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Analysis of Loss of Feedwater Heater Transients for Lungmen ABWR by TRACE/PARCS

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ABSTRACT

The TRACE/PARCS model of Lungmen ABWR was used to evaluate the loss of feedwater heater (LOFH) transient of the Lungmen startup tests. The Loss of Feedwater heater transient is an anticipated operational occurrence (AOO) event. Identifications of the responses of the Lungmen models and verification of the plant vendor's analysis results are crucial in the plant licensing analysis. PARCS, a three-dimensional neutronics simulator, is capable of performing detail transient three-dimensional core power distributions and can be coupled with TRACE for thermal hydraulic feedback analysis. The feedwater enthalpy entering the RPV in this event is modeled as a 30 seconds time constant decay curve. When feedwater temperature drops approximately 37°C, the feedwater control system (FWCS) triggers reactor internal pump (RIP) runback and selected control rod run in (SCRRI) immediately. The colder feedwater temperature collapses the voids, which leads to the void reactivity increase and decreases RPV water level. SCRRI can reduce the core reactivity and core temperature which then increase the Doppler reactivity. The water level would fluctuate between L3 and L8, having enough safety margins to avoid either low or high water level scram setpoints. On the other hand, we have also simulated another case without RIP runback and SCRRI. The sensitivity studies of this transient include different time constants, SCRRI delay times, RIP runback rates and RIP runback delay times. Furthermore, the study of 18 CHANs model and 206 CHANs model performance with TRACE/PARCS has been evaluated. The SNAP animation model can show three dimensional visualized results of different core parameters.

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. To meet this responsibility, the TRACE/PARCS model of Lungmen NPP has been built. In this report, the TRACE/PARCS model of Lungmen NPP was used to evaluate the loss of feedwater heater (LOFH) transient of the Lungmen startup tests.

CONTENTS

FIGURES

TABLES

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 users' experiences and development suggestions. To fulfill this responsibility, the TRACE/PARCS model of Lungmen 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.

PARCS is a multi-dimensional reactor core simulator which involves a 3-D calculation model for the realistic representation of the physical reactor while 1-D modeling features are also available. PARCS is capable of coupling the thermal-hydraulics system codes such as TRACE directly, which provide the temperature and flow field data for PARCS during the calculations.

Lungmen NPP is the first ABWR plant in Taiwan and still under construction. It has two identical units with 3,926 MWt rated thermal power each and 52.2×10^6 kg/hr rated core flow. The core has 872 bundles of GE14 fuel, and the steam flow is 7.637×10^6 kg/hr at rated power. There are 10 RIPs in the reactor vessel, providing 111% rated core flow at the nominal operating speed of 151.84 rad/sec.

The TRACE/PARCS model of Lungmen NPP was used to evaluate the LOFH transient of the Lungmen startup tests. The Loss of Feedwater heater transient is an anticipated operational occurrence (AOO) event. Identifications of the responses of the Lungmen models and verification of the plant vendor's analysis results are crucial in the plant licensing analysis. The feedwater enthalpy entering the RPV in this event is modeled as a 30 seconds time constant decay curve. When feedwater temperature drops approximately 37°C, the feedwater control system (FWCS) triggers reactor internal pump (RIP) runback and selected control rod run in (SCRRI) immediately. The colder feedwater temperature collapses the voids, which leads to the void reactivity increase and decreases RPV water level. SCRRI can reduce the core reactivity and core temperature which then increase the Doppler reactivity. The water level would fluctuate between L3 and L8, having enough safety margins to avoid either low or high water level scram setpoints. On the other hand, we have also simulated another case without RIP runback and SCRRI. The sensitivity studies of this transient include different time constants, SCRRI delay times, RIP runback rates and RIP runback delay times. According to the sensitivity studies, it could be concluded that every case maintains the water level between L3 and L8, so that the scram setpoints would not be triggered. The shorter SCRRI delay time has significant effect on fuel rod temperature which leads to higher Doppler and void reactivity. The studies of different RIP runback delay times and rates affect the void feedback principally during the runback stage. The above sensitivity studies have no significant impacts on the final power and reactivity. Furthermore, the study of 18 CHANs model and 206 CHANs model performance with TRACE/PARCS has been evaluated. Comparing results between 18 CHANs and 206 CHANs model, 18 CHANs model has ability to perform plant response to the transient and 206 CHANs model is proper to local power calculation. The SNAP animation model can show three dimensional visualized results of different core parameters. Besides, the startup tests of Lungmen NPP will be performed in 2014 and the measured data of Lungmen NPP will be used to estimate and modify the TRACE/PARCS model of Lungmen NPP in the future.

ABBREVIATIONS

ABWR	Advanced Boiling Water Reactor
AOO	Anticipated Operational Occurrence
APLS	Advanced Lungmen Plant Specific Simulation
CAMP	Code Applications and Maintenance Program
FSAR	Final Safety Analysis Report
FWCS	Feedwater Control System
INER	Institute of Nuclear Energy Research Atomic Energy Council, R.O.C.
LOFH	Loss of Feedwater Heater
NRC	Nuclear Regulatory Commission
PARCS	Purdue Advanced Reactor Core Simulator
RFCS	Recirculation Flow Control System
RIP	Reactor Internal Pump
RR	RIP Runback
SCRRI	Selected Control Rod Run In
SNAP	Symbolic Nuclear Analysis Package
TPC	Taiwan Power Company
TRACE	TRAC/RELAP Advanced Computational Engine

1. INTRODUCTION

Lungmen NPP, the first advanced boiling water reactor (ABWR) owned by Taiwan power company (TPC) in Taiwan, has two identical units with 3926 MWt rated power and 52.2×10^{6} kg/h rated core flow each, and the reactor core is comprised of 872 GE-14 fuel assemblies with 205 control rods. TRACE (TRAC/RELAP Advanced Computational Engine) code developed by USNRC is an advanced and best-estimate reactor systems code for analysing thermal hydraulic behaviour in nuclear power plant. PARCS (Purdue Advanced Reactor Core Simulator) is a multi-dimensional reactor core simulator which involves a 3-D calculation model for the realistic representation. The coupling between the TRACE and the PARCS with 3-D neutronics models of the reactor core into system transient has been developed successfully. SNAP (Symbolic Nuclear Analysis Package) provides not only a graphical interface for user to develop the TRACE/PARCS model but also animation models to visualize 3-D results of different core parameters.

During the Lungmen startup test, the acceptable plant parameters and responses have been provided by the plant vendor's results. In the same time, Yang etc. verified the plant vendor's results by using a dual RELAP5 advanced Lungmen plant specific simulation platform (APLS) [1]. Loss of feedwater heater (LOFH) transient is an anticipated operational occurrence (AOO) event. There are two reasons to LOFH: First, feedwater heater bypass which causes step change in decreasing temperature of downcomer feedwater. Secondly, steam line of feedwater heater closure, due to the residual heat in feedwater heater can still heat the feedwater, the temperature of downcomer feedwater decreases gradually.

In this study, TRACE/PARCS applies 30 seconds feedwater time constant decay curve to determine feedwater enthalpy entering the RPV. Upon feedwater temperature drops approximately 37°C, the feedwater control system (FWCS) will send a signal to recirculation flow control system (RFCS), which triggers reactor internal pump (RIP) runback and selected control rod run in (SCRRI) immediately. Besides, we compare our 18 CHANs model with 206 CHANs model. The compared results show good agreement with power in LOFH transient. The sensitivity studies of this transient include different time constants, SCRRI delay times, RIP runback rates and RIP runback delay times. And the analysis results of LOFH have been compared with RETRAN-3D data.

