NUREG/IA-0438

International Agreement Report

ATWS Analysis of Lungmen ABWR for MSIV Closure Transient

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Washington, DC 20555-0001

Manuscript Completed: September 2013
Date Published: March 2014

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

The objective of this report is to analyses the MSIV closure ATWS transient for Lungmen ABWR. There are three parts in ATWS analysis: ARI, FMCRD run-in and SLCS initiation.

The ATWS analyses show that the TRACE/PARCS coupling model established in this report indeed have ability to analyze the ARI and FMCRD initiation transient. And the design (RRCS) of Lungmen ABWR is verified to have an ability to mitigate the ATWS transient. In addition, it also shows the importance of control rod. Reactor power will decrease rapidly as control rod run-in. If the ARI and FMCRD run-in fail simultaneously, the peak reactor power would still be controlled by pressure, RVs, void fraction and RIP rotation speed. However, the reactor core shutdown will then rely on the SLCS injection after 300sec.

The peak pressure of ARI, FMCRD run-in, and SLCS initiation analyses is 9.12, 9.12, 9.40 MPaG respectively, which is below the 10.342 MPaG limit. And the peak cladding temperature is 309.5, 309.5, 591.78℃ respectively, which is below the 1204℃ limit. The oxidation under these temperatures is insignificant. Therefore, the primary system criteria and the fuel integrity critria of 10CFR50.46 are met.

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 coupling model of Lungmen NPP has been built. In this report, the TRACE/PARCS coupling model of Lungmen NPP was used to evaluate the Lungmen ATWS transient.

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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 fourth NPP in Taiwan. It has two identical units of ABWRs with 3,926 MWt rated thermal power each, consisted of 872 GE14 assemblies with 205 control rods. The steam flow is 7.64 x 10^6 Kg/h at rated power condition. The designed rated core flow is 52.2 x 10^6 Kg/h. Compared with BWRs, ABWR replaced the recirculation loop by 10 RIPs (reactor internal pumps), eliminating the probability of large LOCA. 10 RIPs provide 111% rated core flow at the nominal operating speed of 151.84 rad/sec.

The object of this report is to analyze the ATWS (Anticipated Transient Without Scram) transient of Lungmen ABWR. Because the normal scram system fails, the reactor cannot be shutdown. ATWS event might lead to severe damage in nuclear reactor. To decrease the risk of ATWS transient, in addition to SLCS (Standby Liquid Control System) found in BWR design, ABWR added diverse scram system logic, ARI (Alternate Rod Insertion), and an additional insertion mechanism, FMCRD (Fine Motion Control Rod Drive) run-in. Thus, in order to know the ability of ATWS mitigation of different control system, ATWS analysis in this report was performed with three cases: ARI, FMCRD run-in, and SLCS initiation. The first case shows the effectiveness of the ARI design. The second case shows the backup capability of FMCRD run-in. The third case shows the indepth ATWS mitigation capability of the ABWR. And it was selected the most unfavorable of the different scenarios that could lead to an ATWS accident: a closure of the main steam isolation valves (MSIVs).

ABBREVIATIONS

ABWR	Advanced Boiling Water Reactor
ADS	Automatic Depressurization System
AOO	Anticipated Operational Occurrence
ARI	Alternate Rod Insertion
ATWS	Anticipated Transient Without Scram
CAMP	Code Applications and Maintenance Program
FMCRD	Fine Motion Rod Drive
FSAR	Final Safety Analysis Report
FWCS	Feedwater Control System
INER	Institute of Nuclear Energy Research Atomic Energy Council, R.O.C.
NRC	Nuclear Regulatory Commission
PARCS	Purdue Advanced Reactor Core Simulator
RIP	Reactor Internal Pump
RPS	Reactor Protection System
RR	RIP Runback
RRCS	Redundant Reactivity Control System
SLCS	Standby Liquid Control System
SNAP	Symbolic Nuclear Analysis Package
SRV	Safety Relief Valve
TPC	Taiwan Power Company
TRACE	TRAC/RELAP Advanced Computational Engine

