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International Agreement Report

Uncertainty Analysis for Maanshan LBLOCA by TRACE and DAKOTA

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ABSTRACT

This research is focused on the Large Break Loss of Coolant Accident (LBLOCA) analysis of the Maanshan power plant by TRACE-DAKOTA code. In the acceptance criteria for Loss of Coolant Accidents (LOCAs), there are two accepted analysis methods: conservative methodology and best estimate methodology. Compared with conservative methodology, the best estimate and realistic input data with uncertainties to quantify the limiting values i.e., Peak Cladding Temperature (PCT) for LOCAs analysis. By the conservative methodology, the PCT_{CM} (PCT calculated by conservative methodology) of Maanshan power plant LBLOCA calculated is 1228.7K. On the other hand, there are five initial conditions taken into account in the uncertainty analysis in this study. In $PCT_{95/95}$ (PCT of 95/95 confidence level and probability) calculation, the $PCT_{95/95}$ is 1131.1K lower than the PCT_{CM} (1228.7K). In addition, the partial rank correlation coefficients between input parameters and PCT indicate that accumulator temperature is the most sensitive parameter in this study.

FOREWORD

The USNRC (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. To meet this responsibility, the TRACE model of Maanshan NPP has been built. In this report, the TRACE model of Maanshan NPP was used to evaluate the Maanshan LBLOCA transient.

CONTENTS

FIGURES

TABLES

Page

EXECUTIVE SUMMARY

An agreement in 2004 which includes the development and maintenance of TRACE has been signed between Taiwan and USA on CAMP. INER is the organization in Taiwan responsible for applying TRACE to thermal hydraulic safety analysis in order to provide user s' experiences and development suggestions. To fulfill this responsibility, the TRACE model of Maanshan Nuclear Power Plant (NPP) is developed by INER.

According to the user manual, TRACE is the product of a long term effort to combine the capabilities of the NRC's four main systems codes (TRAC-P, TRAC-B, RELAP5 and RAMONA) into one modernized computational tool.NRC has ensured that TRACE will be the main code used in thermal hydraulic safety analysis in the future without further development of other thermal hydraulic codes, such as RELAP5 and TRAC. Besides, the 3-D geometry model of reactor vessel, which is one of the representative features of TRACE, can support a more accurate and detailed safety analysis of NPPs. On the whole TRACE provides greater simulation capability than the previous codes, especially for events like LOCA.

Maanshan NPP operated by Taiwan Power Company (TPC) is the only Westinghouse-PWR in Taiwan. The rated core thermal power is 2775 MW. The reactor coolant system has three loops, each of which includes a reactor coolant pump and a steam generator. The pressurizer is connected to the hot-leg piping in loop 2. The main components of LBLOCA model include the pressure vessel, pressurizer, steam generators, steam piping in the secondary side (including four sets of steam dump and vent valves), steam dump system, accumulators, and safety injection of emergency core cooling system (ECCS). The pressure vessel is divided into 12 levels in the axial direction, two rings in the radial direction (internal and external rings) and six equal azimuthally sectors in the "θ" direction. The control rod conduit connects the 12th and 7th layers of the vessel from end to end. The fuel region is between the third and sixth layers, and heat conductors are added onto these structures to simulate the reactor core.

There are two tasks in this study, conservative evaluate and best estimate plus uncertainty for Maanshan LBLOCA analysis. The analysis results of conservative methodology are verified against the Final Safety Analysis Report (FSAR). For a LOCA analysis, the important parameters are peak cladding temperature (PCT). By coupling with DAKOTA, the input parameters with uncertainties of Maanshan model were generated randomly based on specified PDFs. Because the required minimum number of TRACE runs is dependent of the values of confidence level and probability, Wilks' formula was employed to determinate the minimum number of 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.

In the conservative evaluation, analytical results indicate that the Maanshan TRACE model predicts the behavior of important plant parameters in consistent trends with the FSAR data and the PCT_{CM} of Maanshan LBLOCA calculated is 1228.7K. On the other hand, the maximum value of PCT is 1158.4 K from the 59 trials of best estimate plus uncertainty. In PCT of 95/95 confidence level and probability calculation, the mean value (PCT_{mean}) and standard deviation (σ) of the 59 trial are 1022.8 K and 65.8 K respectively. The $PCT_{95/95}$ is 1131.1K lower than the PCT_{CM} and limited valve (1477K). Compared to conservative methodology, the best estimate plus uncertainty provides a greater safety margin for the PCT evaluation.

In addition, 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. The partial rank correlation between input parameters and PCT indicates that accumulator temperature is the most sensitive parameter.

ABBREVIATIONS

BAF	Bottom of the Active Fuel
CAMP	Code Applications and Maintenance Program
DBA	Design Basis Accidents
ECCS	Emergency Core Cooling System
FSAR	Final Safety Analysis Report
HHSI	High Head Safety Injection
INER	Institute of Nuclear Energy Research Atomic Energy Council, R.O.C.
LBLOCA	Large Break Loss of Coolant Accident
LHSI	Low Head Safety Injection
LOCA	Loss of Coolant Accident
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
PCT	Peak Cladding Temperature
PDF	Probability Distribution Functions
PWR	Pressurized Water Reactor
RCP	Reactor Coolant Pumps
RCS	Reactor Coolant System
SI	Safety Injection
SNAP	Symbolic Nuclear Analysis Package
TAF	Top of the Active Fuel
TPC	Taiwan Power Company
TRACE	TRAC/RELAP Advanced Computational Engine
US	United States

1. INTRODUCTION

The Loss of Coolant Accident (LOCA) is one of the most important Design Basis Accidents (DBA). In light water reactors, the severity of a LOCA will limit how high the reactor power can operate. Recently, the trend of nuclear reactor safety analysis reveals an increasing interest to substitute best estimate 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 [1]. Compared with conservative methodologies, the methodologies of best estimate plus uncertainty adopt best estimate codes and realistic input data with uncertainties to quantify the limiting values i.e., PCT for LOCAs. The methodologies of best estimate are divided into two approaches which evaluate the problems based on either propagation of input uncertainties or extrapolation of output uncertainties. For the propagation of input uncertainties, 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, uncertainty is determined by the comparison between numerical results and experimental data. The uncertainty attributes have been divided for convenience into different categories: (1) initial conditions uncertainty, (2) power distribution uncertainty, (3) global model uncertainty, and (4) local model uncertainty. This study is focused on the initial conditions uncertainty analysis, which includes the RCS conditions and ECCS fluid conditions (i.e., pressurizer pressure, RCS average temperature, safety injection temperature, accumulator volume, accumulator water temperature, and accumulator pressure).

2. METHODOLOGY

There are two tasks in this study, conservative evaluate and best estimate plus uncertainty for Maanshan LBLOCA analysis. The analysis results of conservative methodology are verified against the Final Safety Analysis Report (FSAR). For a LOCA analysis, the important parameters are peak cladding temperature (PCT). As defined by the 10CFR50.46 regulation, the PCT does not exceed 1477.6K (2200℉). The detail criteria for the LOCA analysis are described in Appendix K of 10CFR50, as follows:

A. The calculated peak fuel element clad temperature is below the requirement of 2200℉.

B. The amount of fuel element cladding that reacts chemically with water or steam does not exceed 1% of the total amount of Zircaloy in the reactor.

C. The clad temperature transient is terminated at a time when the core geometry is still amenable to cooling. The localized cladding oxidation limits of 17% are not exceeded during or after quenching.

D. The core remains amenable to cooling during and after the break.

E. The core temperature is reduced and decay heat is removed for an extended period of time, as required by the long-lived radioactivity remaining in the core.

Figure 1 shows the best estimate plus uncertainty methodology of LBLOCA in this study. By coupling with DAKOTA, the input parameters with uncertainties of Maanshan model were generated randomly based on specified PDFs. Because the required minimum number of TRACE runs is dependent of the values of confidence level and probability, Wilks' formula [2] 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:

$$1-\alpha^{n} \geq \beta \qquad \text{Eg. 1}$$

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.

Assuming the PDF of PCT is a normal distribution, this research used the mean value and standard deviation of the 59 trial to calculate the PCT which cover 95 % area of the PCT distribution (Fig. 2), which is calculated by Eq. 2.

$$\mathrm{PCT}_{95/95} = \mathrm{PCT}_{\mathrm{mean}} + 1.645\sigma \qquad \text{Eq. 2}$$

where $\mathrm{PCT}_{\mathrm{mean}}$ is the mean value of PCT, σ is the standard deviation of PCT.

All TRACE runs were defined and executed through SNAP job streams [3-4], and TRACE calculation results were read by AptPlot script. The data interactions and communications between TRACE and DAKOTA [5-6] were controlled by SNAP. 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.