2. TRACE/PARCS COUPLING MODEL OF LUNGMEN ABWR

The study of LOFH startup test is modeled at 100% power and 100% flow by using TRACE V5.0p3 and PARCS V3.0 under SNAP V2.2.0.

2.1 Lungmen TRACE Model

The TRACE model for Lungmen Nuclear Power Plant is shown in Figure 1. The RPV is modeled by TRACE 3-D VESSEL component with 11 axial levels, 4 radial rings, and 6 azimuthal sectors (separately in 36°, 36°, 108°, 36°, 36°, 108° apart) for a total of 264 computational cells. The vessel is connected with 4 steam lines (36° azimuth al sectors separately) and 6 feedwater lines (6 azimuthal sectors of the VESSEL). Each of the 10 RIPs is connected to the VESSEL at every 36° azimuthal sectors and modeled as PUMP component at the outer ring of the VESSEL. These 10 RIPs are arranged into three groups. 6 RIPs are connected to M-G sets; the other 4 RIPs are connected to non M-G sets.

The core is modeled by 18 CHAN components (3 inner radial rings of 6 azimuthal sectors individually) to represent 872 GE-14 10X10 fuel assemblies. Moreover, we discuss the difference between 206 CHANs model and 18 CHANs model as shown in Figure 2 and Figure 3. The TRACE model has been verified with the case data of FSAR chapter 15 [2][3]. We expect more improvement on the Lungmen TRACE model after the commercial operation of Lungmen NPP.

