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CANDU 9 Large LOCA Uncertainty Analysis

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ABSTRACT

This paper describes the application of a structured approach for the uncertainty assessment to a postulated limiting large Loss-of-Coolant Accident (LOCA) for the CANDU 9 reactor. The structured approach is based on an integrated three step process of code, representation, and plant uncertainty assessment. The process is made manageable by ranking important phenomena/parameters and assessing only the most important uncertainty sources. The analysis is structured into power pulse phase followed by blowdown phase. A fractional factorial Latin hypercube experimental design is used to determine the calculation matrix for each phase. The power pulses obtained in the power pulse phase are used as one out of a total of five key input (uncertainty source) parameters in the blowdown phase. Based on the results of the calculation matrix of the blowdown phase, a response surface for the maximum sheath temperature as a function of the five input uncertainty source parameters is generated. The response surface is randomly sampled to generate the probability distribution function and the associated 95% confidence level for the maximum sheath temperature. Finally, this maximum sheath temperature is adjusted with additional identified biases. The results show that the acceptance criteria of no sheath melting is met with high confidence level.

INTRODUCTION

Current licensing practice is based on a conservative approach in which the safety analyses are performed with the assumption that the relevant plant operating parameters are set simultaneously at their limit of operating envelope (LOE). This approach can lead to underestimating the margin. A more realistic estimate of the safety margin can be obtained through the use of best-estimate safety analysis methods coupled with estimate of the uncertainty in the calculated acceptance parameters.

This paper describes a detailed uncertainty analysis for the power pulse and blowdown phases of a postulated limiting large LOCA event for the CANDU 9 reactor. It is structured to start with a brief review of the generic methodology (Reference 1), followed by its application on a large LOCA event. The main objective of this analysis is to demonstrate the application of the methodology and to show that by setting few selected parameters at their best estimate values and considering their uncertainties while keeping most of the analysis assumptions and boundary conditions at their conservative values, the acceptance criterion of no sheath melting is met with high confidence level.

THE GENERIC SAFETY UNCERTAINTY ANALYSIS

A systematic methodology for conducting uncertainty analysis has been developed (Reference 1). The structured generic approach of conducting uncertainty analysis is summarized in Figure 1. This methodology is based on an integrated three step process of code, representation, and plant uncertainty assessments. The process is made manageable by ranking important phenomena/parameters and assessing only the most important uncertainty sources. The overall uncertainties for selected safety parameters, with an associated confidence levels, are obtained by combining uncertainties from the identified sources through standard methods.

The main steps of this approach are summarized as follows:

1. Select accident scenario.
2. The event sequence is examined and the important output parameters are identified.
3. An analysis code suite and method for conducting the analysis are selected. The applicability of the code to the phenomena of importance to the specified transient and plant are stated.
4. Parameters and phenomena, which are important to the significant output parameters identified in each phase of the transients are ranked in a Phenomena Key Parameter Importance Ranking Table (PKPIRT). The uncertainty of the parameters and phenomena listed in the PKPIRT are classified into three categories namely code, representation and plant uncertainties.
5. The bias, uncertainty range, and probability distribution for the key parameters, identified in PKPIRT, are specified and documented. Such information which is related to code models and correlations is obtained from code validation, while that related to plant parameters is obtained from plant operation, plant design tolerances , and instrument error and trip setpoints. Other sources of uncertainty which could arise from idealizing the real plant such as nodalization and scaling are included under representation uncertainty.
6. To assess the contribution to overall uncertainty of an output parameter, the sensitivity of the analysis to variations in input/model parameter variability is assessed. In the final assessment, only those input/model uncertainties that make a significant contribution to the output parameters are considered while setting the rest at their conservative values. The calculation matrix for the selected set of input parameters is designed to cover the whole range of each parameter in a balanced fashion and to capture the interactions between the parameters. The calculation matrix generates the data of the output parameter in response to the variation of input parameters.

7. Based on the results of the calculation matrix, a response surface is generated by fitting the output parameter as a function of uncertainty source parameters. If the function form of the equation is not known, a generalized polynomial of sufficient order is usually used.
8. Random number generators are used to sample the response surface to generate the probability distribution function (PDF) and the cumulative distribution function (CDF) of the output variable and the associated statement of confidence levels. In general a 95% confidence levels are appropriate to give the overall random uncertainty in the output variables.
9. Finally, any identified bias, which has not been included in the response surface analysis, is added to the calculated random uncertainty in the output parameters to give the final uncertainty value.