1. INTRODUCTION

The issue of Anticipated Transient Without Scram (ATWS) is one of the first for probabilistic risk analysis (PRA) and cost-benefit analysis used by the Nuclear Regulatory Commission (NRC) Staff in reaching a resolution. ATWS event especially MSIV closure might produce a severe accident such as core melt because the failure of automatic scram system would lead reactor to high neutron flux, heat flux and vessel pressure. Thus, the object of this report is to analyse the MSIV closure ATWS transient of Lungmen ABWR.

In order to know the ability of ATWS mitigation of different control system, three cases were analysed for MSIV closure ATWS analysis. The first one shows the ATWS performance with ARI. This case is intended to show the effectiveness of the ARI design. The second case, which uses FMCRD run-in, assuming a total failure of ARI, was performed to show the backup capability of FMCRD run-in. The third case was analyzed to show the indepth ATWS mitigation capability of the ABWR. In this case, both ARI and FMCRD run-in are assumed to fail. Automatic boron injection with a 180-second delay is relied upon to mitigate the transient event.

U.S. NRC approved a final ATWS rule, 10CFR50.46, on June 1, 1984. According to 10CFR50.46, the design should meet the flowing requirement [1]:

(1) Fuel integrity: The long-term core cooling capability shall be assured by meeting the cladding temperature ($< 1204℃$) and oxidation criteria ($< 17\%$ of the total cladding thickness).

(2) Containment integrity: The long-term containment capability shall be maintained (the maximum containment pressure $< 0.310\text{MPaG}$; the suppression pool bulk temperature $< 97.2℃$).

(3) Primary system: The system transient pressure shall be limited (the maximum primary stress within the reactor coolant pressure boundary $< 10.342\text{MPaG}$).

(4) Long-term shutdown cooling: The reactor shall be bought to safe shutdown condition, and cooled down and maintained in a cold shutdown condition.

In addition, the multitude of equipment and procedures for ATWS mitigation used in this analysis is consistent with those described in the Lungmen FSAR Chapter 15E, ATWS Performance Evaluation. The scenario assumes that after MSIVs closure an ATWS is initiated, and the high reactor pressure activates the ARI and FMCRD run-in. If the ARI and FMCRD run-in fail at the same time, the boron solution will be injected about 300sec from the transient.

2. MODEL OF LUNGMEN ABWR

The study of MSIV closure ATWS analyses 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 preliminary Lungmen TRACE model is established based on the relevant documents, as shown in Figure 1. There are three major control systems implemented in Lungmen TRACE model, including feedwater control system, pressure control system, and RIP control system. The core is modeled by 18 channels in order to simulate the 872 fuel assemblies. According to the assembly in the real reactor, the Vessel is divided into eleven axial levels, four radial rings, and six azimuthal sectors. The six azimuthal sectors are orientated in $36°$, $36°$, $108°$, $36°$, $36°$, $108°$ apart, and each azimuthal sector is connected with the feed water line inlet (six feed water lines). There are four main steam lines connected to the $36°$ azimuthal sector of vessel and ten RIPs connected to six azimuthal sectors, one for every $36°$. The ten RIPs are separated into three groups, four RIPs not connect to M/G sets (RIP3) and six RIPs connect to M/G sets (RIP1 and RIP2, thee for each). There are four sets of valves included in this model. The MSIVs and Turbine control valves (TCVs) are normally opened. The turbine bypass valve (TBV) and six groups of safety relief valves (SRVs), simulating eighteen SRVs distributed at the four main steam lines with different setpoints, are normally closed. In addition, the moody choke flow model is adopted for limiting the maximum SRVs' flow.

TRACE provides three types of core power calculation mode: (1) Power table; (2) Point kinetic; (3) Coupling PARCS. The MSIV closure ATWS analyses were performed by using point kinetic and coupling PARCS.