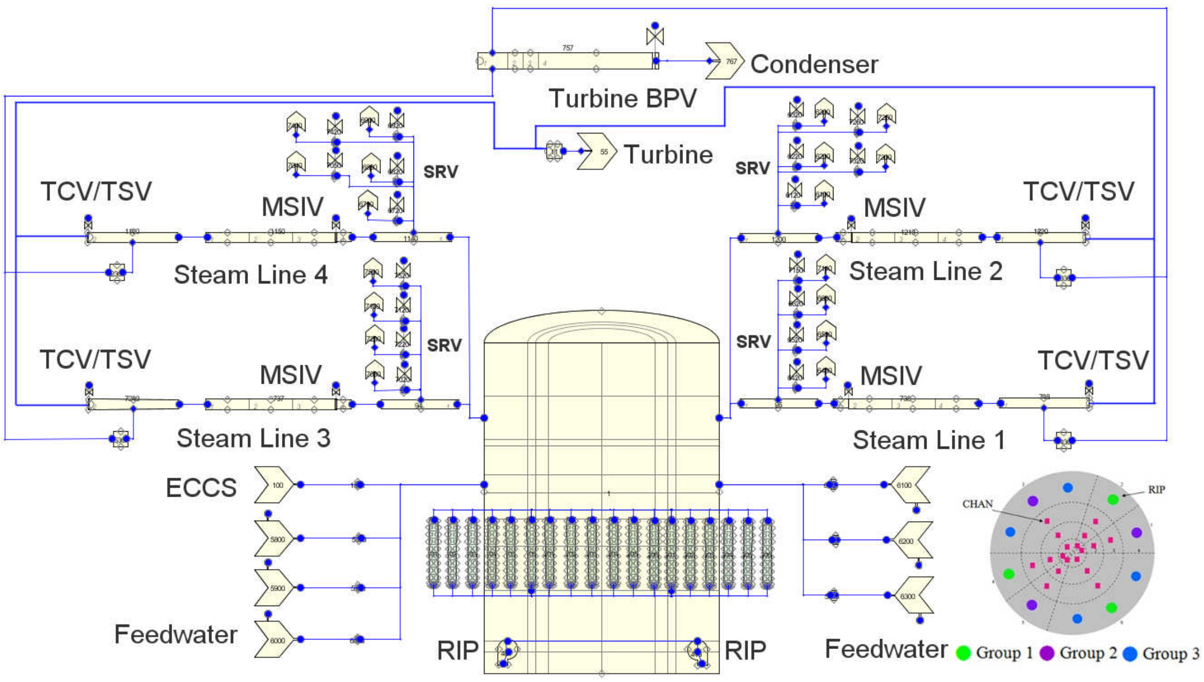

Figure 1 Lungmen TRACE model

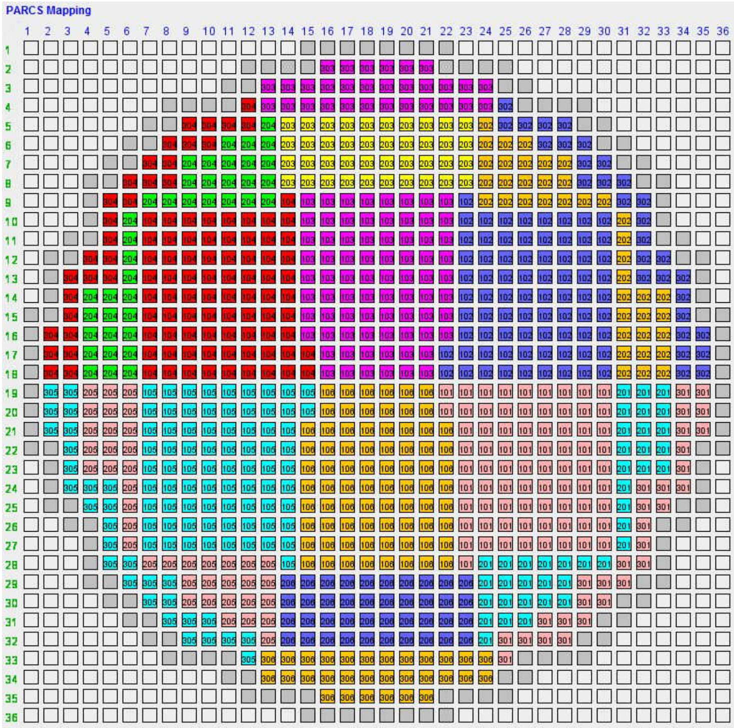

Figure 2 Lungmen TRACE/PARCS 18 CHANs mapping model

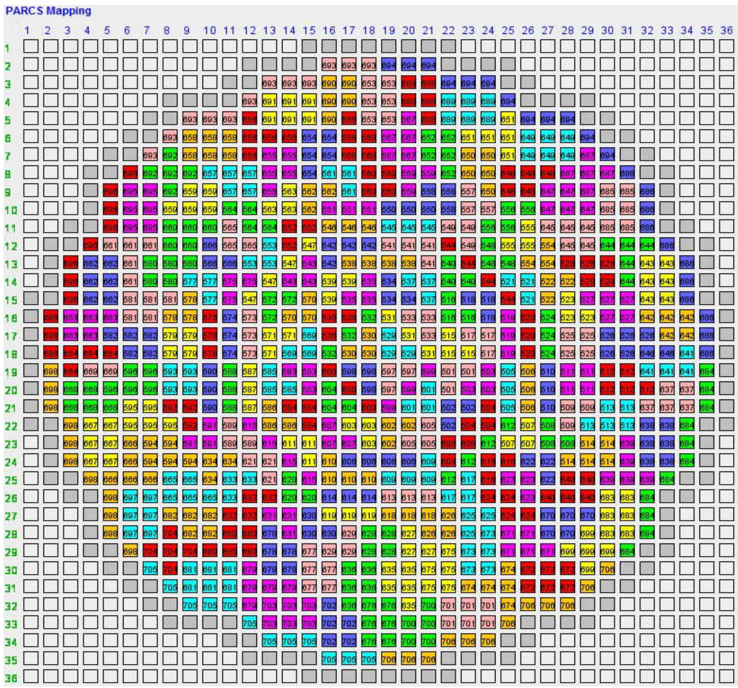

Figure 3 Lungmen TRACE/PARCS 206 CHANs mapping model

2.2 Lungmen PARCS Model

The PARCS model which is based on beginning of cycle consists of 872 fuel assemblies and 205 control rods. Each fuel assembly is represented by a single neutronics node. The active core height is 381cm, with 25 axial levels for active core, and top/bottom axial levels for 15.24-cm-thick axial reflector regions. The 205 control rod are divided into 19 groups, each group has different initial step as shown in Figure 4. The function of SCRRI is simulated in PARCS model and the history of control rod movement is shown in Figure 5. The SCRRI would be fully inserted within 145 seconds.

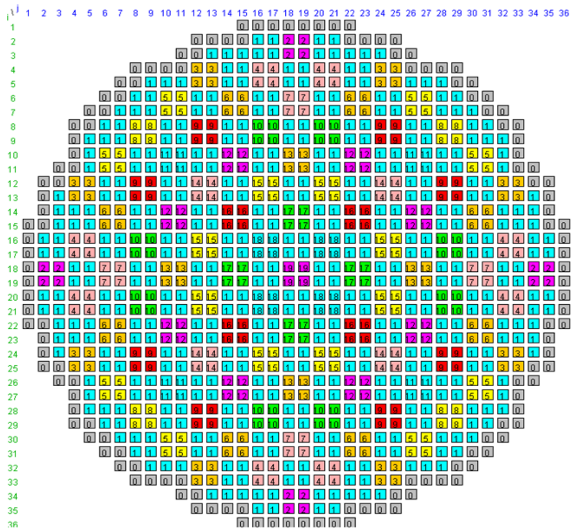

Figure 4 Control rod pattern for Lungmen PARCS model

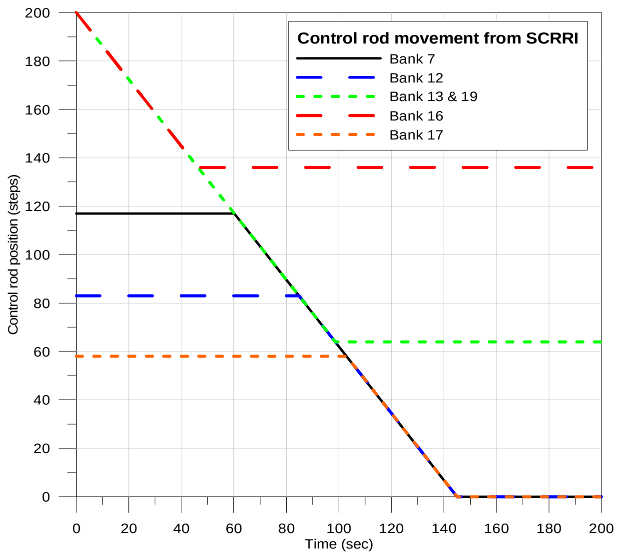

Figure 5 History of control rod movements from SCRRI [4]

2.3 Lungmen TRACE/PARCS Coupling Model

CASMO-4, a lattice physics code, generated the cross-section information which would be processed into the appropriate format by the program GenPMAXS. Then, the PMAXS cross section file that could be read by PARCS. The procedure of TRACE/PARCS coupling calculation is shown in Figure 6. During a transient, TRACE provides the thermal-hydraulic conditions for PARCS which would response the power distribution for TRACE. Table 1 lists the major thermal-hydraulic parameters at steady state condition for Lungmen ABWR.

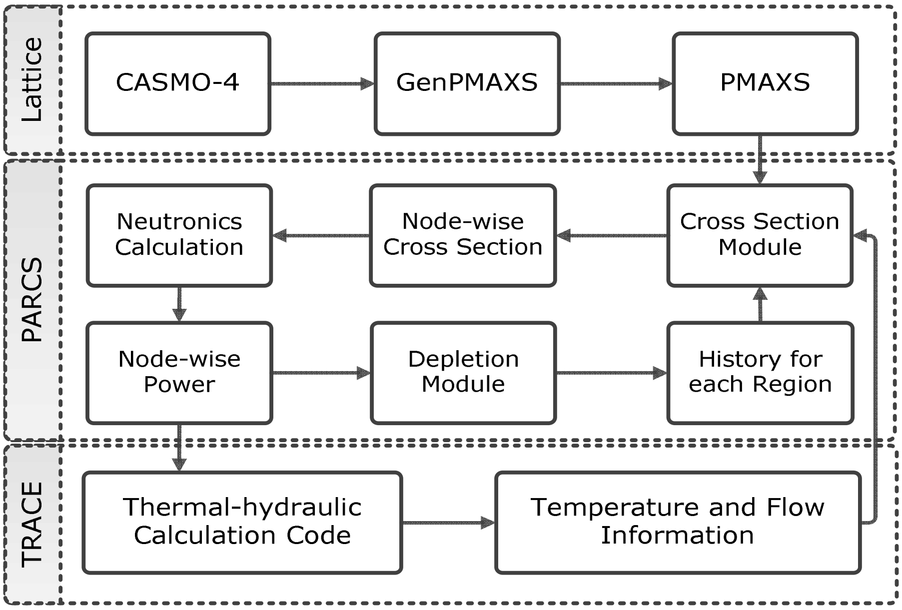

Figure 6 The procedure of TRACE/PARCS coupling calculation [5]

Table 1 Summary of TRACE/PARCS steady state condition

Parameters	FSAR	TRACE/PARCS model
Thermal power (MW)	3926	3926
Steam flow rate (kg/s)	2122	2121.2
Core flow rate (kg/s)	14500	14610
Dome pressure (MPa)	7.2	7.16
Narrow range water level (m)	13.42	13.43

3. RESULTS

The purpose of LOFH startup test is to demonstrate acceptable plant response and associated assumptions used for this transient in the plant licensing analysis. The study of LOFH transient is under the condition of 100% power and 100% flow. Upon sensing the reduction of 37°C in feedwater temperature, the FWCS sends out two signals, which initiate RIP runback and SCRRI in order to reduce the core power. Under normal operation, the RIP runback rate is designed at 5% of rated speed per second, and the delay time is 0.275 second; the delay time for SCRRI initiation is designed to be 0.09 second. Figure 7 shows that the core parameters of the final state of LOFH under SNAP animation. Moreover, the water level fluctuate between L3 and L8, having enough safety margins to avoid either low or high water level scram setpoints.

When the LOFH occurs, the colder feedwater temperature collapses the voids, which leads to the void reactivity increase and decreases RPV water level and followed by the increasing core power in Figure 8. SCRRI and RIP runback can reduce the core reactivity and core temperature which increase the Doppler reactivity as shown in Figure 9.