ANALYSIS SCOPE

The analysis is structured as three phases: break survey, power pulse and blowdown. The break survey phase is to identify the critical break size. The analyses for both the power pulse and blowdown phases are conducted on this limiting break size. The power pulse phase is designed to obtain the power pulse uncertainty range. This power pulse is then used as input boundary conditions for the blowdown phase calculations. The blowdown phase is to obtain the probability distribution of maximum temperature and the associated 95% confidence level.

CODE SUITE AND MODELS

Code Suite

The power pulse calculation is conducted by a coupled CATHENA-RFSP codes. With power pulse as input boundary condition, the thermal-hydraulics and fuel channel calculations are conducted using CATHENA.

CATHENA (Reference 2) is a transient, one-dimensional, two-fluid thermal hydraulic computer code developed by AECL at Whiteshell Laboratories (WL) primarily for the analysis of postulated upset conditions in CANDU nuclear reactors. The CATHENA version (MOD-3.5c/R0) used allows conducting sensitivity analysis by including the ability of varying a number of parameters and correlations implemented in CATHENA.

The RFSP code (Reference 3) is a two neutron group three dimensional finite difference static neutron diffusion code which incorporates CERBERUS for calculation of fast spatial transients, such as large LOCA in CANDU reactors and POWDERPUF to calculate lattice cell cross sections modules

The calculation matrix, which is equivalent to experiment design, for the various phases of the analysis is designed through using SAMPLE2 computer code (Reference 4) which is explicitly written to generate experimental designs. Random value generation is conducted by SAMPLE2 and/or Microsoft EXCEL. Generating response surfaces, and performing statistical analysis on the output variables are conducted using Microsoft EXCEL.

Models

Power Pulse Models. In the reactor physics model, a three dimensional core model is set up with the RFSP code for the static calculation of the initial condition. The model includes adjuster rods, shutdown rods, zone controller compartments, and all in-core structure.
The primary heat transport and steam and feedwater systems are modeled with CATHENA. To provide a better spatial resolution for the neutronics calculations, a 10 average channel CATHENA model is used.

Blowdown Models
A four average channel CATHENA model (i.e. one average channel for each core pass) with an attached emergency core cooling system (ECCS) model is used for the blowdown phase simulations. This model uses the power pulse as a boundary condition and generates the thermalhydraulic conditions in the headers Using the header thermalhydraulic conditions as boundary conditions, a single high power channel model is used to predict the maximum fuel and sheath temperatures.

BREAK SURVEY

The critical size of a primary pump suction break is postulated in the analysis. This phase includes the analysis of various break sizes and starts from coupled thermalhydraulic-physics simulations to determine power pulse and system thermalhydraulic response, followed by evaluating the maximum sheath temperature in a licensing channel model for each break size. This analysis indicated that the worst break size, in terms of maximum sheath temperature, is the 25% break. Accordingly, this break size is identified as the critical break and is used for the subsequent uncertainty analysis reported in this paper.

POWER PULSE PHASE

The main objective of the power pulse phase is to obtain the uncertainty range of the power pulse to be used as one of the input parameters to the uncertainty analysis of the blowdown phase. The range and distribution of the power pulse is calculated by considering the uncertainty in the key phenomena and parameters affecting the power pulse. The output parameter for this phase is the power pulse and its deposited energy.

Phenomena Key Parameter Importance Ranking Table (PKPIRT)

The identified parameters are those that could affect deposited energy. These parameters are identified and ranked according to their importance, in terms of influencing power pulse. The ranking is based on sensitivity calculations, expert judgment and peer review.
In principle, all code, representation and plant parameters should be set to their best estimate values and consider their uncertainties. This approach can quickly lead to a huge number of simulations and become impractical. Accordingly, the current approach is to identify the parameters which have the biggest affect on the power pulse. Only these important parameters are considered in the uncertainty analysis. Other identified parameters are set at their conservative values. The parameters which are set to their conservative values include bulk power, flux tilt, moderator isotopic, coolant isotopic, pressure tube creep and trip set points. The importance of the fuel thermal conductivity and fuel-to-sheath heat transfer is recognized. However, it is found that these parameters mainly affect the steady state stored energy of the fuel rather than the relative power. Accordingly, these parameters are included in the blowdown phase.

