NUREG/IA-0428

International Agreement Report

Performing Uncertainty Analysis of IIST Facility SBLOCA by TRACE and DAKOTA

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Washington, DC 20555-0001

Manuscript Completed: March 2013
Date Published: September 2013

Prepared as part of
The Agreement on Research Participation and Technical Exchange
Under the Thermal-Hydraulic Code Applications and Maintenance Program (CAMP)

Published by
U.S. Nuclear Regulatory Commission

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ABSTRACT

Nowadays, the increasing computing speed realizes the quantification of propagation of input uncertainties to output data with Monte Carlo simulation or modified simulation methods. The best estimate plus uncertainty (BEPU) methods have been proposed to be used instead of typical conservative methodologies. Based on the CAMP activity, this project demonstrates the capability of SNAP-TRACE-DAKOTA for 2 % small break LOCA (SBLOCA) of IIST experiment. The number of samples was determined by Wilks' formula to generate the upper bound of peak cladding temperature (PCT) with 95/95 confidence level and probability. The PCTs by IIST experiment and best-estimate calculation are 804 K and 861 K respectively. The mean value and standard deviation of the 59 trial by SNAP-TRACE-DAKOTA are 938.7 K and 63.6 K respectively, and the maximum value of PCT is 1054 K.

FOREWORD

The US NRC (United States Nuclear Regulatory Commission) is developing an advanced thermal hydraulic code named TRACE for nuclear power plant safety analysis. The development of TRACE is based on TRAC, integrating RELAP5 and other programs. NRC has determined that in the future, TRACE will be the main code used in thermal hydraulic safety analysis, and no further development of other thermal hydraulic codes such as RELAP5 and TRAC will be continued. A graphic user interface program, SNAP (Symbolic Nuclear Analysis Program) which processes inputs and outputs for TRACE is also under development. One of the features of TRACE is its capacity to model the reactor vessel with 3-D geometry. It can support a more accurate and detailed safety analysis of nuclear power plants. TRACE has a greater simulation capability than the other old codes, especially for events like LOCA.

Taiwan and the United States have signed an agreement on CAMP (Code Applications and Maintenance Program) which includes the development and maintenance of TRACE. INER (Institute of Nuclear Energy Research, Atomic Energy Council, R.O.C.) is the organization in Taiwan responsible for the application of TRACE in thermal hydraulic safety analysis, for recording user's experiences of it, and providing suggestions for its development. In this report, the GRS method is applied to perform the uncertainty analysis for IIST 2 % SBLOCA transient. All steps of analysis procedure including random sampling, data communication, TRACE execution, and DAKOTA post-analysis are integrated via SNAP.

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EXECUTIVE SUMMARY

A RHRP IIST facility has been established for safety studies of the Westinghouse three loops PWR. The scaling factors of the IIST facility for height and volume in the RCS are approximately 1/4 and 1/400, respectively. The maximum operating pressure of the IIST facility is 2.1 MPa. The IIST facility has three loops as well as all the systems which are about studying Westinghouse PWR plant system transients. An experiment of the IIST facility was finished which simulated a 2% cold-leg-break LOCA with total HPI failure. This break was located in loop 2 of IIST facility, which is one of the two loops that do not have a pressurizer.

The TRACE model of IIST facility has been developed which described in the NUREG report (IA-0252). Besides, comparing the results of TRACE and IIST data, it indicates that they are in reasonable consistency. In this report, the GRS method is applied to perform the uncertainty analysis for IIST 2 % SBLOCA transient.

The GRS method was used to investigate the propagation of input uncertainties to output data. The input parameters with uncertainties of TRACE IIST model were generated randomly based on specified PDFs. The number of samples was determined by Wilks' formula to generate the upper bound of PCT with 95/95 confidence level and probability. All TRACE runs were defined and executed through SNAP job streams, and TRACE calculation results were read by AptPlot script. The data interactions and communications between TRACE and DAKOTA were controlled by SNAP.

The analysis results indicate that the upper bound of PCT is 1054 K by GRS method. The ranking coefficients indicate that the break area is the most sensitive among 5 selected input parameters (thermal power, U-tube heat transfer area, heater heat transfer area, feedwater temperature, break area). However, users are not able to define all considered input parameters as SNAP UDN variables under SNAP 2.0.6 environment due to the limitation of SNAP numerics module; several important parameters such as initial water level and pressure, and cell volume are not able to be involved in uncertainty analysis via SNAP.

ABBREVIATIONS

ASTRUM	Automated Statistical Treatment of Uncertainty Method
BEPU	Best Estimate Plus Uncertainty
CAMP	Code Applications and Maintenance Program
DAKOTA	Design Analysis Kit for Optimization and Terascale Applications
IAEA	International Atomic Energy Agency
IIST	Institute of Nuclear Energy Research Integral System Test
LOCA	Loss Of Coolant Accident
NPP	Nuclear Power Plant
PCT	Peak Cladding Temperature
PDF	Probability Distribution Function
PWR	Pressurized Water Reactor
RCS	Reactor Coolant System
RHRP	Reduced-High and Reduced-Pressure
SBLOCA	Small Break Loss Of Coolant Accident
SNAP	Symbolic Nuclear Analysis Program
U+S analysis	Uncertainty and Sensitivity analysis

1. INTRODUCTION

Recently, the trend of nuclear reactor safety analysis reveals an increasing interest to substitute best estimate plus uncertainty (BEPU) for conservative methodologies which may apply conservative codes or the combination of best-estimate codes and conservative initial and boundary conditions to achieve the safety margins and regulate the licensing and operations of nuclear reactors.

Compared with conservative methodologies, the methodologies of BEPU adopt best estimate codes and realistic input data with uncertainties to quantify the limiting values i.e., peak cladding temperature (PCT) for loss of coolant accidents (LOCAs). According to the key report of IAEA [1], the methodologies of BEPU are divided into two approaches which evaluate the problems based on either (a) propagation of input uncertainties or (b) extrapolation of output uncertainties. For the propagation of input uncertainties (Fig. 1.1), i.e., GRS method [2], the uncertainty effects are involved by identifying the uncertain input parameters with specified probability distribution functions (PDFs) followed by sample runs. For the extrapolation of output uncertainties (Fig. 1.2), i.e., CIAU [3], uncertainty is determined by the comparison between numerical results and experimental data. The review of accident analysis and BEPU approaches are referred to Pourgol-Mohammad [4], Glaeser [5], and D'Auria, et al [6]. So far, BEPU approaches have been noticeably adopted by venders. Westinghouse proposed a methodology named Automated Statistical Treatment of Uncertainty Method (ASTRUM) [7,8] for realistic large break LOCA (LBLOCA) analysis. AREVA implemented the GRS method to evaluate the convolution of LBLOCA uncertainty contributors to PCT [9].

Not only the vender's codes but several best estimate codes have been involved in BEPU methodologies. One of the best estimate thermal-hydraulic codes, TRACE, has been applied for BEPU evaluation. Jaeger, et al. [10] established the combined usage of TRACE and the uncertainty and sensitivity (U+S) analysis tool SUSA to investigate the applicability of TRACE to supercritical water related thermal-hydraulic properties. The tool SUSA is a stand-alone code, providing the capabilities of random sampling of input parameters, determination of output bounds with 95/95 confidence level and probability, and measurement of sensitivity of code results to input uncertainties. SUSA is also an interface to exchange data with TRACE. On the CAMP 2011 spring meeting, it was announced that modified SNAP is integrated with the toolkit DAKOTA to perform input parameter sampling, statistical analysis and reporting [11]. Jaeger [12], et al., assessed the performance of SNAP-TRACE-DAKOTA against the results of TRACE-SUSA. The comparison shows the agreement between SNAP-TRACE-DAKOTA and TRACE-SUSA results. Now, the uncertainty analysis user's manual is available [13].