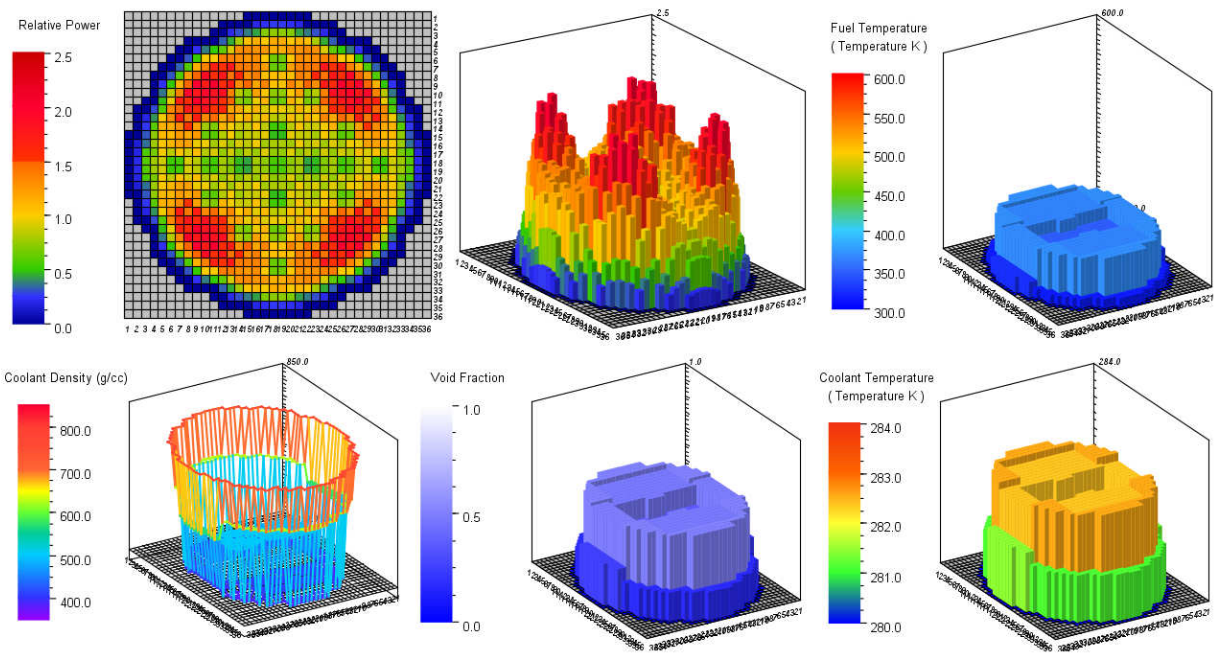

Figure 7 The core parameters of the final state in LOFH

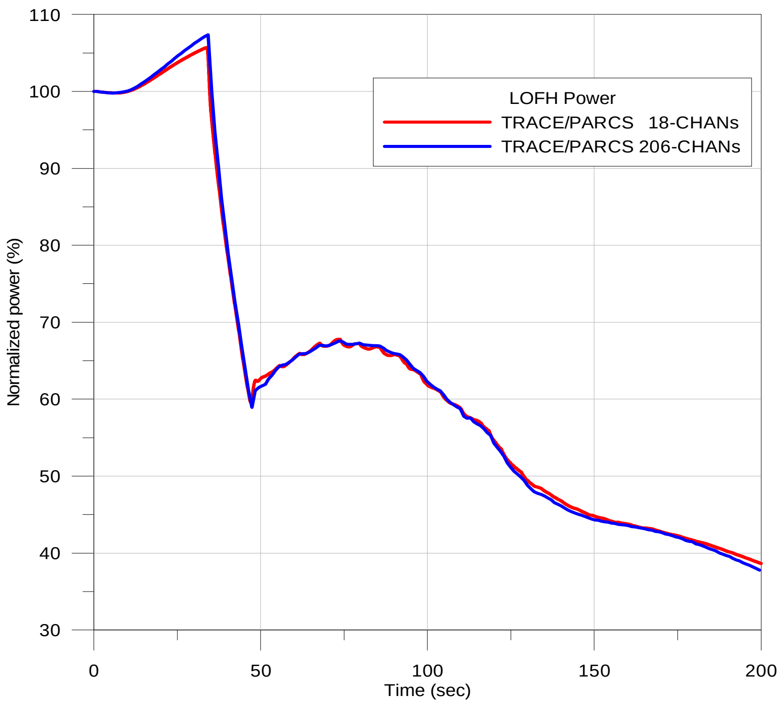

Figure 8 Power responses of the prediction analysis in LOFH

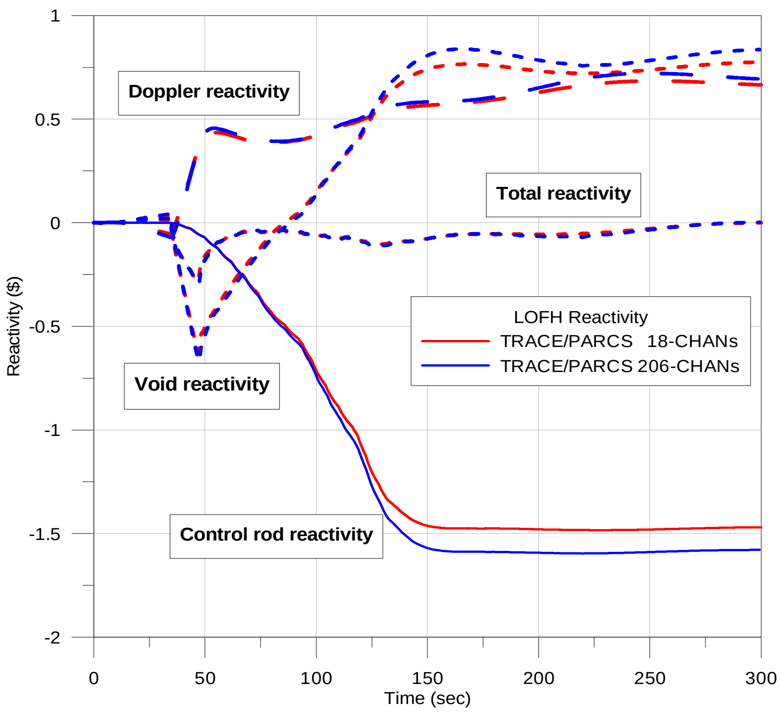

Figure 9 Reactivity responses of the prediction analysis in LOFH

TRACE/PARCS 18 CHANs model shows that the power is similar with 206 CHANs model in Figure 8. Figure 9 illustrates that 206 CHANs model has higher void reactivity than 18 CHANs model .The corresponding SCRRI reactivity has higher control rod worth because lower void fraction leads to more thermal neutrons absorbed by control rod. Due to more channels in RPV, 206 CHANs model can detail the core phenomena like maximum fuel rod temperature. However, it needs smaller timestep to calculate LOFH in 105 hrs. Therefore, 18 CHANs model is suitable for NPP system transient because it has the same trends with 206 CHANs model but less time-consuming (4 hrs).

We also simulate the case without RIP runback and SCRRI to get a range of power and temperature for startup test. Figure 10 presents that this case has higher void fraction which can provide negative reactivity. Hence, the power can reach 110% without triggering reactor scram (120%). Besides, the TRACE/PARCS model results are compared well with RETRAN-3D as shown in Figure 11~ Figure 13. As a result of slight variance in dome pressure, the power difference between TRACE/PARCS and RETRAN-3D is two percent.