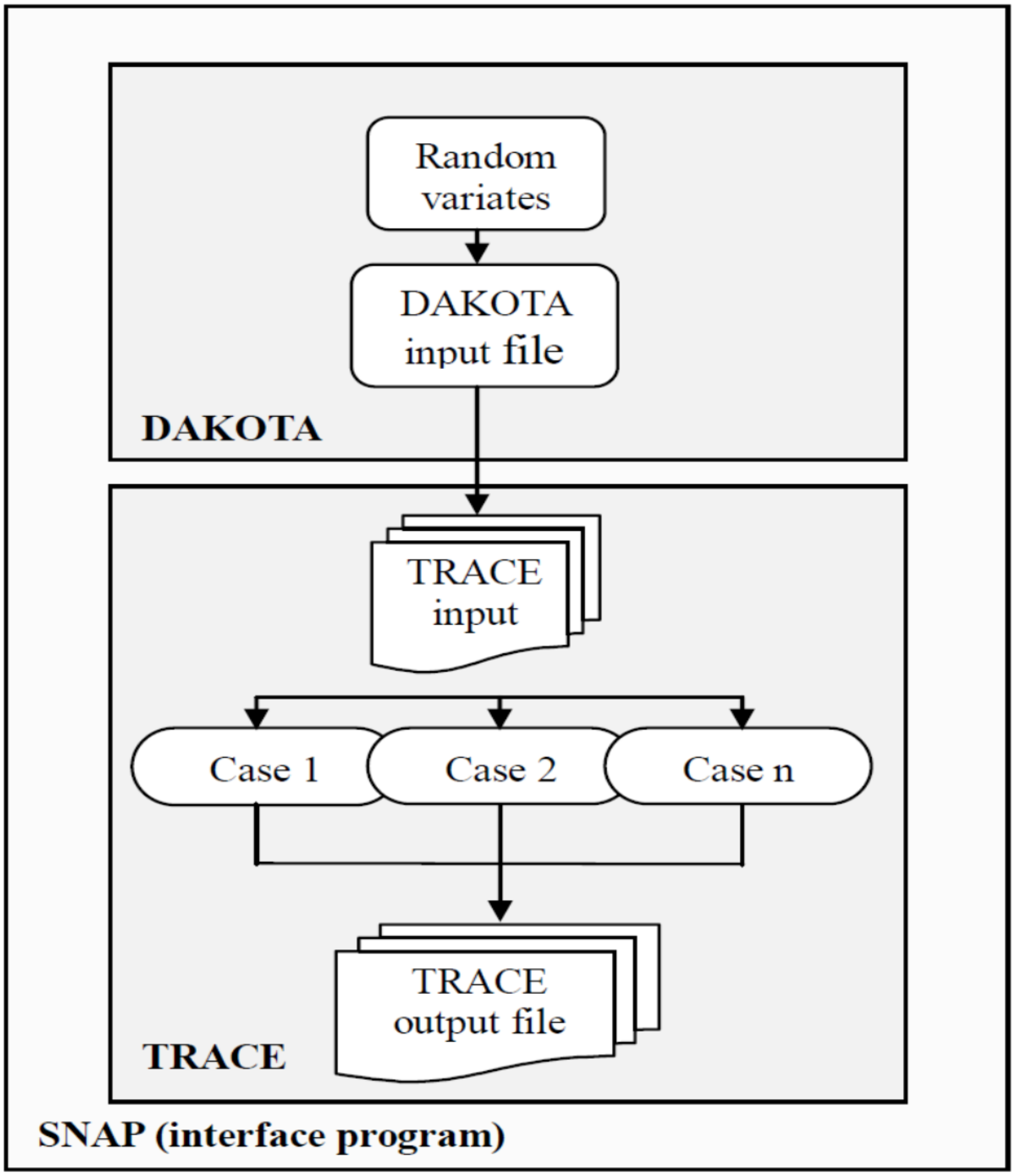


Figure 1 The procedure of uncertainty analysis

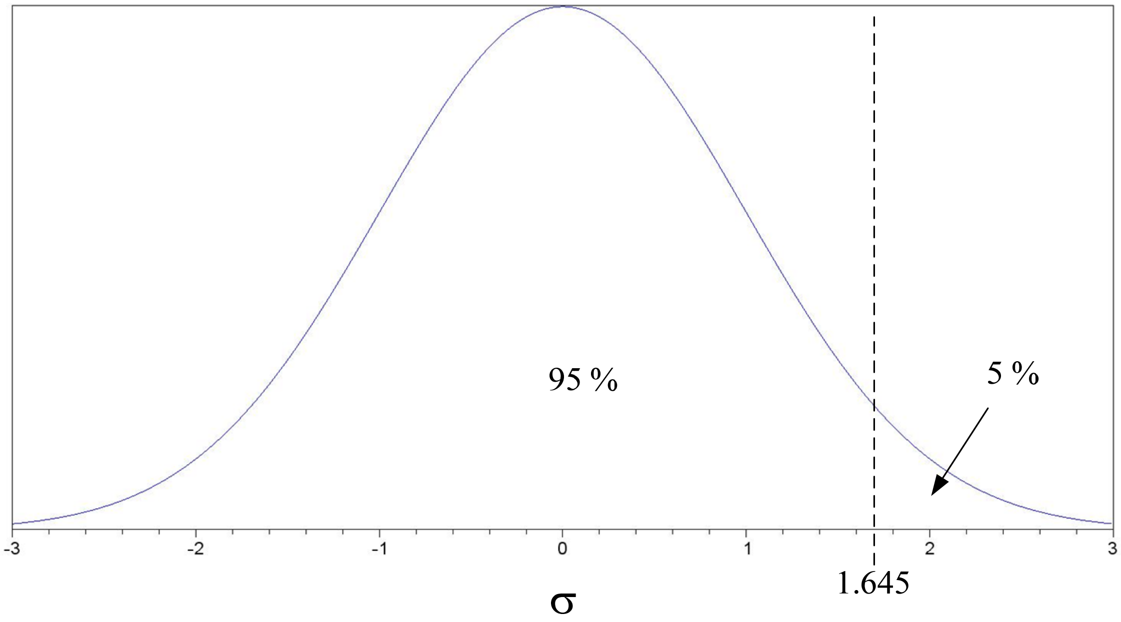


Figure 2 PCT distribution and confidence interval

3. MODEL AND ASSUMPTIONS

3.1 Maanshan TRACE Model

Figure 3 shows the TRACE model of Maanshan NPP. The rated core thermal power is 2775 MW. It is a three-loop model, and each loop has a feedwater control system. The main structure of this model includes the pressure vessel, pressurizer, steam generators, steam piping at the secondary side, the accumulators, and safety injection of ECCS. The pressure vessels are cylindrical, and are divided into 12 levels in the axial direction, two rings in the radial direction (internal and external rings) and six equal azimuthally sectors in the “θ” direction. The control rod conduit connects the 12th and 7th layers of the vessel. The fuel region is between the third and sixth layers, and heat conductors are added onto these structures to simulate the reactor core. In this LOCA study, a LBLOCA is defined as a rupture in cold-leg with a total cross sectional area. The break was located in loop 1, which is one of the two loops that don’t have a pressurizer. In addition, this TRACE model uses the “point kinetic” method to calculate the core power. The decay heat power model is based on the 1973 ANS proposed Standard.

In best estimate plus uncertainty analysis, the setting of input uncertainties and the execution of uncertainty analysis was performed via SNAP. The built-in graphical user interface of uncertainty configuration shown in Figure 4 provides several tabs to define the number of samples, variables, and PDFs. The version of code in this study is TRACE V5.0p3 under SNAP V2.2.1.

3.2 LBLOCA Assumptions

In LBLOCA analysis, it usually adopts conservative assumptions or limited value for initial conditions and boundary conditions. By the conservative assumptions, it must be assumed that the reactor has been operating continuously at a power level at least 1.02 times the licensed power level. Table 1 shows the assumptions of initial input parameters in this study. It’s assumed the pipe break occurred in RCS at 0s. Since the loss of off-site power is assumed, the Reactor Coolant Pumps (RCPs) trip at the inception of the accident. After break occurred, the reactor trip signal subsequently occurs when the pressurizer low pressure trip setpoint is reached. Also, low pressure caused the ECCS injecting water to RCS cold-leg and preventing excessive clad temperatures. A safety injection signal is generated when the appropriate setpoint is reached (1715 psia) and delay time is 27 sec. As single failure assumed, there are only one Low Pressure Head Injection (LHSI) pump and one High Head Safety Injection (HHSI) pump operate in this LBLOCA analysis. When the RCS pressure decreased below 615 psia, accumulator injection started. Cold water in the accumulator was expelled into the reactor coolant system by nitrogen gas. Continued operation of the ECCS pumps supplies water during long term cooling, the core temperatures have been reduced and prevent the fuel cladding damage.