Based on the previous CAMP activity, the current framework of this project is to demonstrate the capability of SNAP-TRACE-DAKOTA for 2 % small break LOCA (SBLOCA) of IIST experiment. The GRS method was used to investigate the propagation of input uncertainties to output data. The input parameters with uncertainties of TRACE IIST model were generated randomly based on specified PDFs. The number of samples was determined by Wilks' formula [14] to generate the upper bound of PCT with 95/95 confidence level and probability. All TRACE runs were defined and executed through SNAP job streams, and TRACE calculation results were read by AptPlot script. The data interactions and communications between TRACE and DAKOTA were controlled by SNAP.

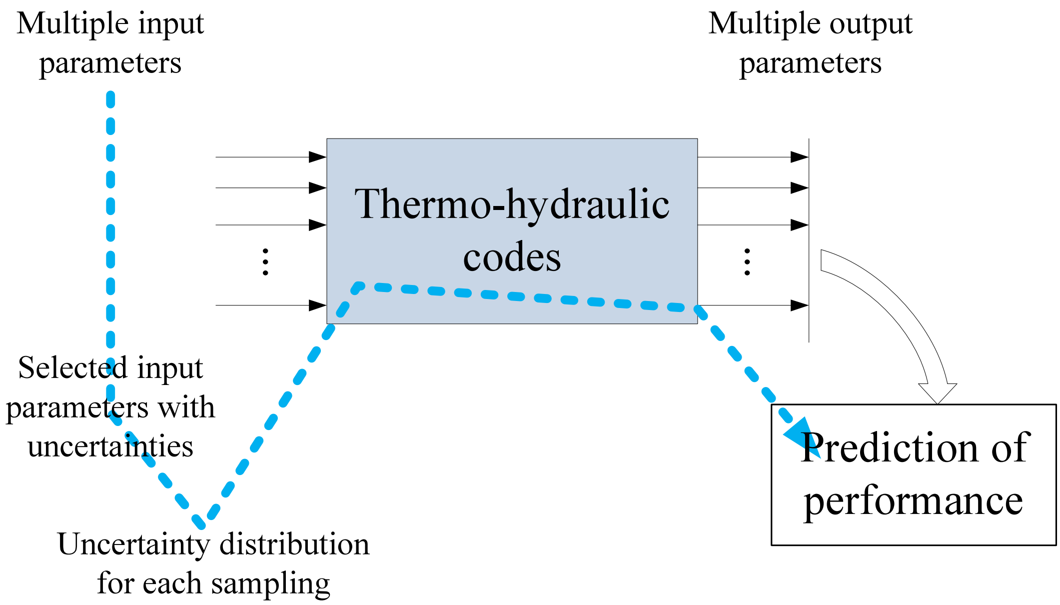

Fig. 1.1 Propagation of input uncertainties

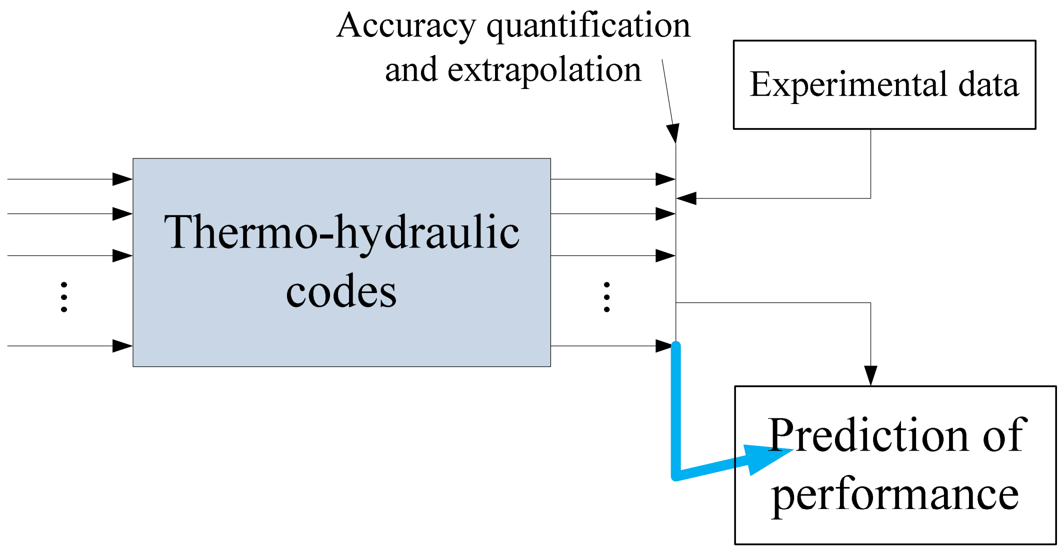

Fig. 1.2 Propagation of output uncertainties

2. IIST FACILITY AND SBLOCA EXPERIMENT

The IIST facility is a reduced-high and reduced-pressure (RHRP) test facility to simulate the thermal hydraulics of a Westinghouse 3-loop pressurized water reactor (PWR) at Maanshan nuclear power plant (NPP) since 1992 [15]. The comparisons of key parameters between Maanshan NPP and IIST facility are listed in Table 2.1. The research purposes of the IIST facility are: (a) to enhance the understanding of thermal hydraulics during transients [16,17] as well as SBLOCAs [18], (b) to contribute to the evaluations and developments of safety computer codes [19,20], (c) to validate the emergency operation procedures during the transients [21].

2.1 DESCRIPTION OF IIST FACILITY

The scaling factors of the IIST facility for height and volume in the reactor coolant system (RCS) are approximately 1/4 and 1/400, respectively, and the maximum operating pressure is 2.1 MPa. The scaling of hot leg is based on the Froude number criterion to simulate the transition of flow regimes in the horizontal pipes during transients and accidents. The key parameters of IIST facility are listed in Table 1. As shown in Fig. 2.1 [19], the IIST facility consists of a pressure vessel and 3 loops. The pressure vessel has 3 inlet and 3 outlet nozzles. Coolant enters the vessel through the inlet nozzles and flows down through the downcomer, and flows up through the heater rods to the outlet nozzles. The bypass flow from the upper plenum to the downcomer is simulated by three external tubes connected with the valves. Each loop has a steam generator and a coolant pump, and the 3 loops are identical, except that there is a pressurizer in the loop 1. The pressurizer connected with loop 1 equips an electrical heater, spray nozzle and pressure relief valves. The capacity of electrical heater is 10 kW, and the penetrations of spray nozzle and pressure relief valves are located on the top of pressurizer. There are 30 U-tubes in each steam generator. However, the steam dome of a steam generator doesn't contain separators and dryers, because the steam velocity in the steam dome is not strong enough to entrain liquid into seam line at the low core power during simulation of the decay heat level. The secondary feedwater flow rate is controlled by flow control valve actuated by the water level controller of each steam generator. The IIST facility incorporates a data acquisition system which measures temperature, pressure, flow rate, liquid level, and differential pressure.

2.2 DESCRIPTION OF IIST SBLOCA EXPERIMENT

This experiment was performed to investigate 2 % cold leg break with total failure of high pressure injection [18]. The horizontal break nozzle was installed in the cold leg of loop 2 which is not connected with pressurizer. The initial conditions of this experiment are listed in Table 2.2. The break was occurred at time zero, and the primary pressure dropped until it become only a little higher than the secondary side pressure. This experiment was terminated at 1734 s because the uncovering of the core was caused by continuous boil-off of vessel coolant inventory without the actuation of coolant makeup system.