In addition, the steady state plant parameters from Lungmen TRACE model had been successfully verified with those from FSAR and RETRAN02. The verified results reveal that there is respectable accuracy in the Lungmen TRACE model [2][3].

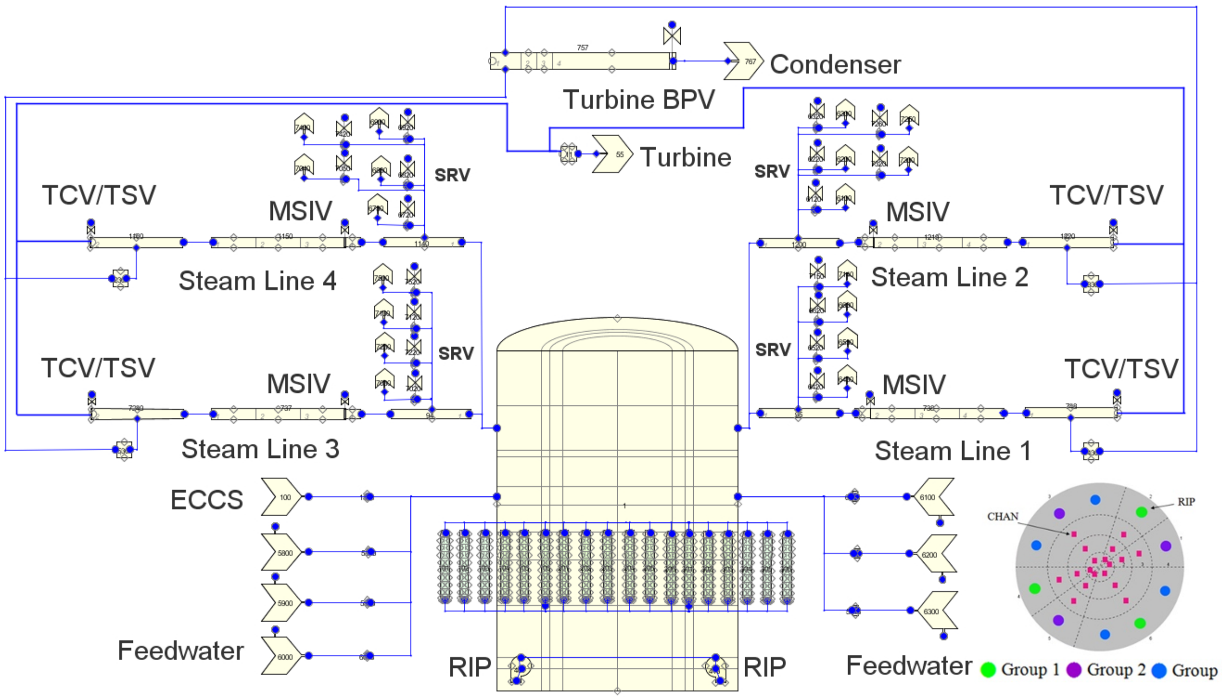

Figure 1 Lungmen TRACE model

2.2 Lungmen PARCS Model

PARCS involves 3D reactor core simulator for the realistic representation of physical reactor, and it can solve steady-state and time-dependent, multi-group neutron diffusion and SP3 transport equations in orthogonal and hexagonal core geometries. Figure 2 shows the core pattern for Lungmen PARCS model. There are 1012 nodes in Lungmen PARCS model: 872 nodes model 872 fuel assemblies (yellow square); 140 nodes model the reflector outside the core (blue square). The cross-section data used in PARCS calculation is provided by PMAXS file which is generated by GenPMAXS program from the macroscopic cross-section libraries and the results of lattice code, CASMO [4]. Figure 3 shows the control rod pattern for Lungmen PARCS model. The 205 control rod are divided into 19 groups, each group has different initial step.