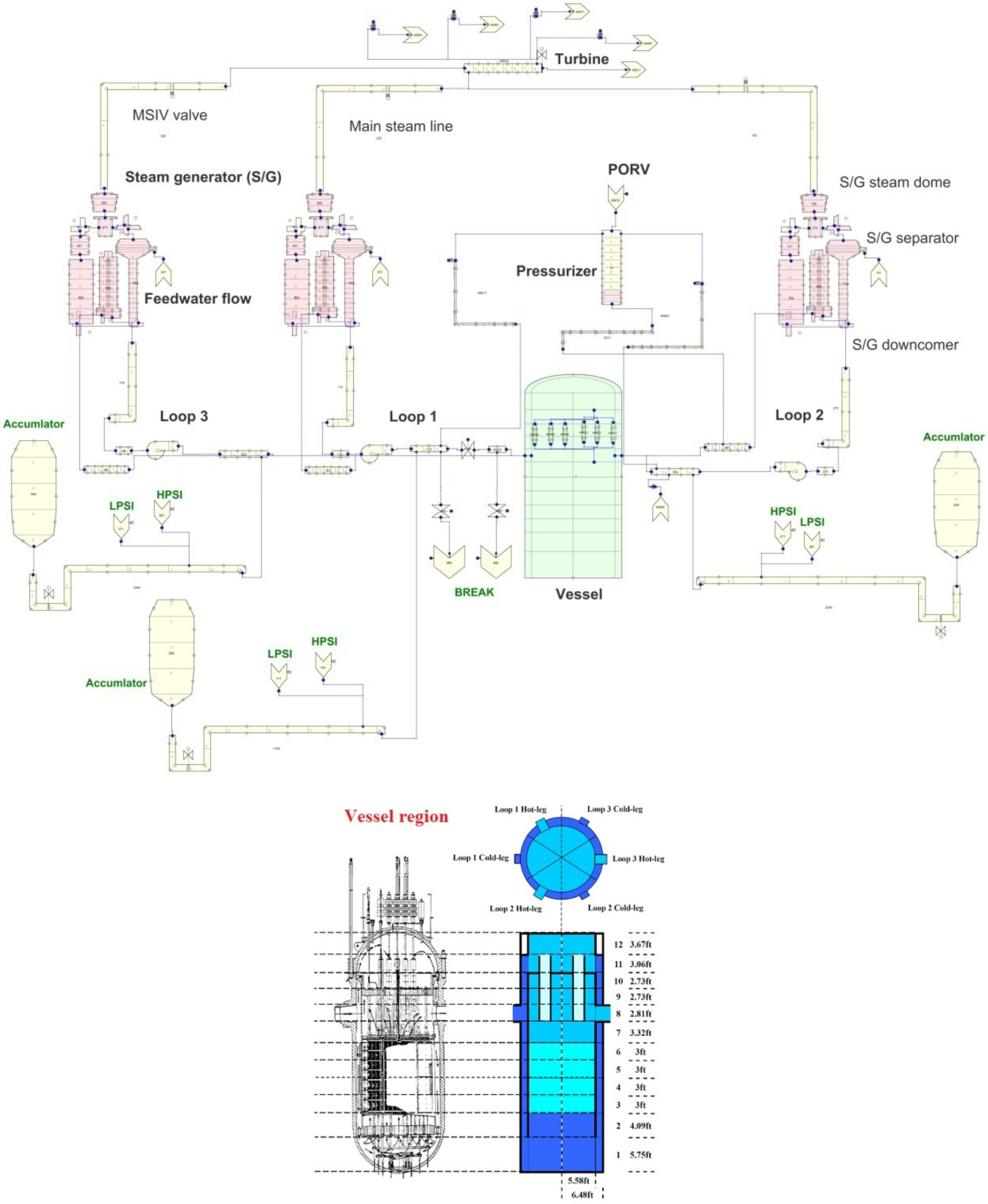
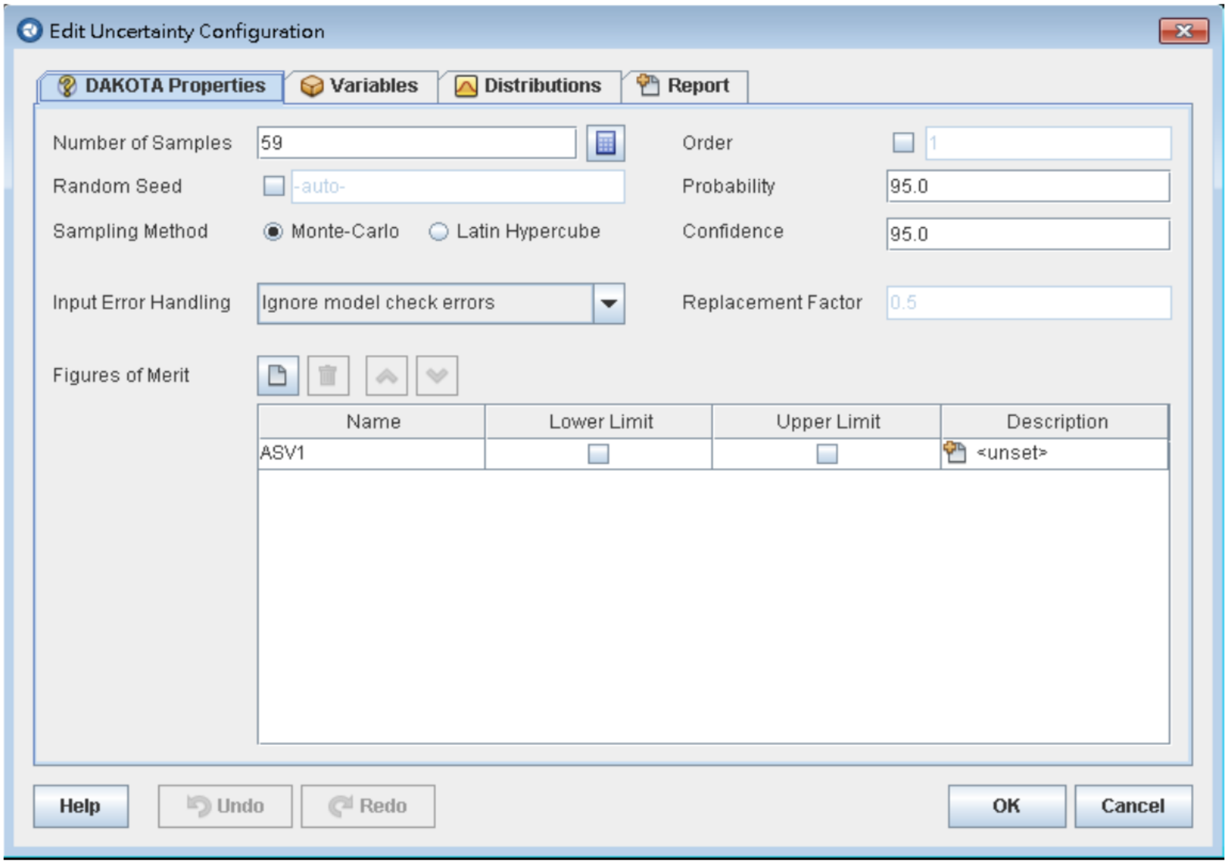


Figure 3 The LBLOCA TRACE model of Maanshan NPP



Number of Samples: 59

Random Seed: ☐ -auto-

Sampling Method: ● Monte-Carlo ○ Latin Hypercube

Input Error Handling: Ignore model check errors

Order: ☐ 1

Probability: 95.0

Confidence: 95.0

Replacement Factor: 0.5

Name	Lower Limit	Upper Limit	Description
ASV1	☐	☐	<unset>

Figure 4 Uncertainty configuration interface

Table 1 The assumptions of initial input Parameters

Input Parameters	Value
Licensed Core Power	102% of 2275MWt
Thermal Design Flow (kg/s/loop)	4331.8
Vessel Average Temperature (K)	584.5
Initial RCS Pressure (MPa)	15.858
Low Pressurizer Pressure Reactor Trip Setpoint (MPa)	12.824
Low Pressurizer Pressure SI Setpoint (MPa)	11.824
Safety Injection Initiation Delay time with loss of offsite power(sec)	27
Accumlator Water Volume (m^3/tank)	27.89
Accumlator Tank Volume (m^3/tank)	41.06
Minimum Accumlator Gas Pressure (MPa)	4.42
Accumlator Water Temperature (K)	310.9
Nominal RWST Water Temperature (K)	302.6

4. RESULTS

4.1 Conservative Evaluation

In TRACE, steady-state initialization was performed. The parameters' results such as the power, the pressure of the pressurizer, the Tavg temperature, and the RCS flow rate are compared with FSAR data. Table 2 shows the comparison between the steady-state results of the TRACE and FSAR. The results are clearly mutually quite consistent. Following the steady-state initialization, the LBLOCA transient predicted results are compared with the FSAR data. Table 3 presents the sequence of LBLOCA and the timings of the LBLOCA predicted by TRACE. The sequence of TRACE arose from the actuation of the related control system, which in turn had to be actuated by physical parameter signals. If the parameters predicted by TRACE differ from the FSAR data, then the event sequences will also be difference. Such deviations can be observed in the comparisons of transient event analyses.