Table 2.1 The comparisons of key parameters between Maanshan NPP and IIST facility[19]

Parameters	IIST	Maanshan	IIST/Maanshan
Design pressure (MPa)	2.1	15.6	0.135
Maximum core power (MW)	0.45	2775	1.62×10^{-4}
Core			
Height (m)	1.0	3.6	0.277
Hydraulic diameter (m)	0.108	1.22×10^{-2}	8.85
Bypass area (m^2)	7.2×10^{-5}	1.54×10^{-2}	4.67×10^{-3}
Hot leg			
Inner diameter, D (m)	5.25×10^{-2}	7.35×10^{-1}	7.13×10^{-2}
Length, L (m)	2.0	7.28	2.75×10^{-1}
$L/D^{0.5}$ ($m^{0.5}$)	8.72	8.48	1.03
Cold leg			
Inner diameter, D (m)	5.25×10^{-2}	7.87×10^{-1}	6.67×10^{-2}
Length, L (m)	5.0	15.7	3.18×10^{-1}
$L/D^{0.5}$ ($m^{0.5}$)	21.8	17.69	1.22
U-tube in one SG			
Number	30	5626	5.33×10^{-3}
Average length (m)	4.08	16.85	2.24×10^{-1}
Inner diameter (mm)	15.4	15.4	1.0
Pressurizer			
Volume (m^3)	9.32×10^{-2}	39.64	2.35×10^{-3}
Surge-line flow area (m^2)	3.44×10^{-4}	6.38×10^{-2}	5.39×10^{-3}

Table 2.2 The initial conditions of IIST SBLOCA[19]

Parameter	Value
Core power (kW)	126
PZR pressure (MPa)	0.958
PZR water level (mm)	1459
Loop flow rate (kg/s)	
Loop1	0.210
Loop2	0.217
Loop3	0.217
Hot leg temp. (K)	
Loop1	450
Loop2	449
Loop3	451
Cold leg temp. (K)	
Loop1	409
Loop2	408
Loop3	409

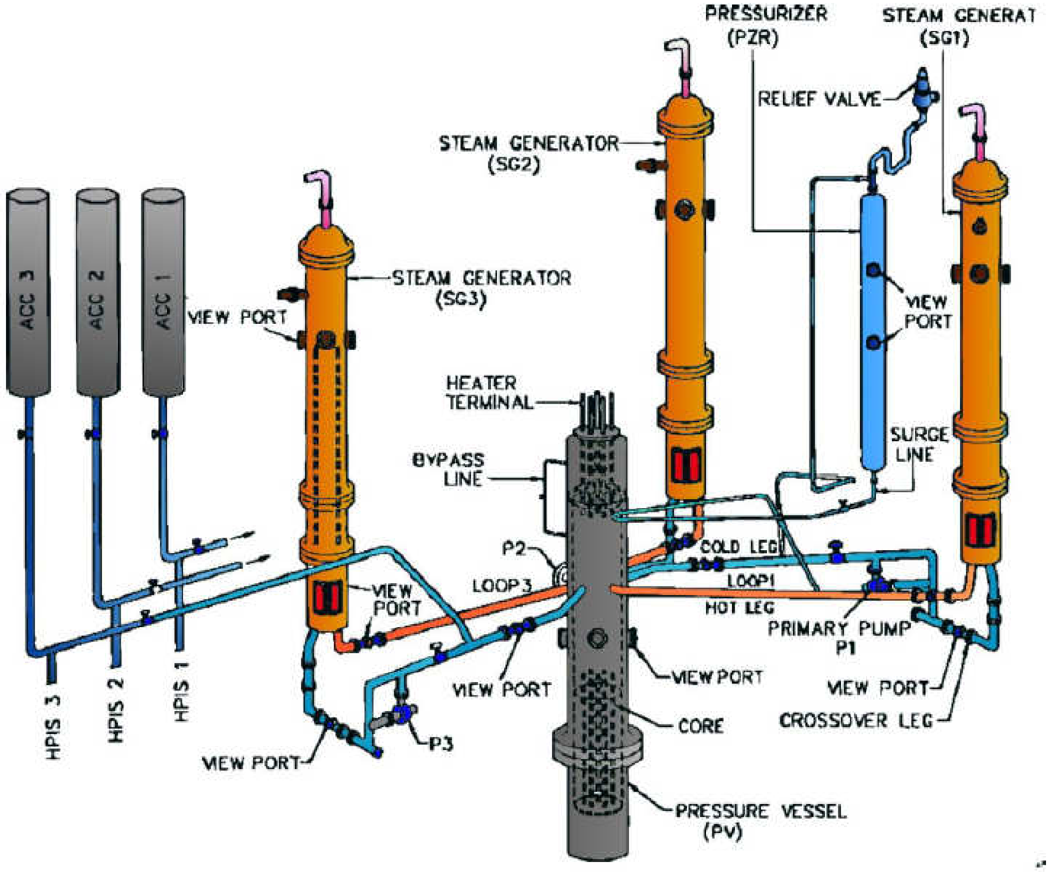

Fig. 2.1 The schema of IIST facility

3. IIST TRACE MODEL AND UNCERTAINTY EVALUATION

3.1 IIST TRACE MODEL

The IIST TRACE model was developed based on the relevant documents [15,17, 21], and two generations of IIST facility TRACE model has been assessed against experimental data. The major difference of these two models is the simulation of reactor pressure vessel (RPV). The model A simulates the RPV by pipe components (Fig. 3.1), while the model B simulates the RPV by a 3-D vessel component (Fig. 3.2). The assessment results indicate that the predictions by model B are better than those by model A in the primary system pressure and break flow [22]. Therefore, the vessel modeling of model B was adopted for the uncertainty analysis.
Fig. 3.3 shows the nodolization of model B, which consists of 101 hydraulic components, 212 control blocks, 39 heat structures and a power component. The primary loops include hot legs, steam generator U-tubes, crossover leg, coolant pump and cold legs. These loops are identical except that the pressurizer is located in loop1. The break area is controlled by a valve component and located in loop 2. A break component is used to simulate ambient condition. Each of the 3 identical steam generators consists of downcomer, boiling section and steam dome. The feedwater flow rates are simulated by time-dependent junctions, and the downstream condition of each steam line is simulated by a break component with constant boundary condition.

3.2 UNCERTAINTY EVALUATION

3.2.1 FUNDAMENTAL METHODOLOGY

The GRS method was applied to investigate the uncertainty effect propagating from input parameters through TRACE to PCT, as shown in Fig. 1.1. Because the required minimum number of TRACE runs is dependent of the values of confidence level and probability, Wilks' formula [14] was employed to determinate the minimum number of runs. The correlations between number of code runs, confidence level, and probability of Wilks' formula are defined in Eq. (3-1) and Eq. (3-2) for one-side tolerance limit and two-sided tolerance limit respectively. The minimum number of code runs is tabulated in Table 3.1.

$$1-\alpha^{n} \geqq \beta \qquad \text{Eq. 3-1}$$

$$1-\alpha^{n}-n(1-\alpha)\alpha^{n-1} \geqq \beta \qquad \text{Eq. 3-2}$$

Where α is probability, β is the confidence level, and n denotes the number of code runs.

Since the value of PCT is the safety criterion to ensure the integrity of fuel assemblies for LOCAs, the minimum number of 59 was used to generate the maximum bound of PCT which achieve 95/95 criterion. Finally, correlations between input parameters and PCTs are calculated for sensitivity study and ranking to investigate what input parameters dominate the contribution of uncertain distribution of PCT.