The parameters that are considered in the uncertainty analysis of the power pulse are critical heat flux, coolant void reactivity, post dryout heat transfer and moderator poison. The uncertainty range and distribution of these four parameters used in the analysis are shown in Table 1.

Calculation of the Power Pulse Range

A calculation matrix of 24 runs is designed using SAMPLE2 (Reference 4). The fractional factorial / latin hypercube option is selected. The fractional factorial part of the design guarantees getting good coverage of the combinations of parameters. The latin hypercube part guarantees covering the entire range of each parameter in a balanced fashion.

The 24 runs are performed through coupled CATHENA-RFSP simulations. For each run, based on the uncertainty values of the input parameters, the steady state conditions are obtained. Then two transient coupled CATHENA-RFSP simulations, the first to identify the trip time and the second to calculate the power pulse using the identified trip time, are performed. Using POWDERPUFS, the required CVR level of each run is achieved by changing the coolant purity.

The power pulse uncertainty range is defined by the limits of the power pulses calculated for the 24 designed runs. For each run, both the worst bundle and core averaged power pulses are obtained. The power pulse with the uncertainty range is used as one of the key input parameters in the blowdown phase analysis.

BLOWDOWN PHASE

The analysis of this phase is conducted from the initiation of event (t=0) to about 60 seconds where channel heat-up is terminated by the emergency core cooling system (ECCS) injection. The objective of this phase is to estimate the uncertainty in the output parameter, i.e. maximum fuel sheath temperature.

Phenomena Key Parameter Importance Ranking Table (PKPIRT)

The PKPIRT of this phase includes parameters that affect the maximum fuel and sheath temperatures. The fuel peak temperature follows the power pulse very closely, practically without time delay. The maximum sheath temperature occurs around 20 s after event initiation due to flow degradation. Accordingly, the output parameter, i.e. maximum fuel sheath temperature is not sensitive to parameters that only affect the late blowdown phase. The parameters which affect the late blowdown phase (e.g. ECCS related parameters) could influence the uncertainty of the pressure tube heatup which is not the topic of this paper.

Based on ranking of importance, the selected parameters which are included in the blowdown uncertainty analysis are power pulse, maximum channel power, fuel thermal conductivity, fuel gap conductance and fuel sheath emissivity. The range and distribution of these parameters, used in the analysis, are shown in Table 2. Other identified parameters are either set at their conservative values, having no effect on the present case or dealt with as a bias.

Blowdown Phase Calculations

A calculation matrix of 32 runs is designed using SAMPLE2. Similar to the power pulse phase analysis, the fractional factorial / latin hypercube option is selected.

With the exception of the power pulse, all parameters are set at their nominal values in the circuit model. For each of the 32 runs, the core averaged power pulse is used in the circuit model to generate the header thermal hydraulic boundary conditions. Then, the single channel model is modified based on the uncertainty values suggested by the calculation matrix. These include the worst bundle power pulse, channel power, fuel sheath emissivity, fuel gap conductance and fuel thermal conductivity. Prior to simulate the transients, a steady state run is conducted to obtain the new starting conditions of the transient.

Response Surface

The procedure of generating the response surface of the maximum sheath temperature is summarized by the following steps:

1. Check sensitivities of the output parameter to every input parameter by plotting the whole 32 data points and conducting an analysis of variance (ANOVA). This helps in identifying the trends, importance and dependencies of the various parameters.

2. Fitting the response surface in steps. Starting with linear terms, followed by adding second degree terms and then interaction terms. In each step, the coefficient of determination (r^2), F statistic, and t-statistics are obtained. The F statistic is to determine whether the results, with high r^2 value, occurred by chance. There is a relationship among the variables if the F-observed statistic is greater than an F-critical value which is based on the number of variables, number of observations and confidence level. The t statistics (coefficient divided by its standard error) of each coefficient of the obtained polynomial determines whether each coefficient is valuable for the proposed response surface to eliminate terms with small t statistics.
3. In principle, it is better to validate the obtained response surface using data set which are not used in fitting the response surface. However, the use of the fractional factorial/latin hypercube experimental design ensures good coverage of the uncertainty domain. Accordingly, the present analysis only adds a bias to account for the added uncertainty due to the fitting process. This bias is based on the root mean square (RMS) of the residuals.