Figure 5 plots the power curve that calculated from TRACE in the case of LBLOCA, and then compares with the FSAR data. In TRACE, the core power can be calculated using the built-in point kinetics model, and the power calculated includes decay heat. It displays that the power curve of TRACE is almost the same as those of FSAR data. Figure 6 compares the pressures of the vessel and suggests that the pressure calculated by TRACE approximately follows the trend of the FSAR data. Figure 7 compares the break mass flow rate of cold-leg pipe. It reveals that break mass flow rate predicted by TRACE agrees closely with the results of the FSAR data. Figure 8 shows the comparisons of accumulator mass flow rate of intact loops between TRACE model and FSAR data. Figure 9 compares the core inlet flow rate, revealing that the flow rate calculated by TRACE is in agreement with the FSAR data except for the period between 6 and 18 sec. It reveals that the flow rate calculated by TRACE is slightly lower between 6 and 18 sec. Figure 10 plots the results for core outlet flow rate. The difference results of core outlet flow before 6 sec are consideration of the nature flow in TRACE. Analytical results indicate that the Maanshan TRACE model predicts the behaviors of important plant parameters in consistent trends with the FSAR data. The PCT_{CM} of TRACE calculated by conservative method was 1228.7K (1752▯).

Table 2 The comparison of the steady state data

Parameter	FSAR	TRACE	Error (%)
Power (MWt)	2830	2830	0
Tavg * (K)	584.5	584.53	0.0001
Pressurizer pressure (MPa)	15.858	15.859	0.0001
Loop Flow (kg/sec)	4331.8	4347	0.0035

*Tavg = (Hot-leg temperature +Cold-leg temperature)/2

Table 3 The LBLOCA sequences of TRACE and FSAR

LBLOCA	FSAR (sec)	TRACE (sec)
Break began	0.0	0.0
Reactor scram setpoint reached	0.50	0.50
SI signal generated	1.4	1.5
Accumulators Injection	15.0	14.2
Start of Pumped SI	28.4	28.5
Accumulators empty	52.1	59.5