3.2.2 DAKOTA TOOLKIT

The DAKOTA [23] toolkit was applied for the sampling of input parameters and the calculation of correlations and ranking of input parameters. The uncertainty quantification package [24] of DAKOTA provides Monte Carlo sampling and Latin Hypercube sampling methods combined with various PDFs including normal, lognormal, uniform, logunifrom, hypergeometric, and user-supplied histograms. As for correlations mentioned in the previous section, four types of correlations including simple and partial raw correlations and simple and partial rank correlations are returned in DAKOTA output files [24]. The coefficients of first two correlations are obtained by Pearson's correlation shown in Eq. 3-3, and the other two are calculated by Spearman's rank correlation.

$$\mathbf{r} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

Eq. 3-3

where r is the Pearson's correlation coefficient, n is the number of samples, and x and y denote two quantities.

The formula of Spearman's rank correlation is the same as Pearson's (Eq. 3-3); however, the difference is that Spearman's rank correlation employs the rank data which substitute the ranked values for raw data.

3.2.3 UNCERTAINTY ANALYSIS PROCEDURE

DAKOTA provides users an interface to couple other codes for uncertainty analysis. Fig. 3.4 illustrates the concept of a loosely-coupled interface [24] between DAKOTA and simulation codes (i.e., TRACE) by which data can be exchanged between DAKOTA and other simulation codes. Thanks for the modified SNPA, it is able to integrate TRACE and DAKOTA via SNAP job stream. The integration of SNAP-TRACE-DAKOTA is shown in Fig. 3.5 where the Extract Data is a plug-in tool to read TRACE output data.

Table 3.1 Minimum number of code runs for one-side and two-side tolerance limits

	One-side tolerance limits			Two-side tolerance limits		
β \ α	0.90	0.95	0.99	0.90	0.95	0.99
0.90	22	45	230	38	77	388
0.95	29	59	299	46	93	473
0.99	44	90	459	64	130	662