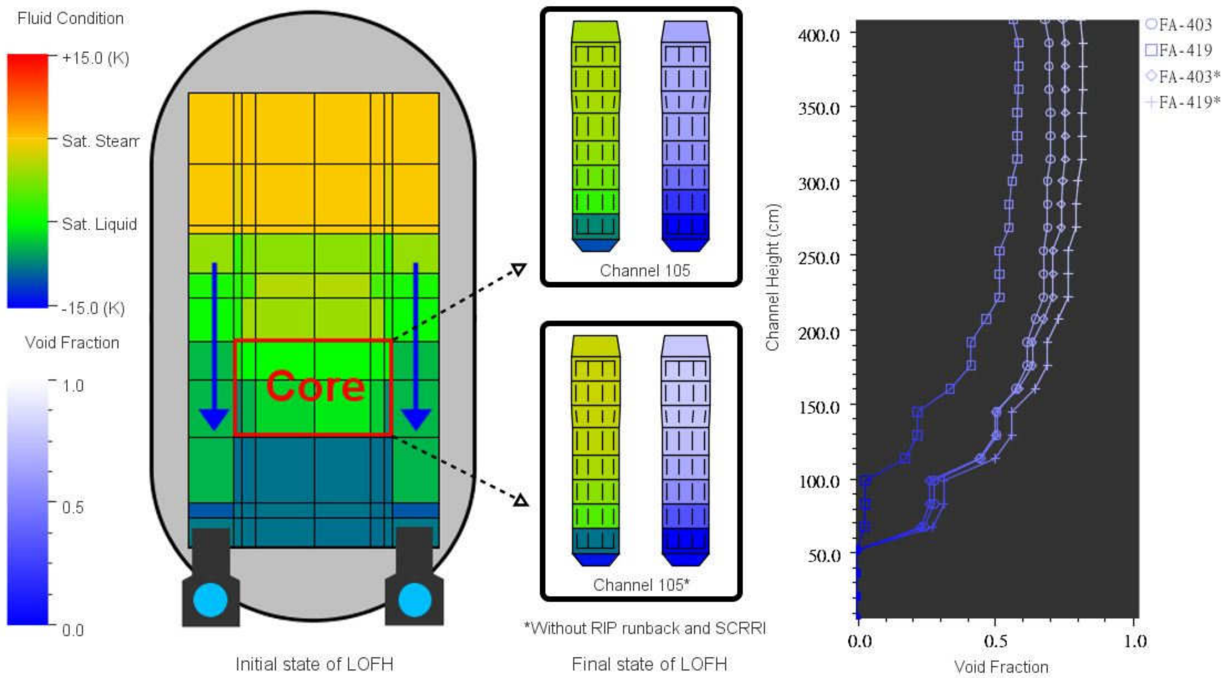

Figure 10 The initial state and final state under the SNAP animation

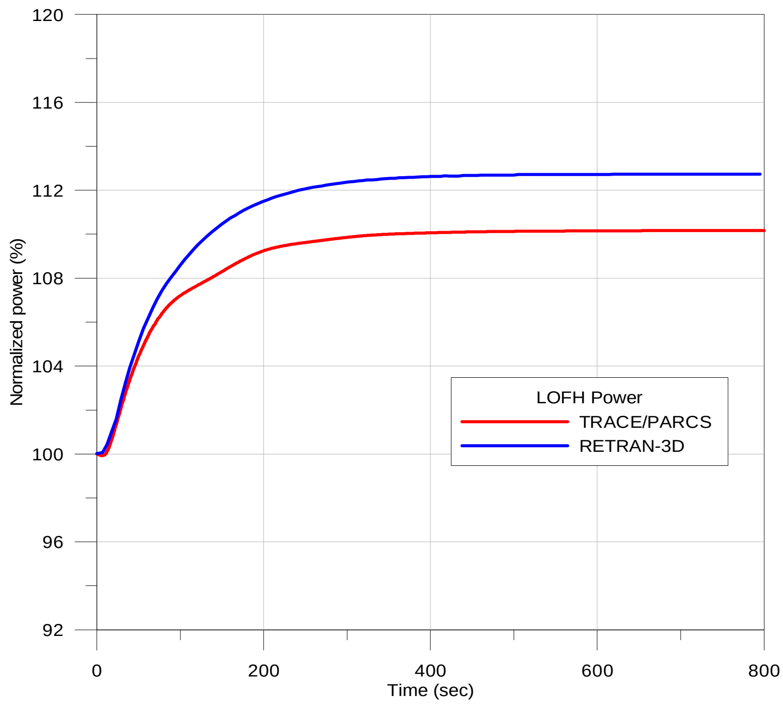

Figure 11　Power responses of the prediction analysis in LOFH

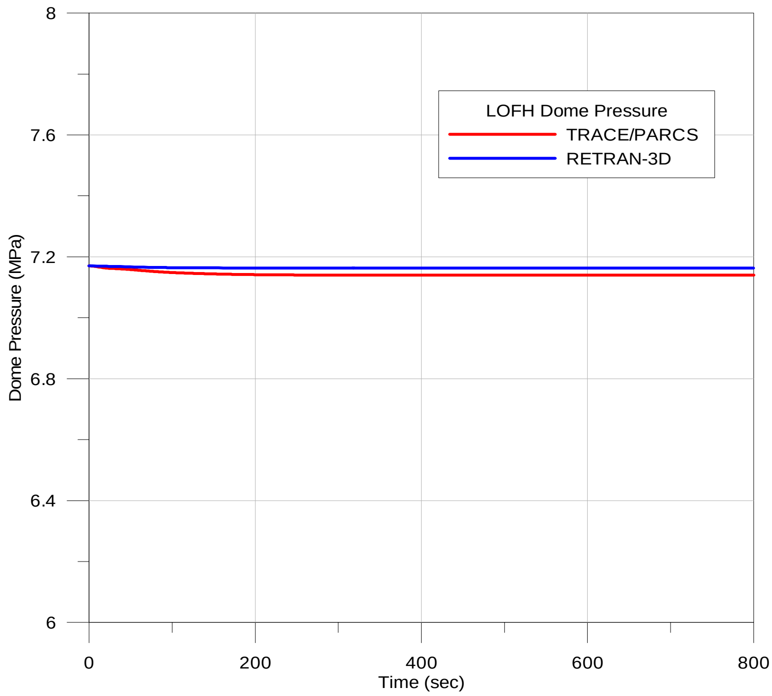

Figure 12　Dome pressure responses of the prediction analysis in LOFH

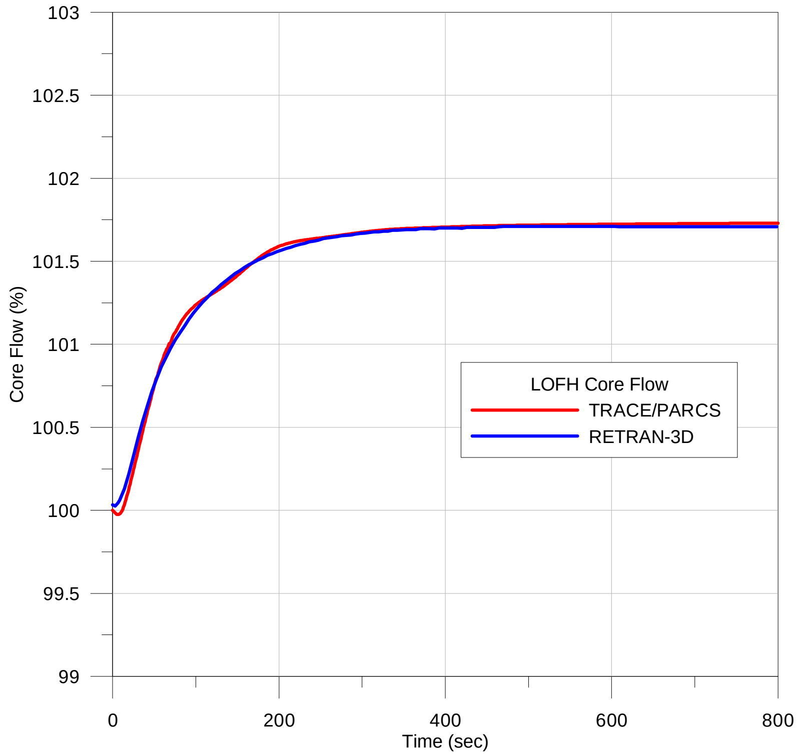

Figure 13 Core flow responses of the prediction analysis in LOFH

4. SENSITIVITY STUDIES

The following sensitivity studies are simulated by TRACE/PARCS 18 CHANs model. It is believed that 18 CHANs model with less CPU time is more suitable for demonstrating the acceptable plant response to the LOFH. The sensitivity studies of this transient include different time constants, SCRRI delay times, RIP runback delay times and RIP runback rates.

4.1 Different FW Heater Time Constant

The feedwater heater time constant for Lungmen NPP is not known, so we run a set of sensitivity cases to demonstrate the effect of different time constant. The summary of different time constant studies is shown in Table 2. With larger time constant, the enthalpy decay more slowly and then a temperature reduction of 37°C will be delayed. In the same time, two signals from the FWCS will also be delayed. As shown in Figure 14, the 90 second time constant has the highest water level at 1375 cm, however, still having safety margins to keep water level between L3 (1280 cm) and L8 (1395 cm).

4.2 SCRRI Delay Time