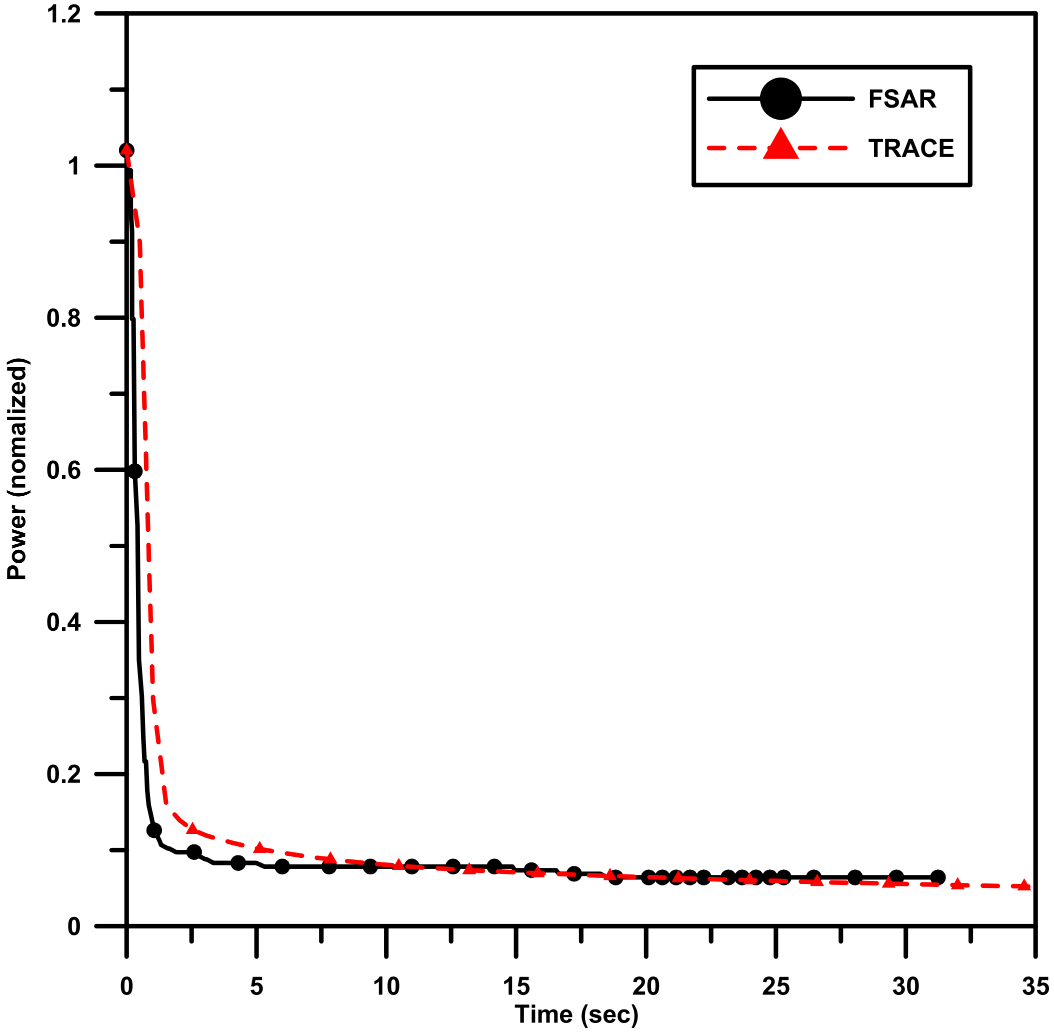


Figure 5 The results of power between TRACE and FSAR

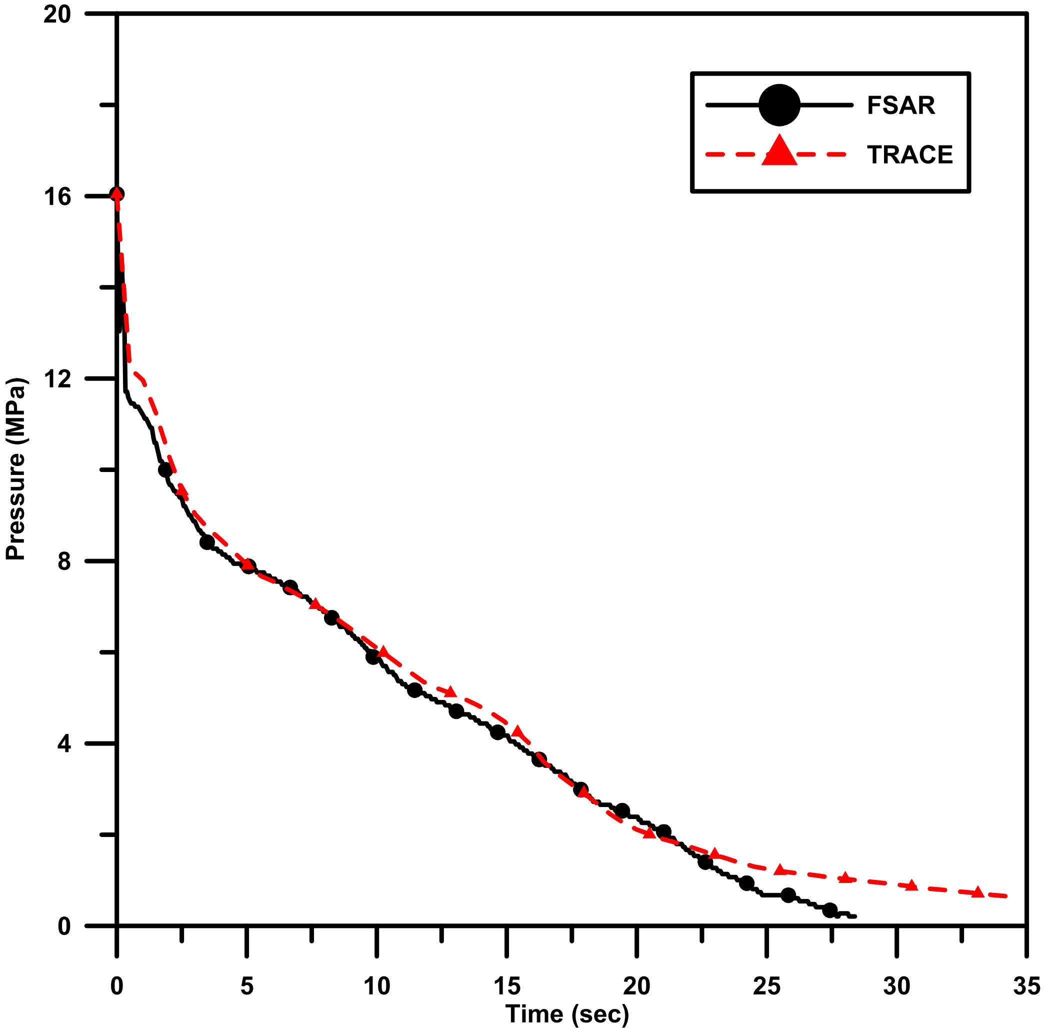


Figure 6 The results of vessel pressure between TRACE and FSAR

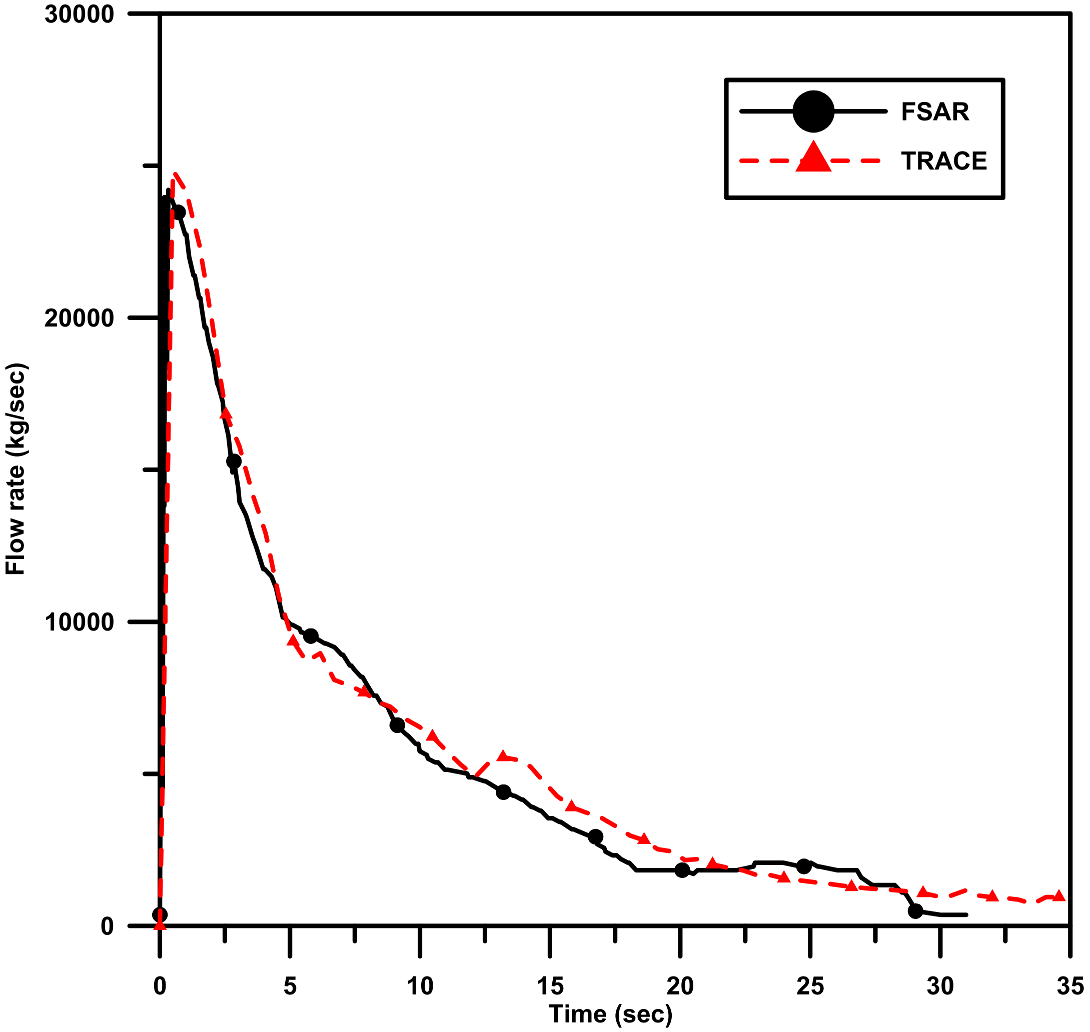


Figure 7 The results of break mass flow rate between TRACE and FSAR

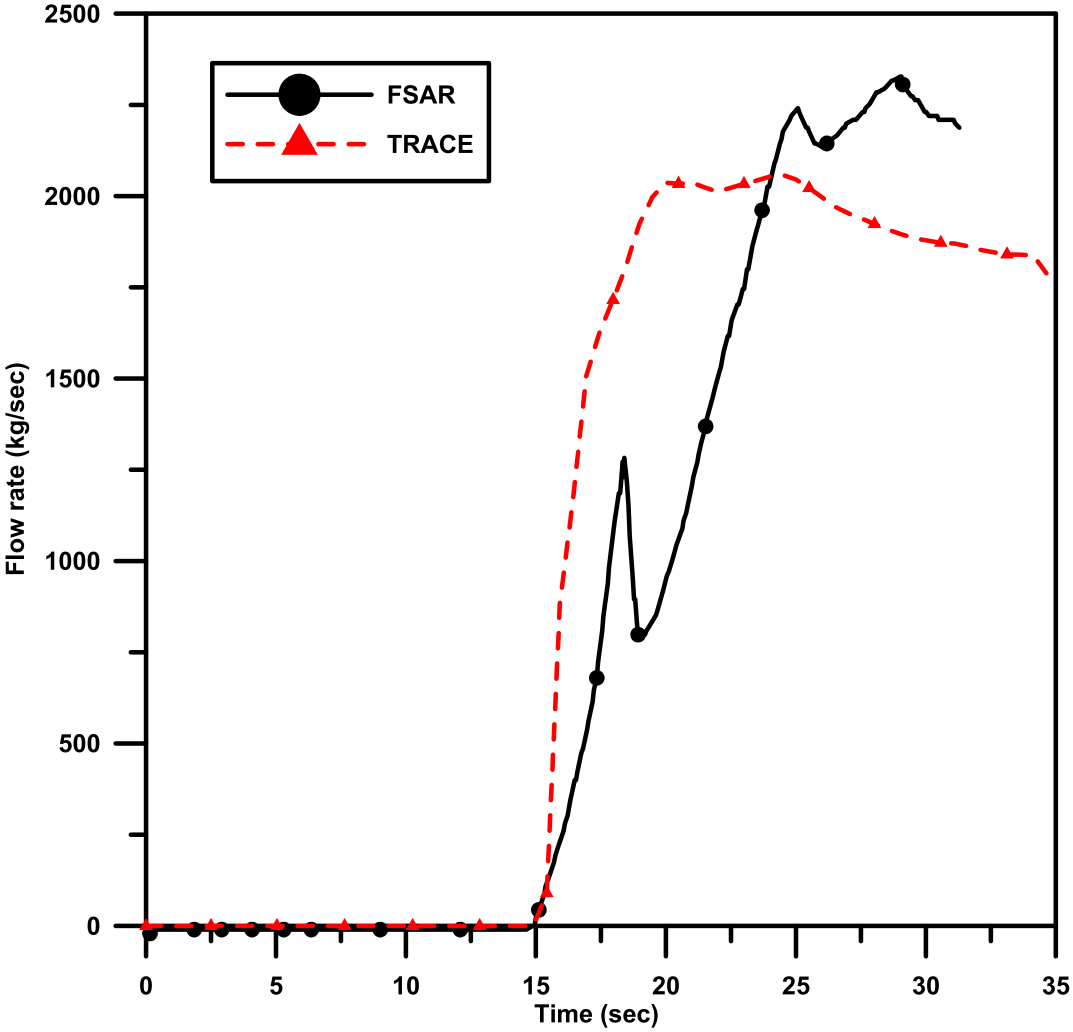


Figure 8 The results of accumulator mass flow rate between TRACE and FSAR

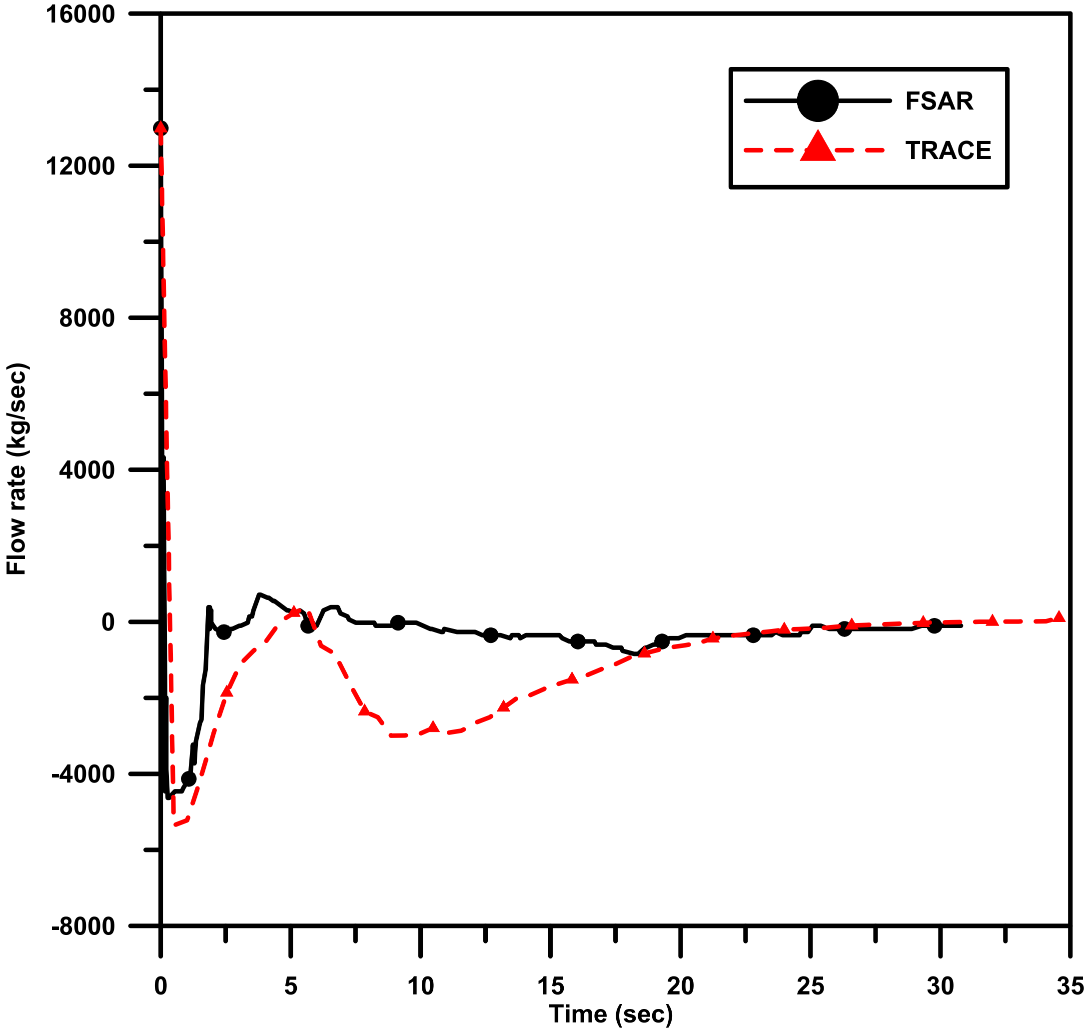


Figure 9 The results of core inlet flow between TRACE and FSAR

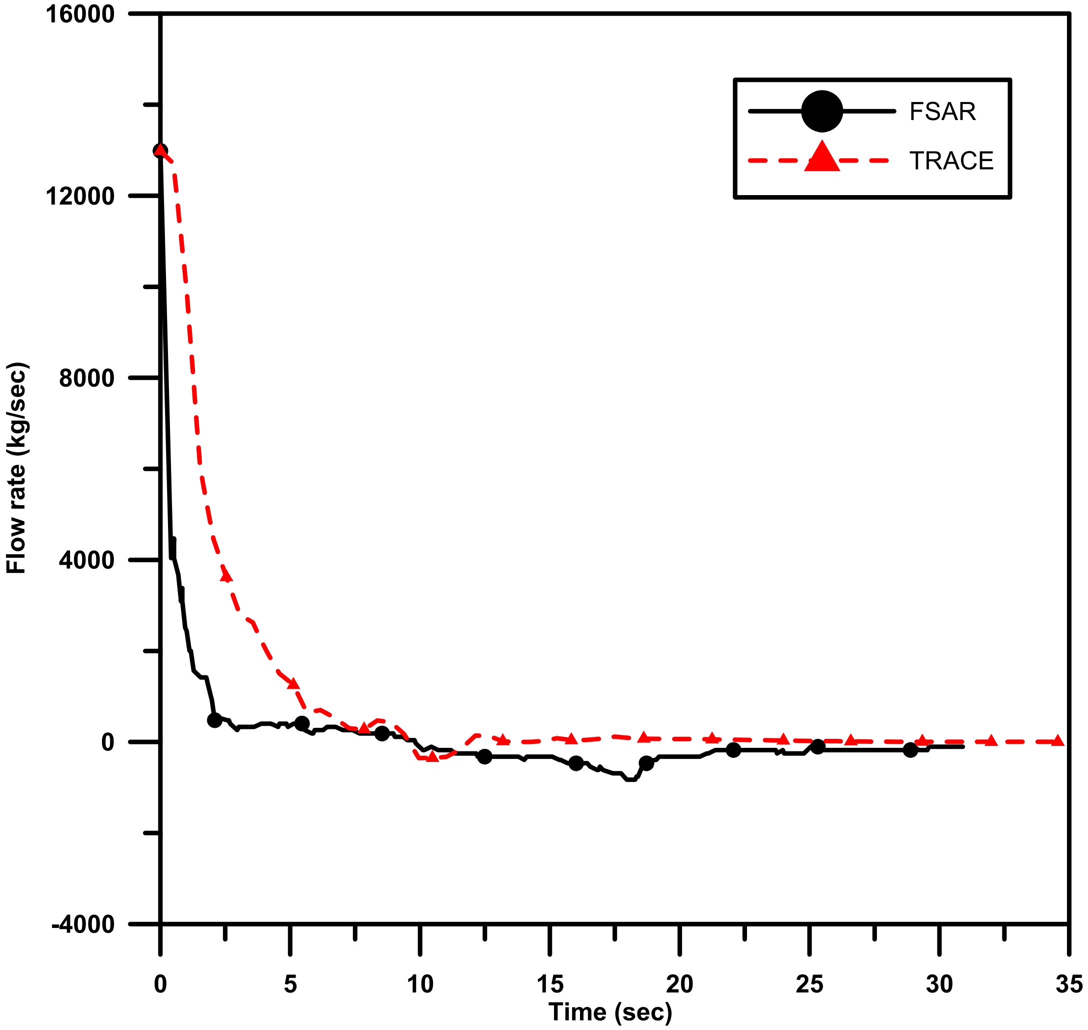


Figure 10 The results of core outlet flow between TRACE and FSAR

4.2 Best Estimate

In best estimate plus uncertainty of LBLOCA analysis, several plant parameters were considered in the uncertainty quantified. These include RCS conditions and ECCS fluid conditions. Table 4 lists the 5 parameters (i.e., pressurizer pressure, safety injection temperature, accumulator volume, accumulator water temperature, and accumulator pressure) taken into account in this uncertainty analysis, which are defined as the SNAP user-defined numeric variables (see Figure 11) and linked with uncertainty configuration to generate TRACE input files. In particular, the statistical theory predicts that 59 calculations are required to simultaneously bind the 95th percentile of one parameters (PCT) with a 95-percent confidence level. Figure 12 shows the PCTs calculated by conservative methodology and best estimate methodology during LBLOCA. By the conservative methodology, the PCT_{CM} of Maanshan power plant LBLOCA calculated is 1228.7K. On the other hand, the maximum value of PCT is 1158.4 K from the 59 trials of best estimate. In PCT of 95/95 confidence level and probability calculation, the mean value (PCT_{mean}) and standard deviation (σ) of the 59 trial are 1022.8 K and 65.8 K respectively. From the Eq. 2, the $PCT_{95/95}$ is 1131.1K lower than the PCT_{CM} and limited valve (1477K). Compared to conservative methodology, the best estimate provides a greater safety margin for the PCT evaluation.