After going through the steps of generating the response surface discussed above, the final form is a 14 terms function which consist of five linear terms, three second degree terms and six interaction terms. The regression analysis is conducted by EXCEL after including the second degree and interaction terms for the 32 runs.

Probability Distribution Function and the Associated 95% Confidence Level

In generating the probability distribution function for the maximum sheath temperature, the following steps are followed.

1. Using SAMPLE2, 10000 random values (0-1) for the five parameters are generated.
2. Based on the uncertainty range and distribution of each parameter, the random values are converted to uncertainty values.
3. Using the response surface, the maximum sheath temperature for the 10000 runs are calculated.
4. The probability distribution function (PDF) and the cumulative distribution function (CDF) of the maximum sheath temperature are plotted.
5. Descriptive statistics and the one sided 95% confidence level of the maximum sheath temperature are obtained.

The PDF and CDF of the maximum sheath temperature is shown in Figure 2. The calculated mean value of the maximum sheath temperature is 1398 ^{o}C and the standard deviation of the distribution is 63 ^{o}C. The one sided 95% confidence level is 1512 ^{o}C which is represented by the highest 500th among the 10000 runs.

The convergence of the probability distribution function and the effect of selecting different random seed as well as the different random generators are also investigated. The convergence is tested by comparing the results when only 6000 or 8000 random runs are considered in generating the distribution of the maximum sheath temperature. As shown in Table 3, convergence is achieved since the number of random numbers has insignificant effect. Moreover, both SAMPLE2 and EXCEL, and the two different 10000 sampling result in a difference of less than 2 ^oC.

Biases

The results should be corrected for additional biases which are identified but have not been considered in the analysis. Sources of biases in the current analysis are discussed below.

Minimum Film Boiling Temperature The uncertainty in minimum film boiling temperature (rewetting temperature) predicted by CATHENA shows some effect on the maximum sheath temperature . However, the uncertainty of this parameter is neither included nor set at its conservative value. Lowering the rewetting temperature by ε-2σ, where ε is the bias and σ is the standard deviation, results in increasing the maximum sheath temperature of the licensing channel by 15 ^oC. Accordingly, a bias of 15 ^oC is added to the maximum sheath temperature.

Fuel Gap Conductance The analysis shows that the results are very sensitive to gap conductance. The analysis is conducted with assuming that during the transient, the fuel gap conductance remains at its steady state value. The effect of this assumption on the results, is investigated through conducting more detailed fuel analysis using ELOCA computer code that has been developed to estimate the thermo-mechanical response of, and associated gaseous fission product release from, CANDU fuel elements during transients (References 5). The results of a coupled CATHENA-ELOCA analysis for the single channel model used in the present analysis indicated that after bundle power peaking, the gap conductance of the high power bundles (center bundles) drop sharply to very small values. This drop in gap conductance results in significant reduction in the predicted maximum sheath temperature. The results show no effect of the drop in fuel-to-sheath heat transfer on the maximum fuel centerline temperature. This is because the maximum fuel centerline temperature occurs prior to the sharp drop in gap conductance. To isolate such effect, the transient gap conductance is implemented in CATHNEA as an input table rather than using constant value. This resulted in a conservative estimate of 71 ^oC overprediction in the maximum sheath temperature.

Response Surface Fitting and Random Value Generation

The calculated root mean square of the residuals of 5 ^oC is considered as an additional uncertainty source due to the curve fitting process. Moreover, a 2 ^oC difference between the results obtained using two different random value generators, i.e. SAMPLE2 and EXCEL, is also considered as an additional bias.

RESULTS

Considering the identified biases, discussed in above, to the calculated 95% confidence values results in a maximum sheath temperature of 1463 ^{o}C as shown in Table 4. Based on sheath melting temperatures of 1760 ^{o}C, the margin to sheath melting is 297 ^{o}C. It should be noted that even for 99% confidence limit with including biases, a margin to sheath melting of 249 ^{o}C is obtained.