The preliminary Lungmen PARCS model is established by our laboratory colleagues, Shu-Juan Chen and Chia-Ying Chang [5][6]. The k_{inf} calculated from PARCS had been verified by that from CASMO. The result shows the respectable accuracy in Lungmen PARCS model that the error bar is small than 10^{-5}.

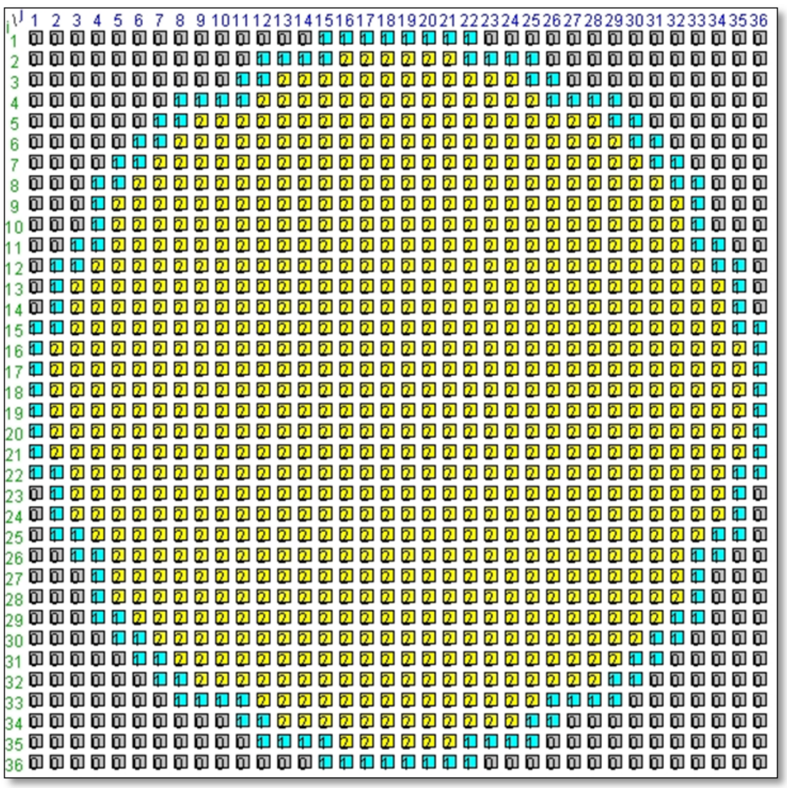

Figure 2 Core pattern for Lungmen PARCS model

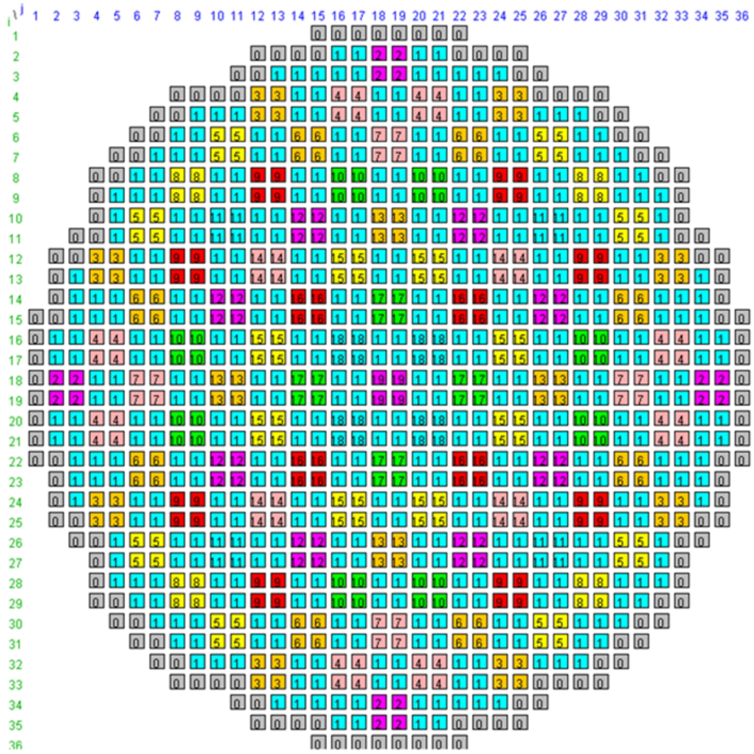

Figure 3 Control rod pattern for Lungmen PARCS model

2.3 Lungmen TRACE/PARCS Coupling Model

Figure 4 displays the flowchart of TRACE/PARCS coupling model. During the transient calculation, PARCS determines the core power distribution by using thermal-hydraulic (T-H) conditions provided by TRACE. The power information is then transferred back to TRACE to calculate the new T-H conditions for PARCS. Thus the TRACE/PARCS coupling model gives the actual core power and T-H distribution at any time point.