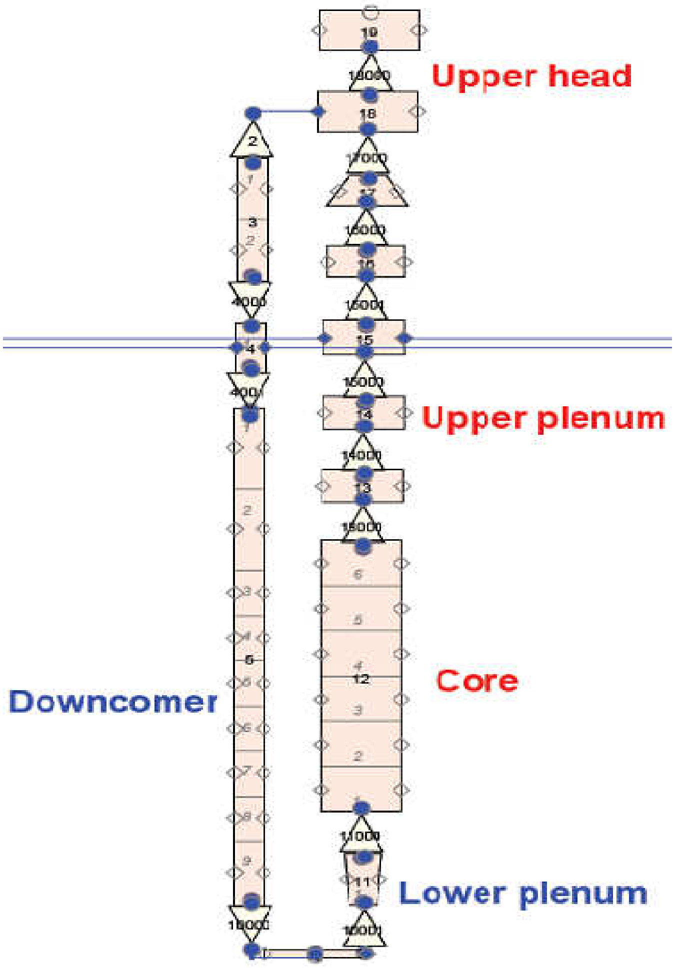

Fig. 3.1 The simulation of RPV in model A

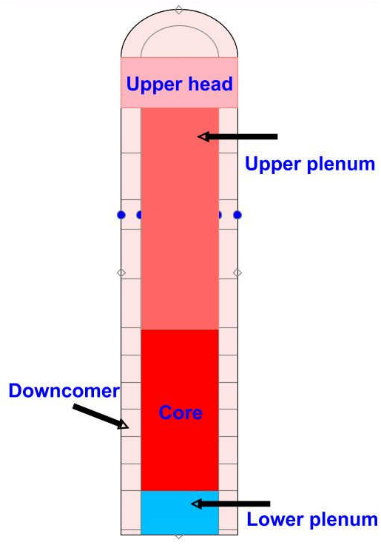

Fig. 3.2 The simulation of RPV in model B

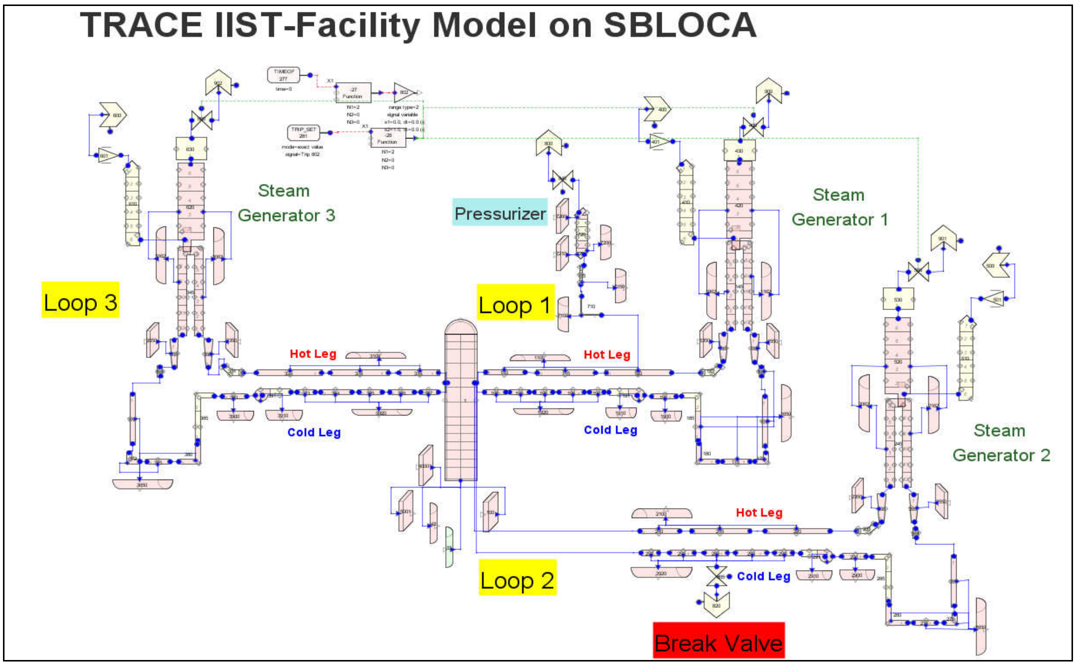

Fig. 3.3 The nodolization of model B

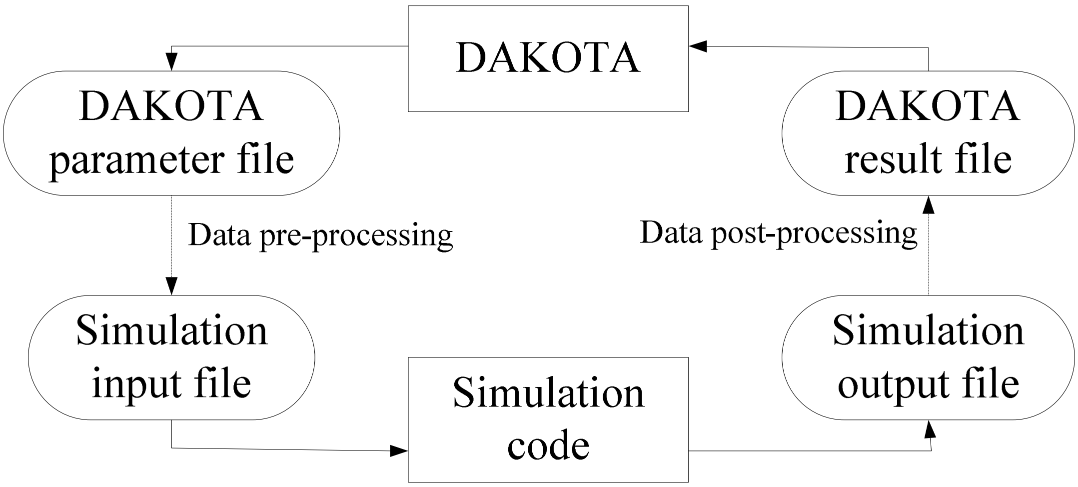

Fig. 3.4 The loosely-coupled interface

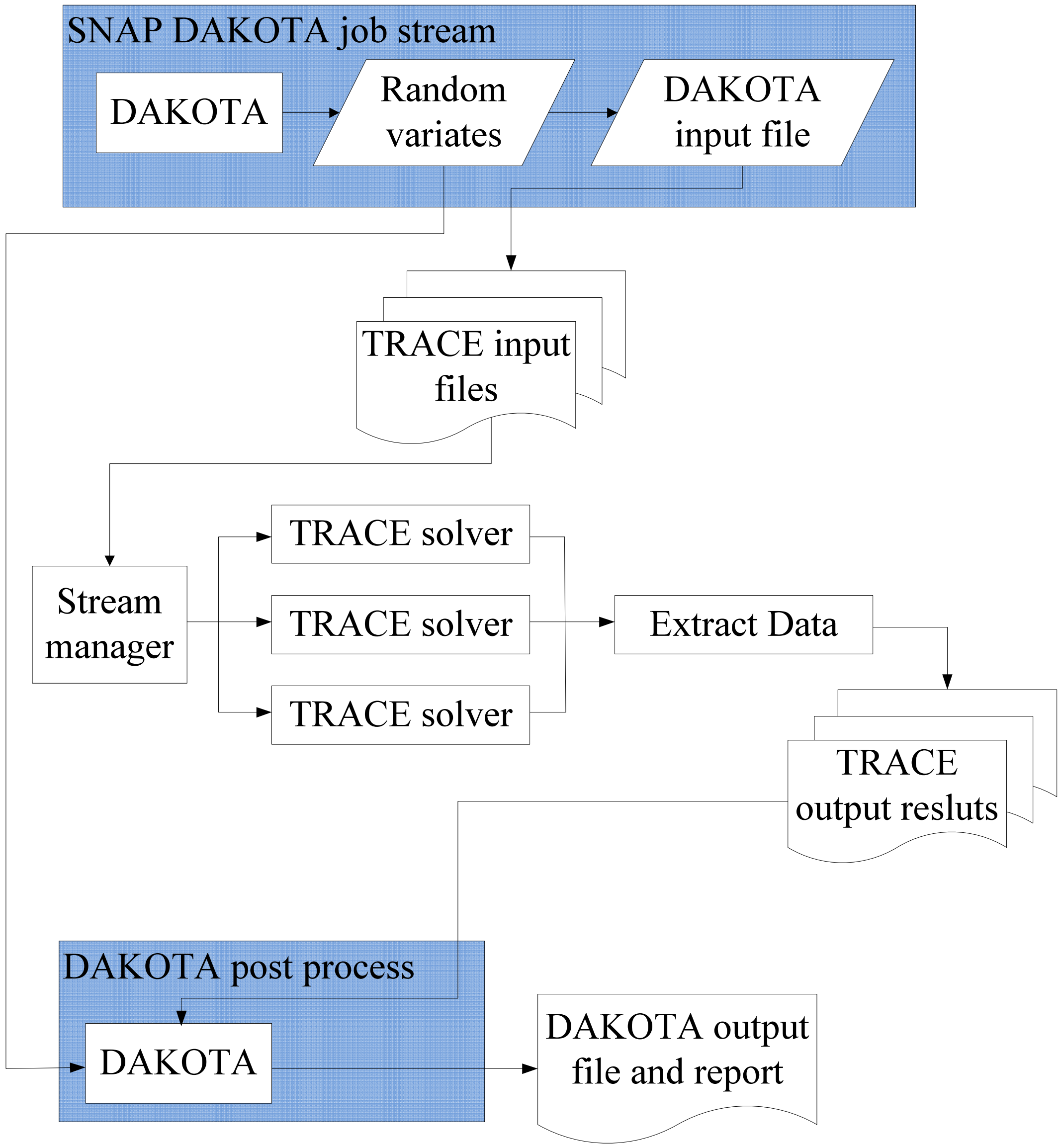

Fig. 3.5 The integration of SNAP-TRACE-DAKOTA

4. RESULTS AND DISCUSSIONS

The initial conditions of IIST 2% SBLOCA are listed in Table 2.2. As mentioned in section 3.2.3, the setting of input uncertainties and the execution of uncertainty analysis was performed via SNAP. The built-in graphical user interface (GUI) of uncertainty configuration shown in Fig. 4.1 provides several tabs to define the number of samples, variables, and PDFs. Table 4.1 lists the 5 key parameters taken into account in the uncertainty analysis, which are defined as the SNAP user-defined numerics (UDN) variables and linked with uncertainty configuration to generate 59 TRACE input files. Fig. 4.2 shows the overall SNAP job stream for uncertainty analysis.

Fig. 4.3 shows the histograms of the 5 input parameters and 59 resultant PCTs. Fig. 4.4 displays the 59 PCTs as a function of time. According to Wilks' formula, the maximum value (1054 K at 1734 s) from the 59 trials represents the upper-side tolerance limit with a confidence level of 95 % and probability of 95 %. The PCTs by IIST experiment and best-estimate calculation are 804 K and 861 K respectively. The mean value and standard deviation of the 59 trial are 938.7 K and 63.6 K respectively. The partial rank correlation coefficients between input parameters and PCT shown in Fig. 4.5 indicate that break area is the most sensitive parameter.

Assuming the PDF of PCT is a normal distribution, two approaches were applied to confirm the upper bound of PCT derived by the GRS method. The first approach used the mean value and standard deviation of the 59 trial to calculate the PCT which cover 95 % area of the PCT distribution (Fig. 4.6), which is calculated by Eq. 4-1.

$$PCT_{95} = PCT_{mean} + 1.645\sigma \qquad \text{Eq. 4-1}$$

where PCT_{mean} is the mean value of PCT, σ is the standard deviation of PCT

The second approach applies the t distribution and chi-squared distribution to estimate the population mean and population standard deviation of PCT from 59 sample PCT data. Consequently, the upper bound of PCT covers 95 % probability is estimated by the above population mean and population standard deviation.