CONCLUSION

The application of the generic methodology for uncertainty analysis is demonstrated on large LOCA event applied to the CANDU 9 reactor. This analysis shows that by setting few selected parameters at their best estimate values and considering their uncertainties while keeping most of the analysis assumptions and boundary conditions at their conservative values, the acceptance criteria of no sheath melting is met with high confidence level.

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Table 1 Uncertainty Range and Distribution of Power Pulse Parameters

Parameter	Uncertainty Range	Notes	Distribution
CHF	Multiplier 1 to 6	3 for dryout spread over the bundle 2 for transient effect (Multiplier 3x2)	uniform
CVR	+3 mk to +5 mk	4 mk for the bias between PPV and WIMS ±1 mk for random uncertainty	uniform
Poison	0 to 4.26 ppm	0 for normal load, 4.26 ppm for max. load	Beta
PDO	bias -1.2% standard deviation 6.9%		normal

Table 2 Parameter Uncertainty Range and Distribution of Blowdown Phase

Parameter	Uncertainty Range	Notes	Distribution
Power Pulse (worst bundle)	3192 - 3984 kJ	from power pulse phase results	uniform
Max. Channel Power	6.865 - 7.3 MW	lower bound - fuelling study upper bound - licensing limit	uniform
Fuel Thermal Conductivity	standard Deviation 0.2 W/m.K		normal
Fuel Gap Conductance	5 - 15 $kW/m^2.K$	nominal 10 $kW/m^2.K \pm 50\%$	uniform
Fuel Sheath Emissivity	0.7 - 0.85	range for oxidized sheath	uniform

Table 3 Convergence and Sensitivity Studies on the 95% Confidence level of the Maximum Sheath Temperature

Convergence

No. of Runs	Mean	Std. Deviation	95%
6000	1397.78	62.93	1511.12
8000	1398.06	63.14	1511.34
10000	1398.28	63.21	1511.71

SAMPLE2 Sensitivity to Random Seed

Seed #	Mean	Std. Deviation	95%
1	1398.28	63.21	1511.71
3	1398.73	63.55	1513.29

EXCEL Sensitivity to Random Seed

Seed #	Mean	Std. Deviation	95%
1	1399.94	63.77	1515.56
3	1398.71	64.12	1513

Table 4 Final Results

Parameter	Max. Fuel Sheath Temperature (^oC)
Calculated value with 95% confidence level	1512
Response Surface Fitting Bias	5
Random Value Generator Bias	2
Minimum Film Boiling Bias	15
Fuel Gap Conductance Bias	-71
Total	1463