Table 3 lists the analysis results for SCRRI delay times in LOFH. The curves of control rod reactivity resulted from SCRRI shift parallel with SCRRI delay times in Figure 15. It also shows that earlier initiating SCRRI will lead to lower fuel rod temperature which causes higher Doppler and void reactivity. The lowest power is, however, due to control rod reactivity. Moreover, different SCRRI delay times have the same state in the end of this study.

4.3 RIP Runback Delay Time

Table 4 exhibits the analysis results for RIP runback (RR) delay times in LOFH. With longer RR delay times, more cold feedwater collapses the voids which leads to the void reactivity increase in Figure 17. Before the RIP runback, the power increase leads to Doppler reactivity decrease. However, different RR delay times do not affect the final state in this study.

4.4 RIP Runback Rate

Table 5 summarizes the sensitivity study on RIP runback rates in LOFH. Figure 19 presents that the RIP runback mechanism lessens the core inlet flow, the void in core increase such that the void reactivity rises in proportional to the RIP runback rate. Besides, faster RIP runback rate reduces the core temperature with corresponding to Doppler reactivity increase. Different RIP runback rates have significant effect on power history where power drops faster as RIP runback rate increases.

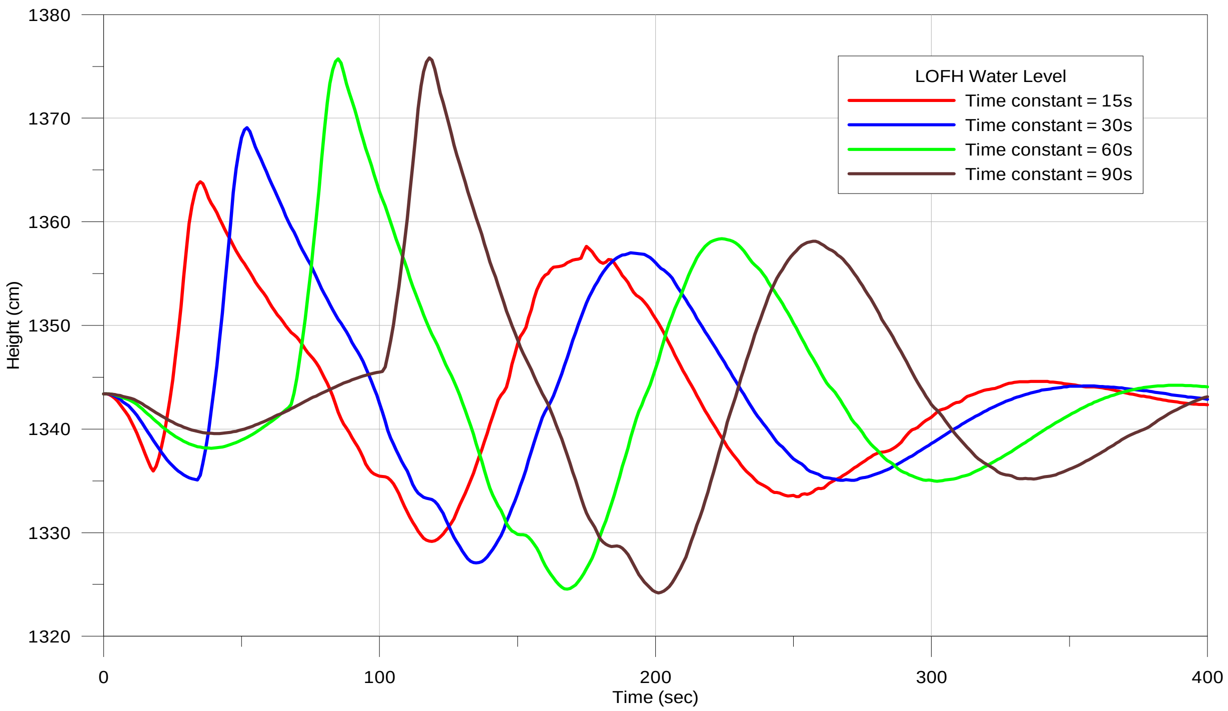

Figure 14 Water level responses of the sensitivity studies for different time constant