The ratio t defined in Eq. 4-2 follows the t distribution, which estimates the population mean with a specific confidence level by the number of samples, sample mean, and sample standard deviation.

$$t = \frac{\bar{X} - \mu}{S_{\bar{x}}} \qquad \text{Eq. 4-2}$$

where $\bar{X}$ is sample mean, μ is population mean, $S_{\bar{x}}$ is standard deviation of sample mean by sample mean defined in Eq. 4-3.

$$S_{\bar{x}} = \frac{S}{\sqrt{N}} \qquad \text{Eq. 4-3}$$

where S is sample standard deviation, N is the number of samples.

Similarly, the ratio X defined in Eq. 4-4 follows the Chi-squared distribution, which estimates the population standard deviation in terms of sample standard deviation and number of samples.

$$\chi^2 = \frac{(N-1)S^2}{\sigma^2} \qquad \text{Eq. 4-4}$$

where N is the number of samples, S is sample standard deviation, σ is population standard deviation.

Table 4.2 lists the different upper bounds with 95/95 criterion estimated by GRS method and the other two approaches mentioned above. The comparison shows that the GRS method provides a reasonable estimation to quantify the propagation of input uncertainties on output results.

Although the uncertainty analysis procedure is integrated via SNAP job stream, there is a major limitation. All input parameters associated with uncertainties are defined as UDN variables to generate the values with specified uncertainties. Fig. 4.7 illustrate that the initial thermal power is defined as a UDN variable. However, not all input parameters are able to be UDN variables; only five input parameters listed in Table 4.1 were used in IIST uncertainty analysis because of this limitation.

Table 4.1 The key parameters for the uncertainty analysis

Input parameters	Nominal values	Uncertainty range	PDFs
Thermal power	126 (kW)	[-8, +8] (%)	
U-tube heat transfer area	100 (%)	[-15, +15] (%)	
Heater heat transfer area	100 (%)	[-15, +15] (%)	Uniform distribution
Feedwater temperature	399.4 (K)	[-10, +10] (%)	
Break area	2 (%)	[2, 2.1] (%)	

Table 4.2 The upper bounds of PCT by different methods

Methods	Upper bound (K)	Confidence level/probability
GRS	1054	95/95
Eq. 4-1	1159	
Eq. 4-1 + t distribution + Chi-squared distribution	1136	