In addition, 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. The DAKOTA toolkit was applied for the sampling of input parameters and the calculation of correlations and ranking of input parameters. The coefficients are obtained by Pearson's correlation shown in Eq. 3.

$$r = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2 \sum_{i=1}^{n}(y_i-\bar{y})^2}} \qquad \text{Eq. 3}$$

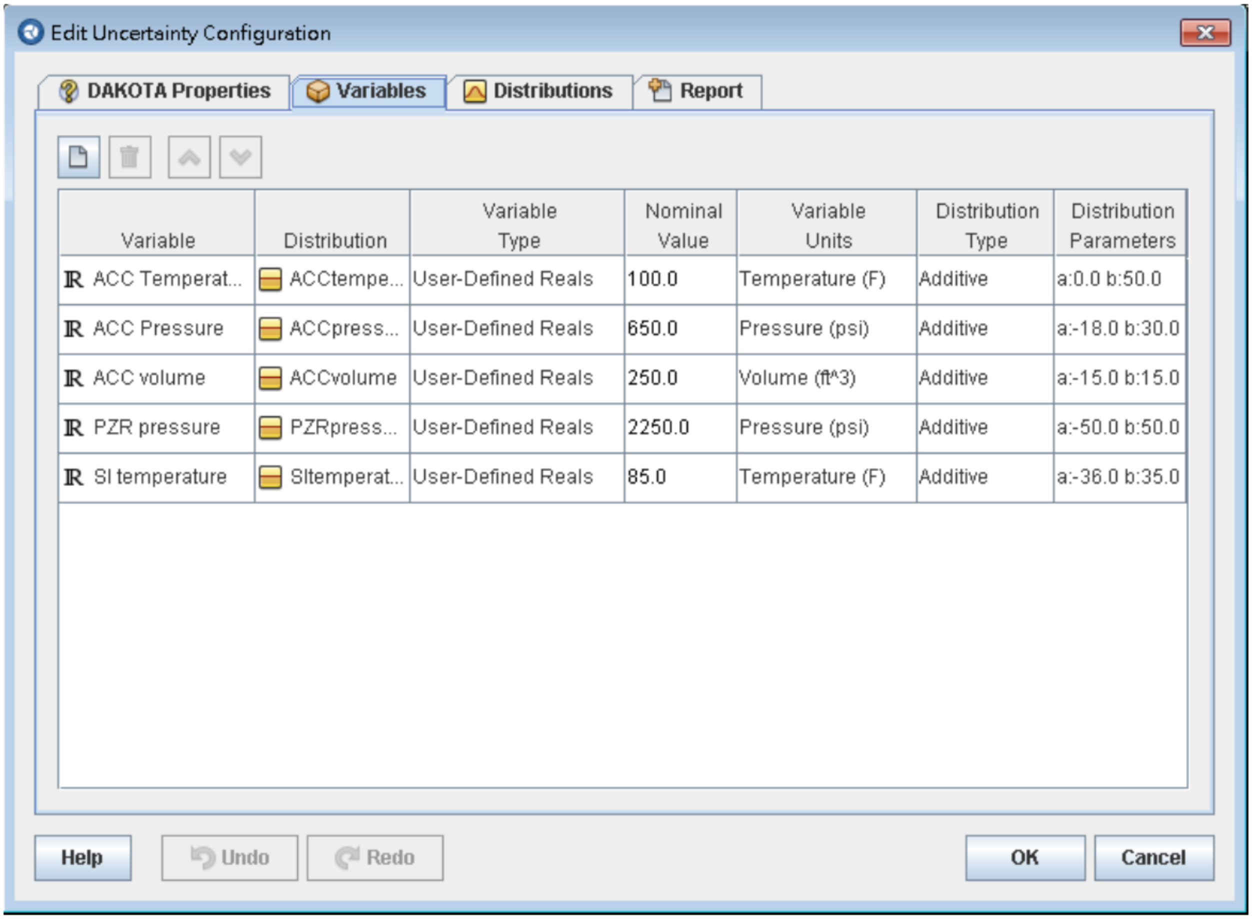
where r is the Pearson's correlation coefficient, n is the number of samples, and x and y denote two quantities.

The influence and partial rank correlation between input parameters and PCT are shown in Figure 13-14, and the results indicate that accumulator temperature is the most sensitive parameter.

Table 4 The initial conditions for the uncertainty analysis

Input parameters	**Nominal values**	**Uncertainty range**	**PDFs**
Pressurizer pressure	15.513 (MPa)	[-3.45, +3.45]	Uniform distribution
Accumulator pressure	4.482 (MPa)	[-1.25, +1.25]	
Accumulator volume	28.32 (m^3)	[-0.43, +0.43]	
Accumulator temperature	311 (K)	[0, +27.78]	
Safety injection temperature	303(K)	[-20, +19.45]	

Note: normal distributions are sampled over ±4σ



Variable	Distribution	Variable Type	Nominal Value	Variable Units	Distribution Type	Distribution Parameters
ℝ ACC Temperat...	ACCtempe...	User-Defined Reals	100.0	Temperature (F)	Additive	a:0.0 b:50.0
ℝ ACC Pressure	ACCpress...	User-Defined Reals	650.0	Pressure (psi)	Additive	a:-18.0 b:30.0
ℝ ACC volume	ACCvolume	User-Defined Reals	250.0	Volume (ft^3)	Additive	a:-15.0 b:15.0
ℝ PZR pressure	PZRpress...	User-Defined Reals	2250.0	Pressure (psi)	Additive	a:-50.0 b:50.0
ℝ SI temperature	SItemperat...	User-Defined Reals	85.0	Temperature (F)	Additive	a:-36.0 b:35.0

Figure 11 The user-defined numeric variables in SNAP

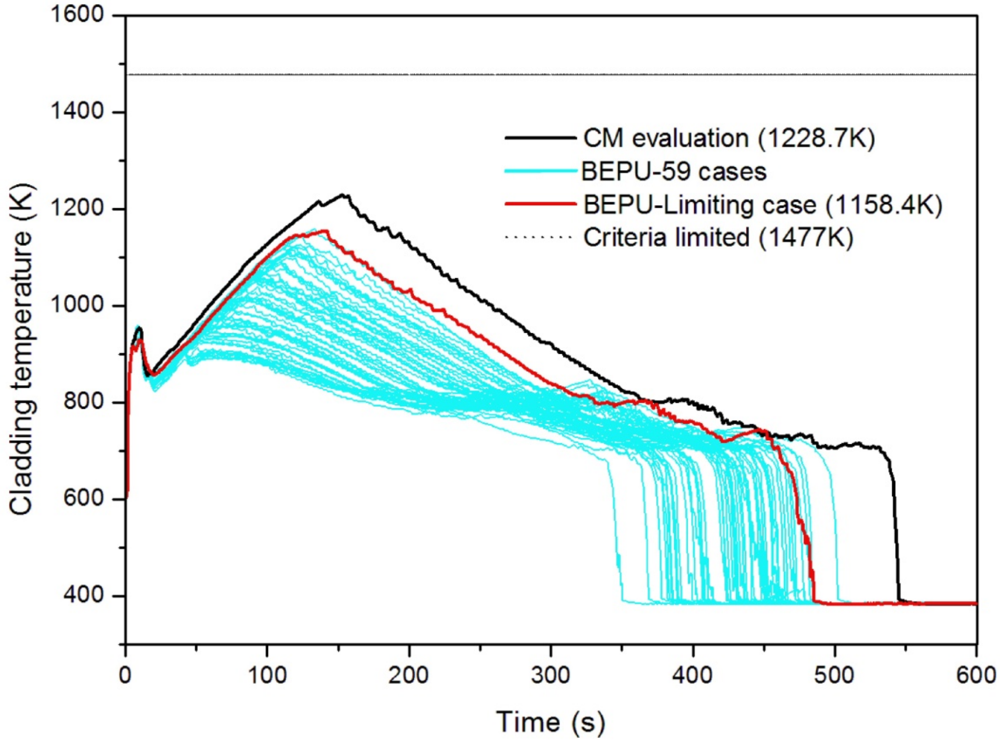


Figure 12 The PCTs during LBLOCA (included PCT_{CM} and PCT_{BE})

