuclear Installation Safety Analysis (BE-2000), Washington DC, November 2000.
5. P.N. Somerville, "Tables for Obtaining Non-Parametric Tolerance Limits", the Annals of Mathematical Statistics, 29, 1958, pp 599-601.
6. J.R. Buell, D.P Byskal, M.R. Desrosiers, E.M.A. Hussein, P.J. Ingham and R.S. Swartz, "A Neutron Scatterometer for Void-Fraction Measurement in Heated Rod-Bundle Channels Under CANDU LOCA Conditions, " International Journal of Multiphase Flow, Volume 31, Issue 4, April 2005, pp. 452-472.
7. F. Campolongo, J. Cariboni, A. Saltelli and W. Schoutens, " Enhancing the Morris Method," Sensitivity Analysis of Model Output K. Hanson and F. Hernez, eds. 2005, LANL.
8. I. M. Sobol', "Sensitivity Estimates for Non-Linear Mathematical Models," Matematicheskoe Modelirovanie, Vol. 2, 1990.