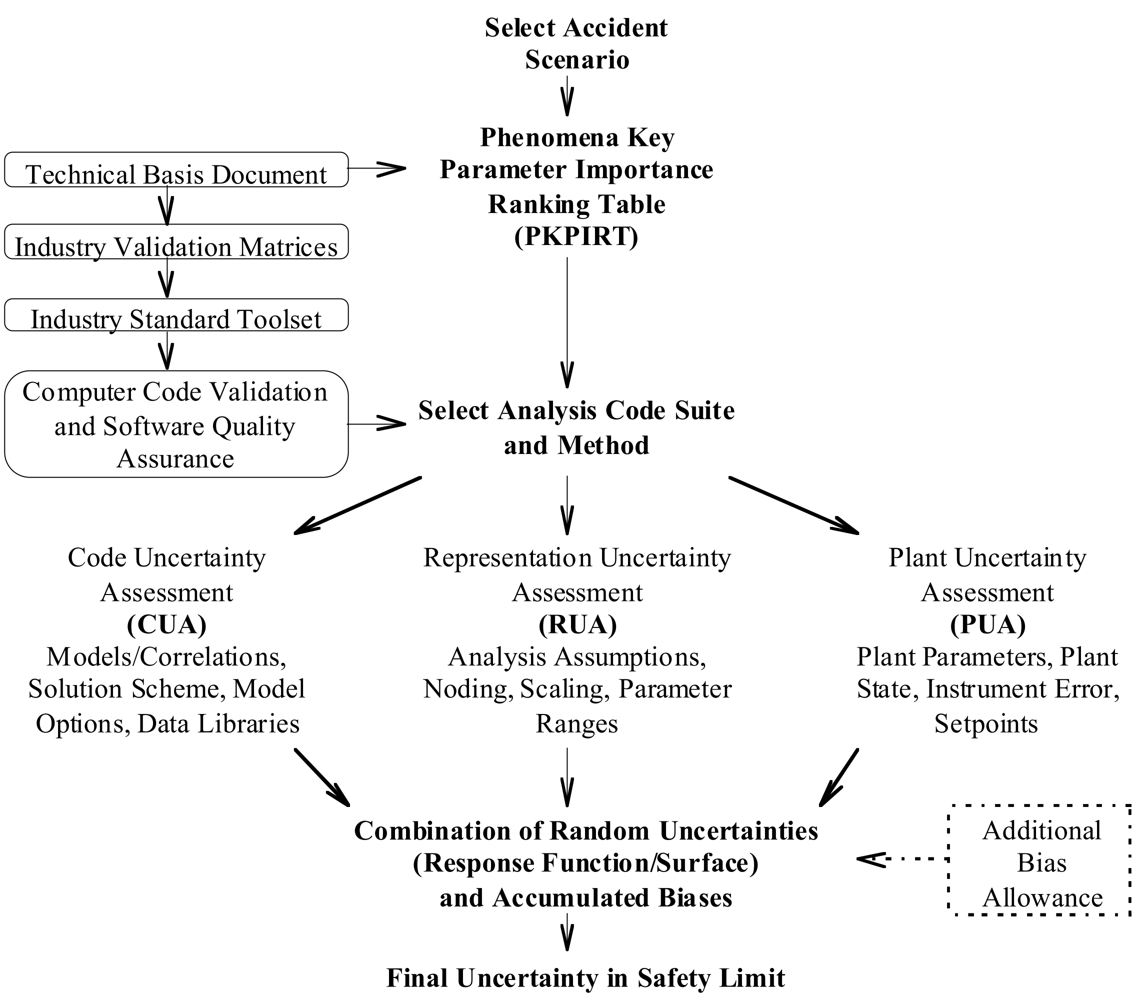

Figure 1 Information and Process Flow Within the Structured Approach to Uncertainty

Assessment

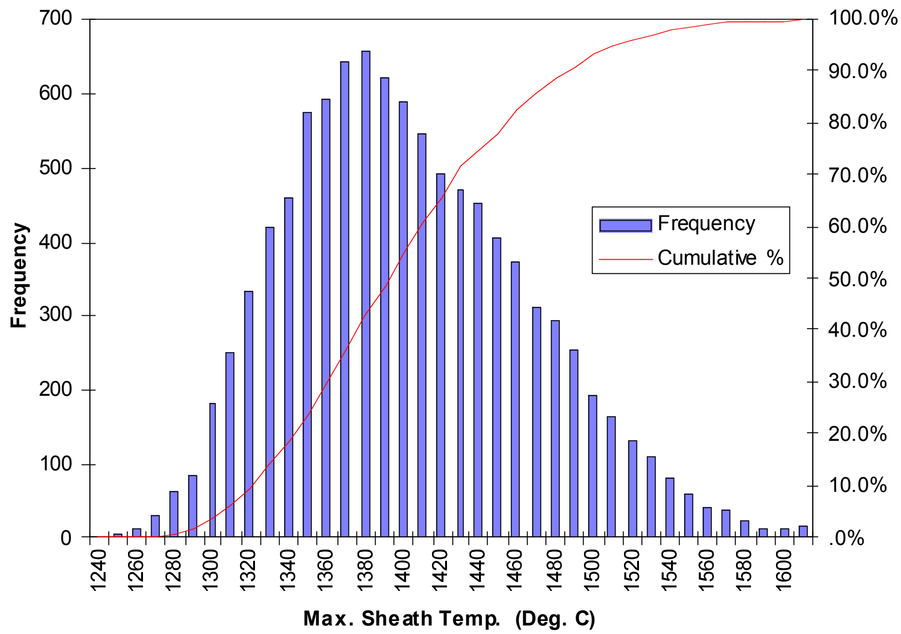

Figure 2 PDF and CDF of the Maximum Sheath Temperature