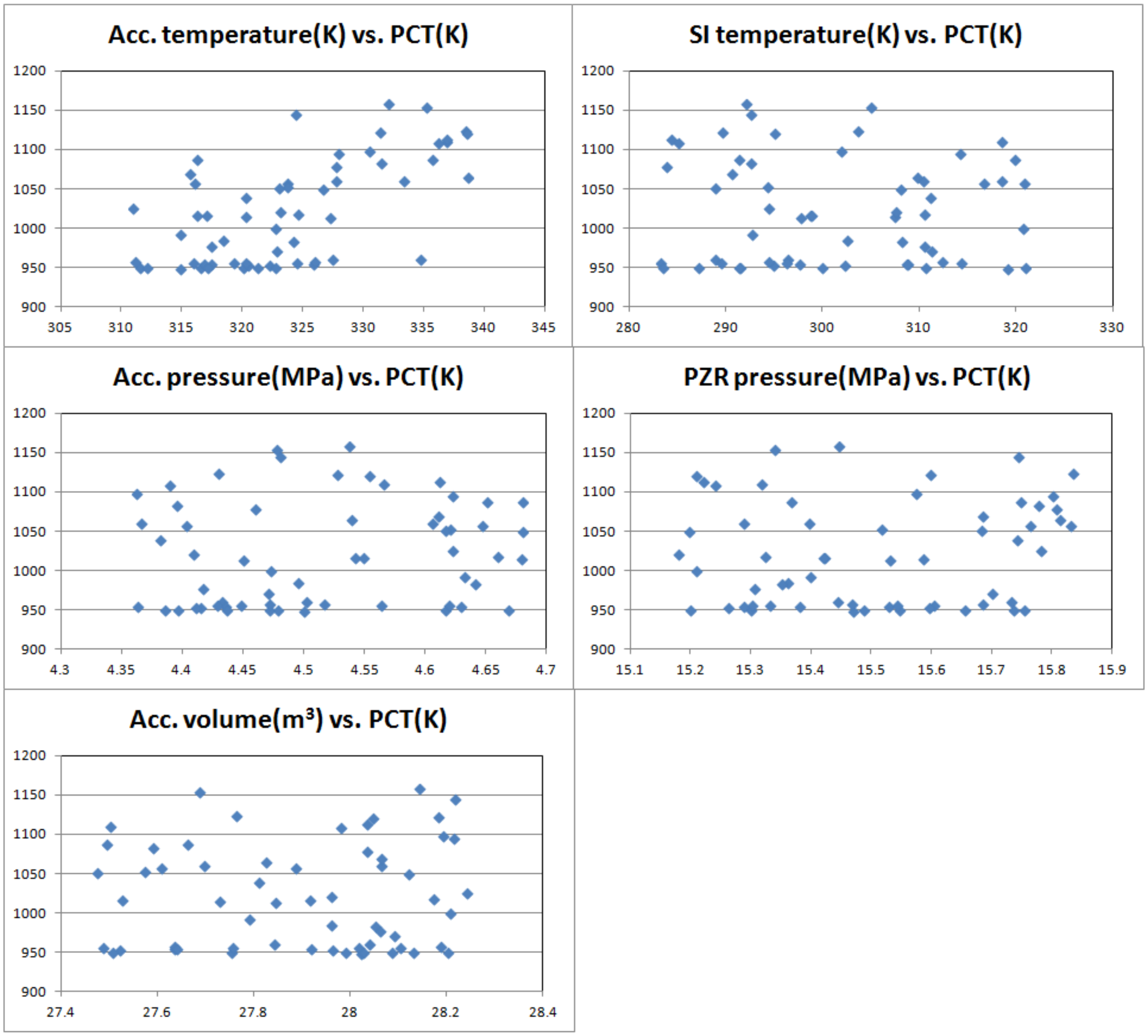


Figure 13　The influences of input parameter for PCT

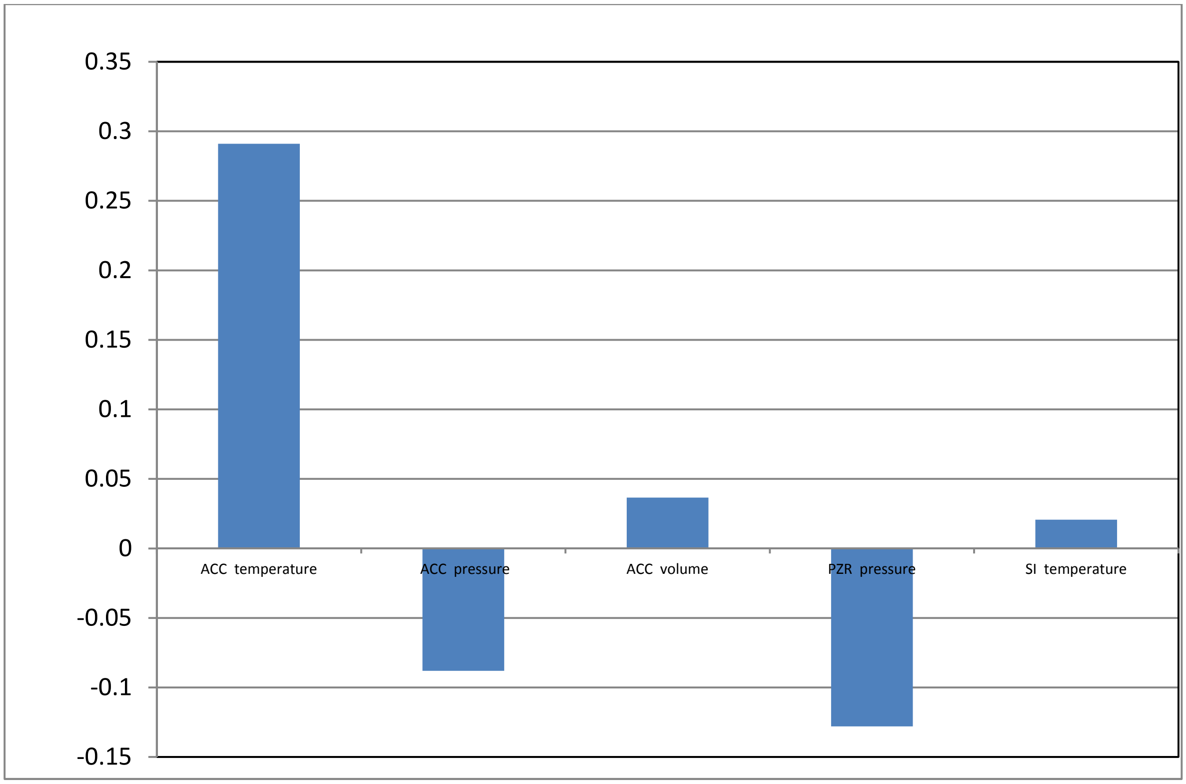


Figure 14 The partial rank correlations between input parameters and PCT

5. CONCLUSIONS

In this study, the LBLOCA analysis results of conservative methodology are verified against the FSAR data. The analysis results indicate the Maanshan TRACE model could predict the behaviors of important plant parameters (i.e., power, break flow rate, vessel pressure, accumulate flow rate, core inlet flow rate, and core outlet flow rate) in consistent trends with the Maashan FSAR data.

In best estimate plus uncertainty of LBLOCA analysis, five plant parameters were considered in the uncertainty quantified and taken into account in this uncertainty analysis. 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 $PCT_{95/95}$ which achieve 95/95 criterion. The PCTs by conservative method and best estimate plus uncertainty calculation are 1228.7 K (PCT_{CM}) and 1131.1 K ($PCT_{95/95}$) respectively. The mean value and standard deviation of the 59 trial by TRACE-DAKOTA are 1022.8 K (PCT_{mean}) and 65.8 K (σ) respectively, and the maximum value of PCT is 1158.4 K. Compared to conservative methodology, the best estimate plus uncertainty provides a greater safety margin for the PCT evaluation. In addition, the partial rank correlation coefficients between input parameters and PCT indicate that accumulator temperature is the most sensitive parameter in this study.

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

This research is focused on the Large Break Loss of Coolant Accident (LBLOCA) analysis of the Maanshan power plant by TRACE-DAKOTA code. In the acceptance criteria for Loss of Coolant Accidents (LOCAs), there are two accepted analysis methods: conservative methodology and best estimate methodology. Compared with conservative methodology, the best estimate and realistic input data with uncertainties to quantify the limiting values i.e., Peak Cladding Temperature (PCT) for LOCAs analysis. By the conservative methodology, the PCTcm (PCT calculated by conservative methodology) of Maanshan power plant LBLOCA calculated is 1228.7K. On the other hand, there are five initial conditions taken into account in the uncertainty analysis in this study. In PCT95/95 (PCT of 95/95 confidence level and probability) calculation, the PCT95/95 is 1131.1K lower than the PCTCM (1228.7K). In addition, the partial rank correlation coefficients between input parameters and PCT indicate that accumulator temperature is the most sensitive parameter in this study.

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