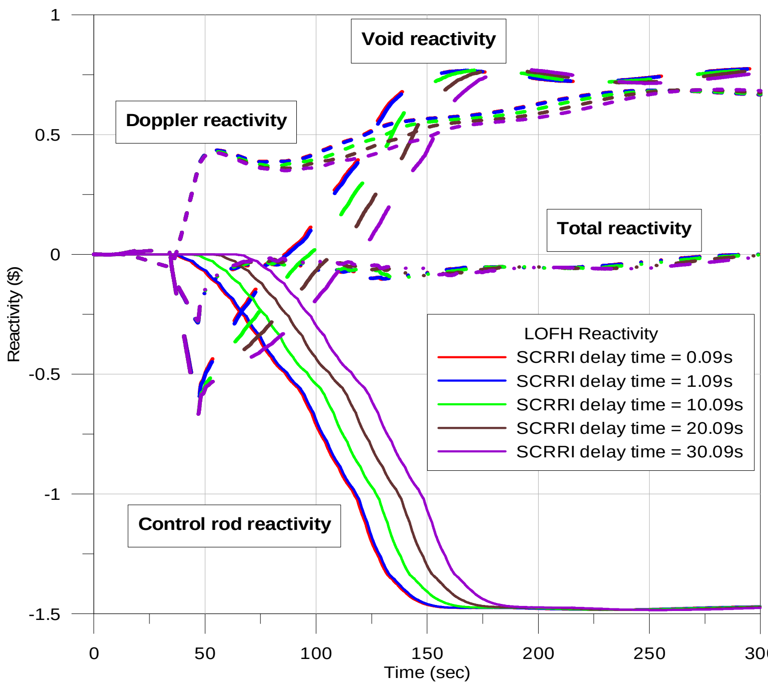

Figure 15 Reactivity responses of the sensitivity studies for SCRRI delay time

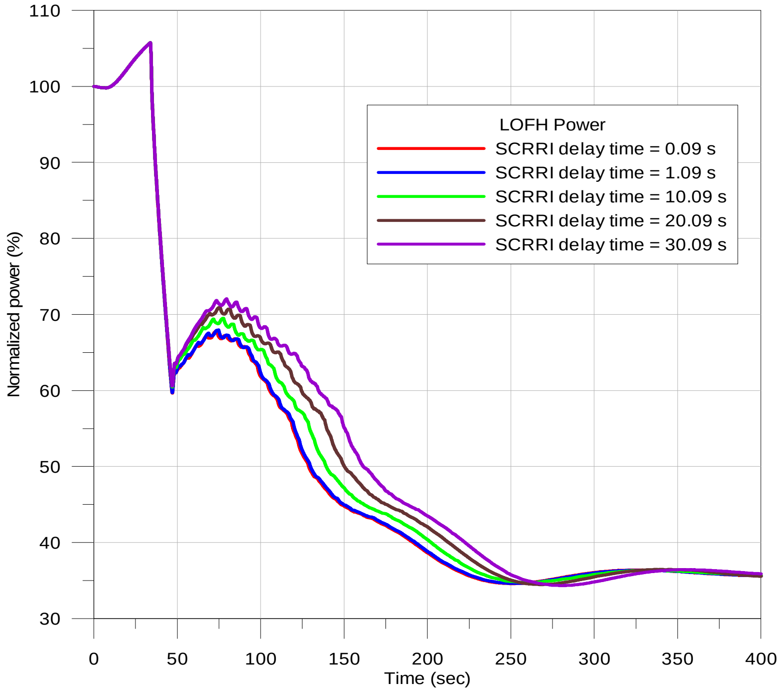

Figure 16 Power responses of the sensitivity studies for SCRRI delay time

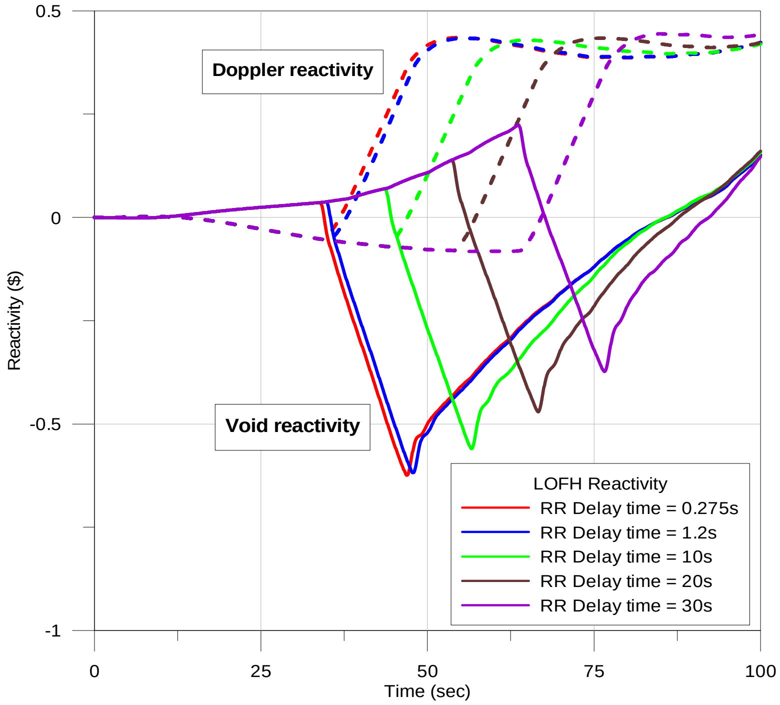

Figure 17 Reactivity responses of the sensitivity studies for RR delay time

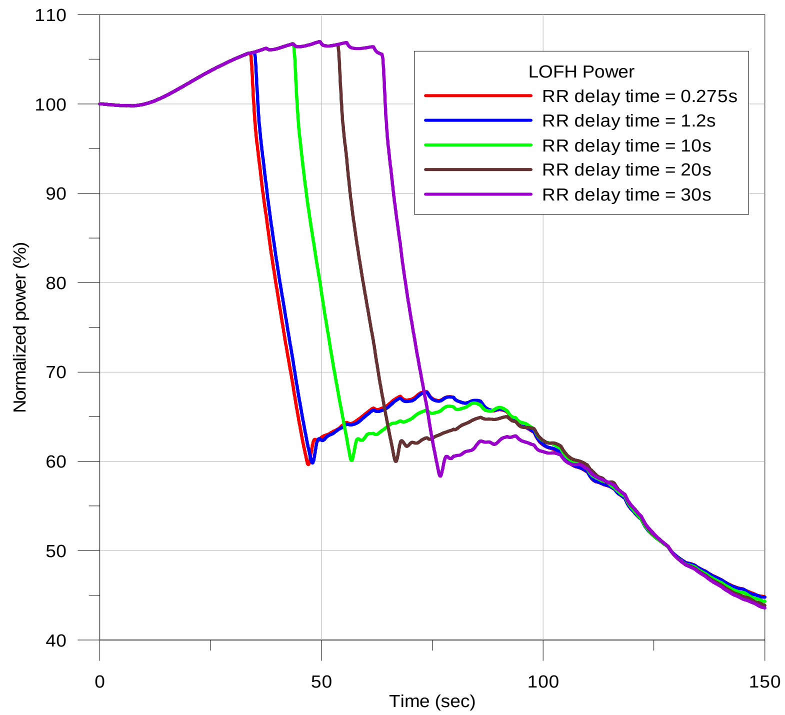

Figure 18　Power responses of the sensitivity studies for RR delay time

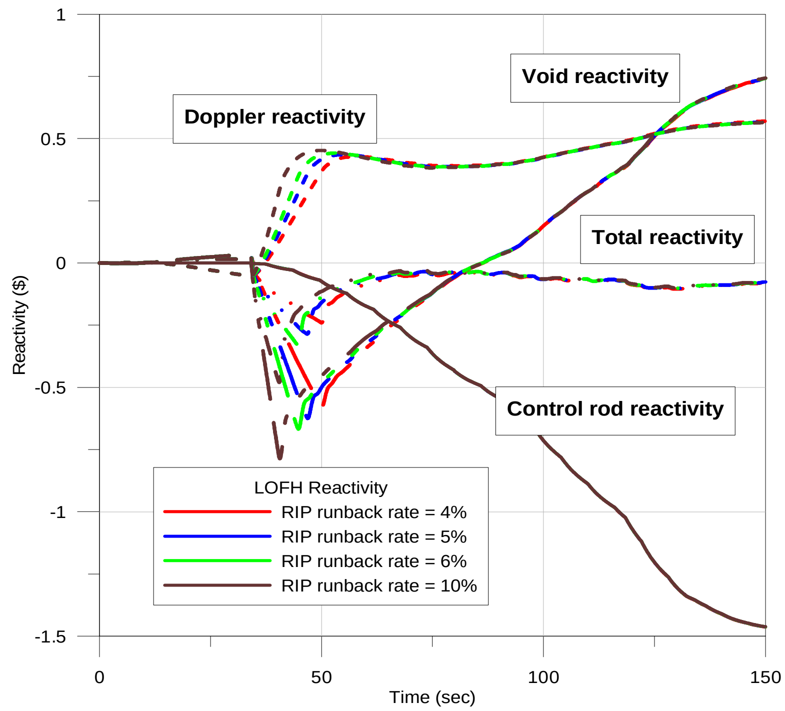

Figure 19　Reactivity responses of the sensitivity studies for RIP runback rate

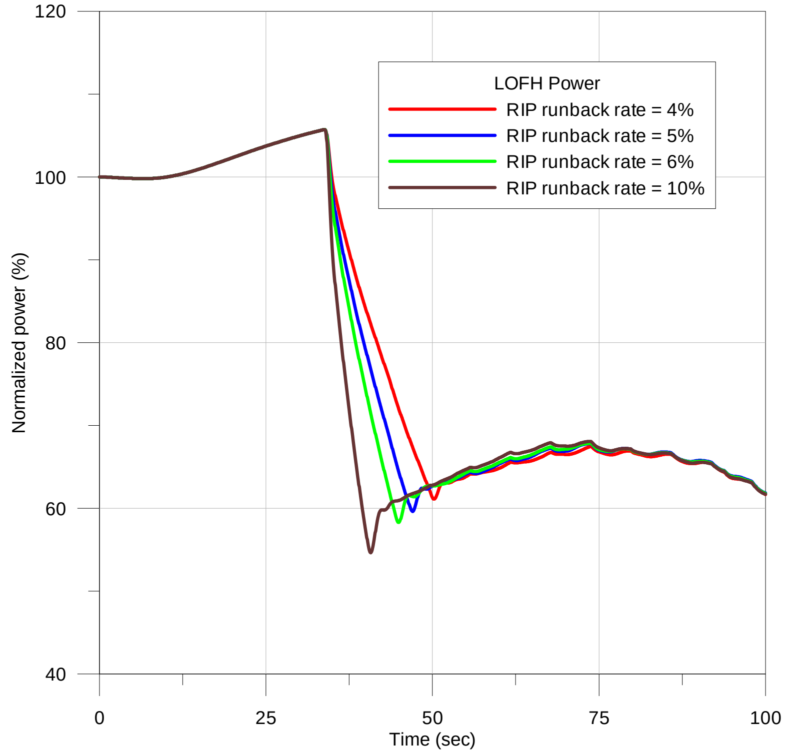

Figure 20 Power responses of the sensitivity studies for RIP runback rate

Table 2 Summary of TRACE/PARCS analysis for different time constant studies in LOFH

Time constant (s)	15	30	60	90
Max. power (%)/ time (s)	103/17	106/34	107/67	107/101
Max. water level (cm)	1363.9	1369.1	1375.7	1375.8

Table 3 Summary of TRACE/PARCS analysis for SCRRI delay time studies in LOFH

SCRRI delay time (s)	0.09	1.09	10.09	20.09	30.09
Max. power after RR (%)	67.8	67.9	69.5	70.9	72.0
Max. water level (cm)	1369.0	1369.2	1370.1	1370.5	1370.6

Table 4 Summary of TRACE/PARCS analysis for RR delay time studies in LOFH

RR delay time (s)	0.275	1.2	10	20	30
Min. void reactivity ($)	-0.625	-0.618	-0.56	-0.471	-0.373
Max. power after RR (%)	67.8	67.8	66.2	64.9	62.3

Table 5 Summary of TRACE/PARCS analysis for RIP runback rate studies in LOFH

RIP runback rate (%/s)	4	5	6	10
Min. power within 100sec (%)	61.1	59.64	58.3	54.7
Min. void reactivity ($)	-0.579	-0.625	-0.667	-0.786

5. CONCLUSIONS

The Lungmen TRACE/PARCS coupling model indicates that the response results of the plant is consistent with the plant vendor's results in LOFH transient. Two main mechanisms, RIP runback and SCRRI, reduce the power without reactor scram successfully as feedwater temperature drops approximately 37°C. In summary, comparing results between 18 CHANs and 206 CHANs model, 18 CHANs model has ability to perform plant response to the transient and 206 CHANs model is proper to local power calculation. According to the sensitivity studies of different time constants, SCRRI delay times, RIP runback delay times and RIP runback rates, it could be concluded that every case maintains the water level between L3 and L8, so that the scram setpoints would not be triggered. The time constant is crucial for predicting water level. The 90 second time constant has the highest water level at 1375 cm. The shorter SCRRI delay time has significant effect on fuel rod temperature which leads to higher Doppler and void reactivity. The studies of different RIP runback delay times and rates affect the void feedback principally during the runback stage. The above sensitivity studies have no significant impacts on the final power and reactivity. The SNAP animation model demonstrates our three dimensional results visually of the plant parameters and phenomena.