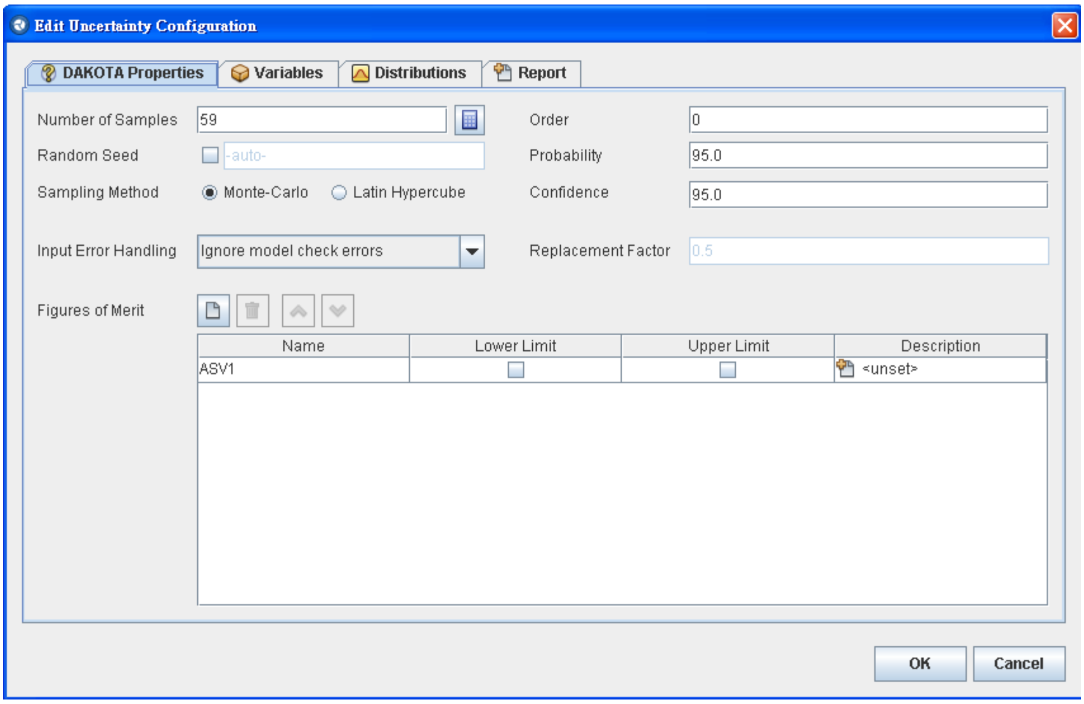

Fig. 4.1 Uncertainty configuration interface

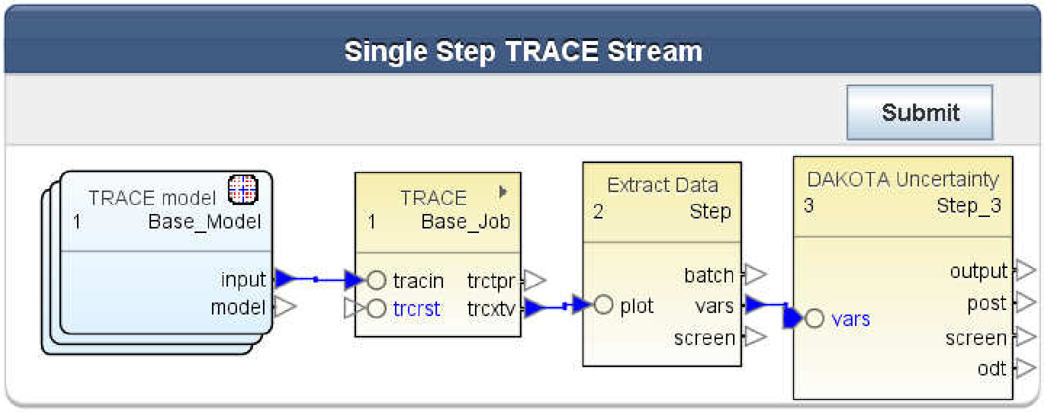

Fig. 4.2 The SNAP job stream for uncertainty analysis

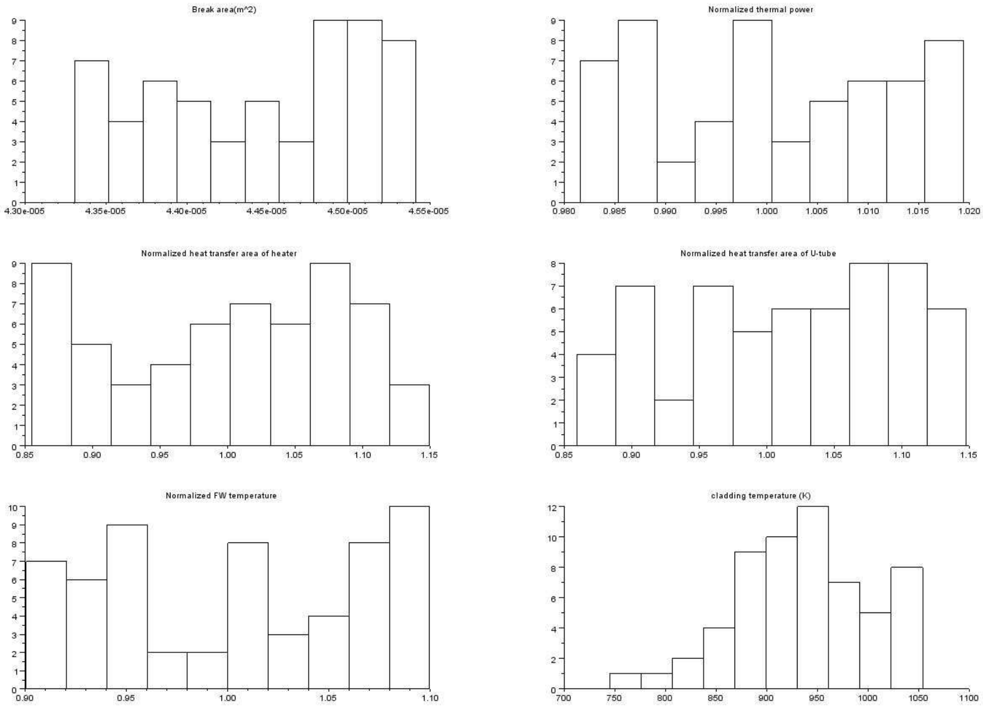

Fig. 4.3 The histograms of the input parameters and resultant PCTs

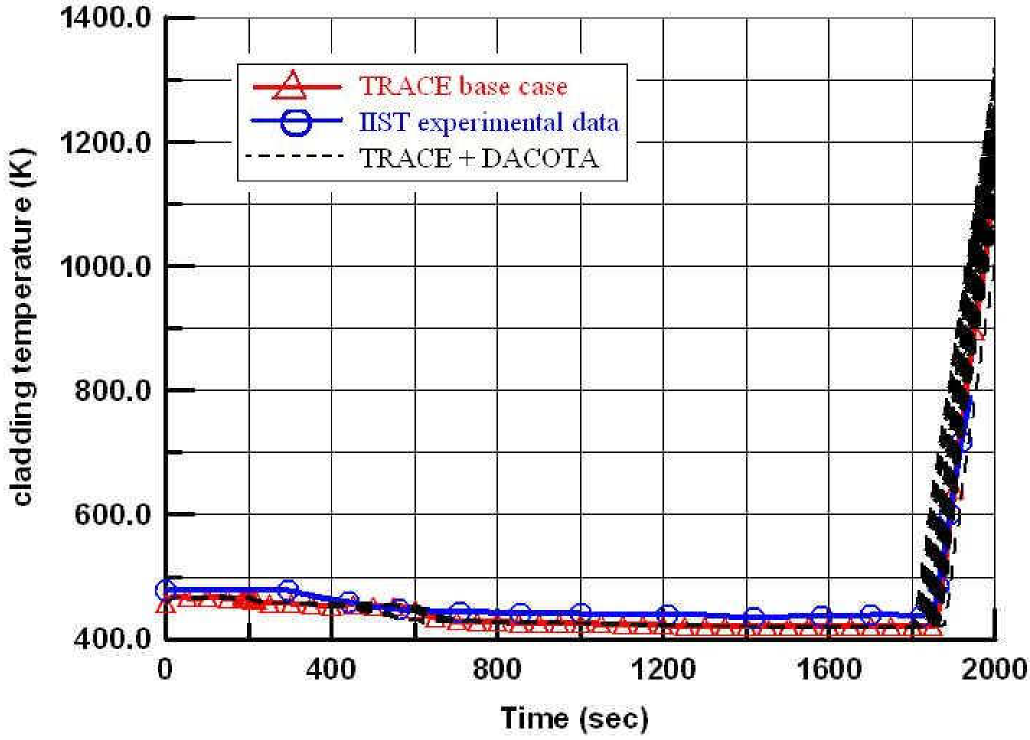

Fig. 4.4 The PCTs during SBLOCA

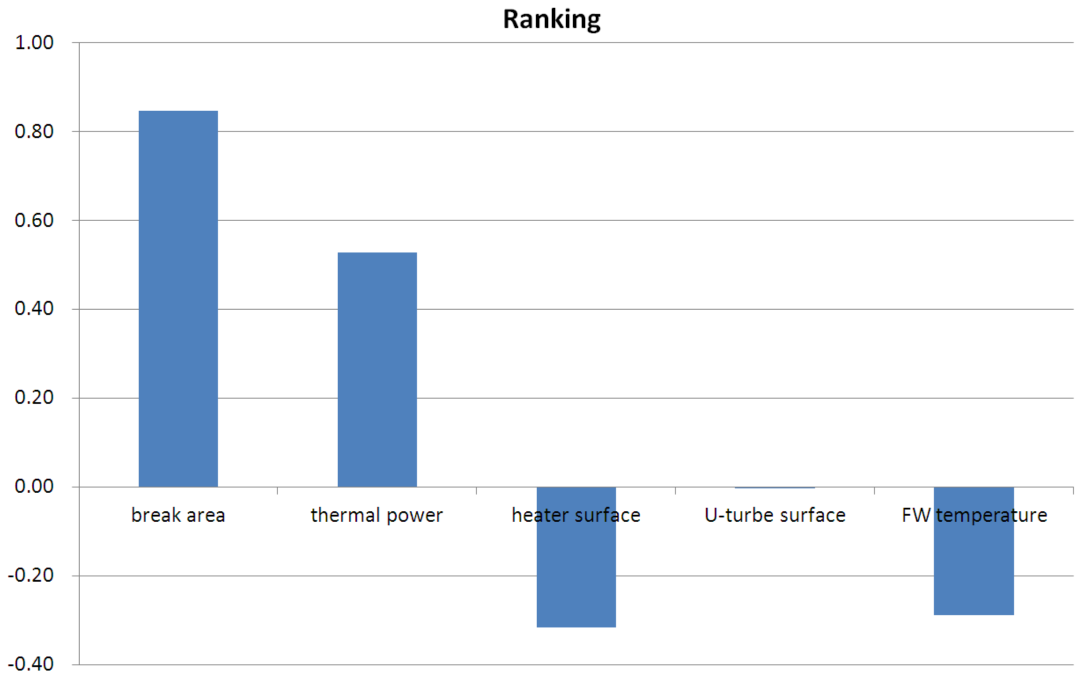

Fig. 4.5 The partial rank correlation coefficients between input parameters and PCT

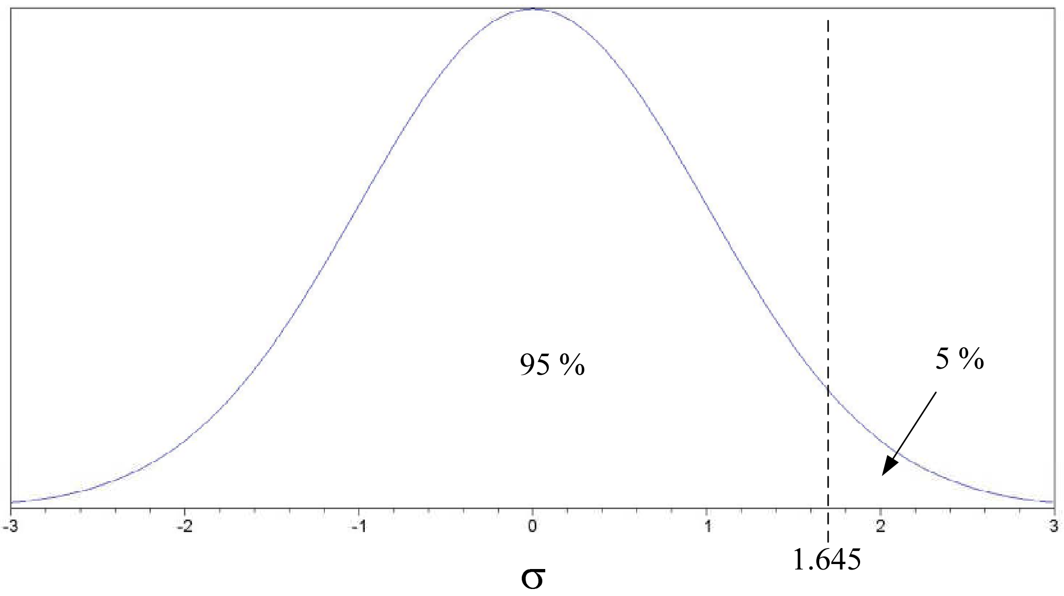

Fig. 4.6 PCT distribution and confidence interval

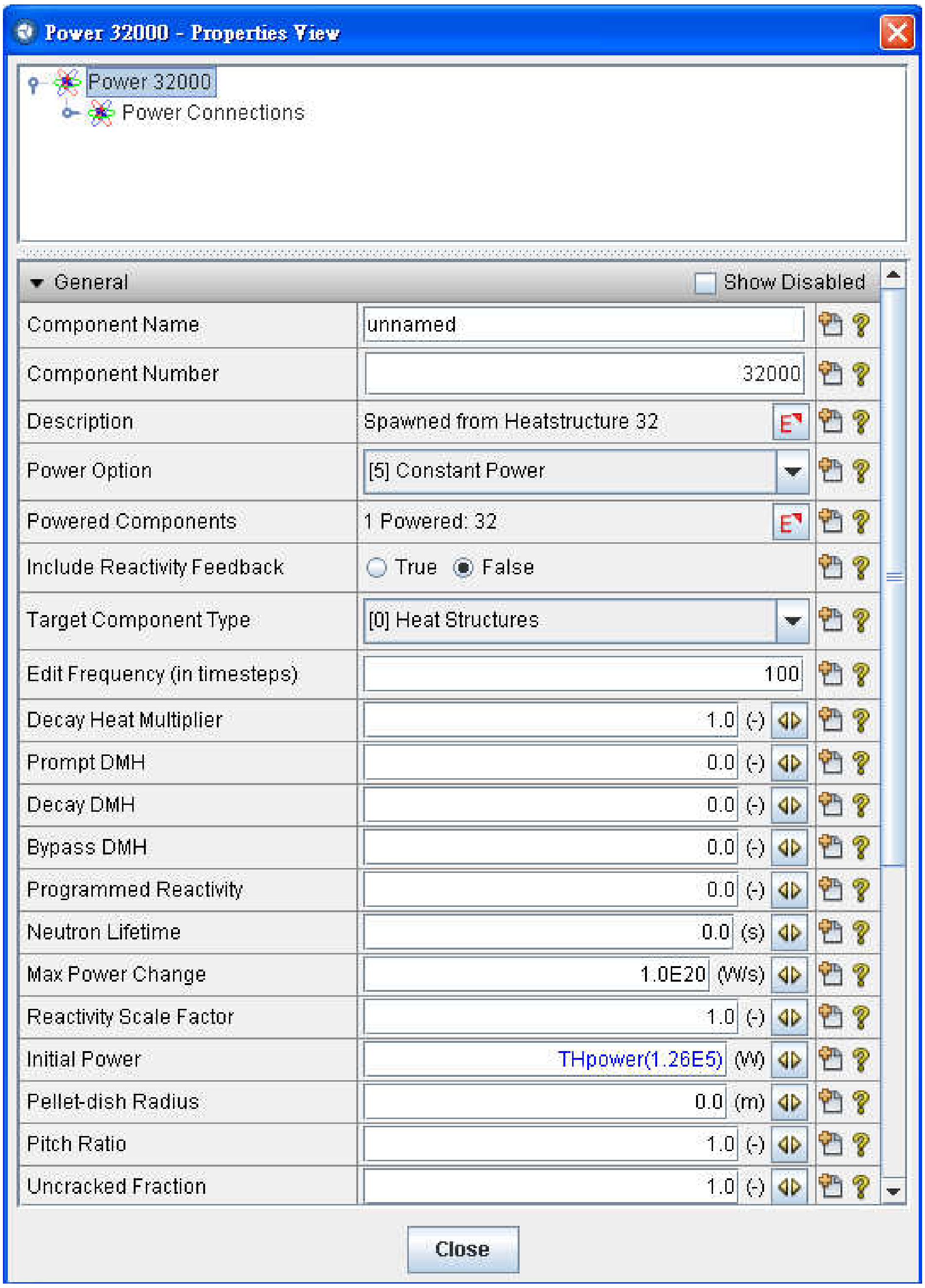

Fig. 4.7 Power component and initial power

5. CONCLUSIONS

The GRS method is applied to perform the uncertainty analysis for IIST 2 % SBLOCA. All steps of analysis procedure including random sampling, data communication, TRACE execution, and DAKOTA post-analysis are integrated via SNAP. The upper bound of PCT is 1054 K by GRS method. The ranking coefficients indicate that the break area is the most sensitive among 5 selected input parameters. However, users are not able to define all considered input parameters as SNAP UDN variables under SNAP 2.0.6 environment due to the limitation of SNAP numerics module; several important parameters such as initial water level and pressure, and cell volume are not able to be involved in uncertainty analysis via SNAP.

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NRC FORM 335 (9-2004) NRCMD 3.7

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)
NUREG/IA-0428

2. TITLE AND SUBTITLE
Performing Uncertainty Analysis of IIST Facility SBLOCA by TRACE and DAKOTA

3. DATE REPORT PUBLISHED

MONTH	YEAR
September	2013

4. FIN OR GRANT NUMBER

5. AUTHOR(S)
Jong-Rong Wang, Chiung-Wen Tsai*, Hao-Tzu Lin, Chunkuan Shih*

6. TYPE OF REPORT
Technical

7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION - NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

Institute of Nuclear Energy Research
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1000, Wenhua Rd., Chiaan Village, Lungtan, Taoyuan, 325
Taiwan

*Institute of Nuclear Engineering and Science
National Tsing Hua University
101 Section 2, Kuang Fu Rd., HsinChu
Taiwan

9. SPONSORING ORGANIZATION - NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of Systems Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES
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11. ABSTRACT *(200 words or less)*

Nowadays, the increasing computing speed realizes the quantification of propagation of input uncertainties to output data with Monte Carlo simulation or modified simulation methods. The best estimate plus uncertainty (BEPU) methods have been proposed to be used instead of typical conservative methodologies. Based on the CAMP activity, this project demonstrates the capability of SNAP-TRACE-DAKOTA for 2 % small break LOCA (SBLOCA) of IIST experiment. The number of samples was determined by Wilks' formula to generate the upper bound of peak cladding temperature (PCT) with 95/95 confidence level and probability. The PCTs by IIST experiment and best-estimate calculation are 804 K and 861 K respectively. The mean value and standard deviation of the 59 trial by SNAP-TRACE-DAKOTA are 938.7 K and 63.6 K respectively, and the maximum value of PCT is 1054 K.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

SNAP-TRACE-DAKOTA
Best estimate plus uncertainly (BEPU)
Code Application & Maintenance Program (CAMP)
INER (Institute of Nuclear Energy Research, Atomic Energy Council, R.O.C.)
Thermal hydraulic safety analysis
Taiwan
RELAP5
SNAP
Monte Carlo simulation

13. AVAILABILITY STATEMENT
unlimited

14. SECURITY CLASSIFICATION
(This Page) unclassified
(This Report) unclassified

15. NUMBER OF PAGES

16. PRICE

Printed on recycled paper

Federal Recycling Program

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001

OFFICIAL BUSINESS

NUREG/IA-0428

Performing Uncertainty Analysis of IIST Facility SBLOCA by TRACE and DAKOTA

September 2013