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

The TRACE/PARCS model of Lungmen ABWR was used to evaluate the Loss of Feedwater heater (LOFH) transient of the Lungmen startup tests. The Loss of Feedwater heater transient is an anticipated operational occurrence (AOO) event. Identifications of the responses of the Lungmen models and verification of the plant vendor's analysis results are crucial in the plant licensing analysis. PARCS, a three-dimensional neutronics simulator, is capable of performing detail transient three-dimensional core power distributions and can be coupled with TRACE for thermal hydraulic feedback analysis. The feedwater enthalpy entering the RPV in this event is modeled as a 30 seconds time constant decay curve. When feedwater temperature drops approximately 37°C, the feedwater control system (FWCS) triggers Reactor Internal Pump (RIP) runback and Selected Control Rod Run In (SCRRI) immediately. The colder feedwater temperature collapses the voids, which leads to the void reactivity increase and decreases RPV water level. SCRRI can reduce the core reactivity and core temperature which then increase the Doppler reactivity. The current calculations of void, Doppler and SCRRI reactivity are consistent with plant vendor's results. The water level would fluctuate between L3 and L8, having enough safety margins to avoid either low or high water level scram setpoints. On the other hand, we have also simulated another case without RIP runback and SCRRI. The sensitivity studies of this transient include different time constants, SCRRI delay times, RIP runback rates and RIP runback delay times. Furthermore, the study of 18 CHANs model and 206 CHANs model performance with TRACE/PARCS has been evaluated.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*	
TRACE PARCS Lungmen ABWR Loss of Feedwater heater (LOFH) Code Application & Maintenance Program (CAMP) INER (Institute of Nuclear Energy Research, Atomic Energy Council, R.O.C.) Thermal hydraulic safety analysis Taiwan RELAP5 SNAP	13. AVAILABILITY STATEMENT unlimited 14. SECURITY CLASSIFICATION *(This Page)* unclassified *(This Report)* unclassified 15. NUMBER OF PAGES 16. PRICE

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