Base on this preliminary Lungmen TRACE/PARCS coupling model, T.S. Feng et al. analyzed the loss feed water heater transient and compared the results with plant vender data [7]. It shows that the Lungmen TRACE/PARCS coupling model has an ability of transient simulation of Lungmen NPP.

Note that the case ARI and FMCRD run-in was performed by TRACE/PARCS coupling model, but in case SLCS initiation we substituted PARCS for point kinetics because Lungmen PMAXS file used in core power calculation has problems in boron reactivity calculation.

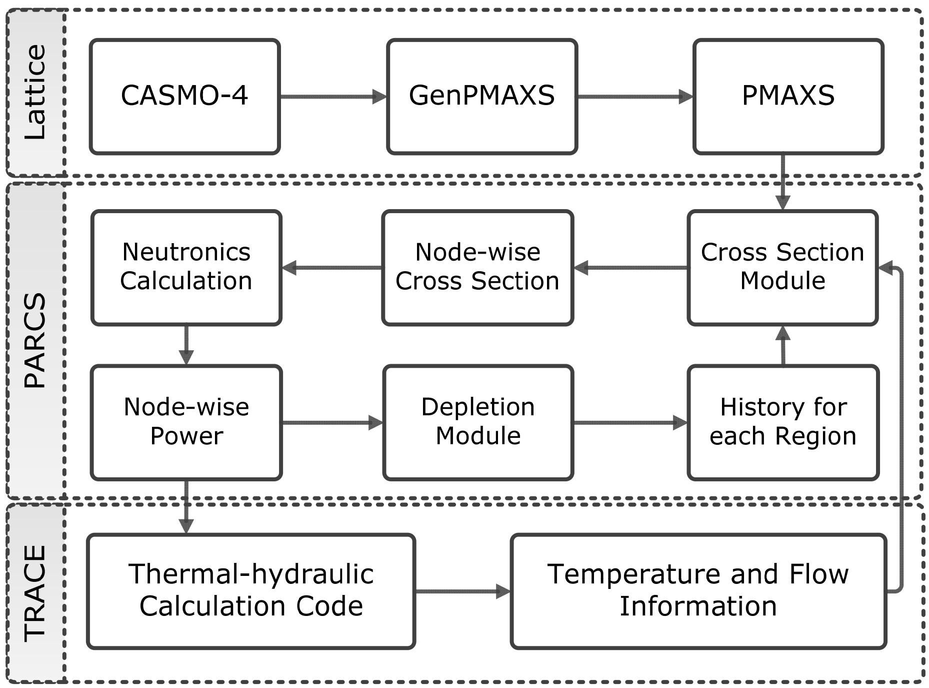

Figure 4 The procedure of TRACE/PARCS coupling calculation [4]

3. RESULTS

Figure 5 displays the initial steady sate condition and the animation model of Lungmen NPP. Three cases were analyzed in MSIV closure ATWS analysis:

- ARI: to show the effectiveness of the ARI design.
- FMCRD run-in, assuming a total failure of ARI: to show the backup capability of FMCRD run-in.
- SLCS initiation, assuming a total failure of both ARI and FMCRD run-in: to show the in-depth ATWS mitigation capability of the ABWR.

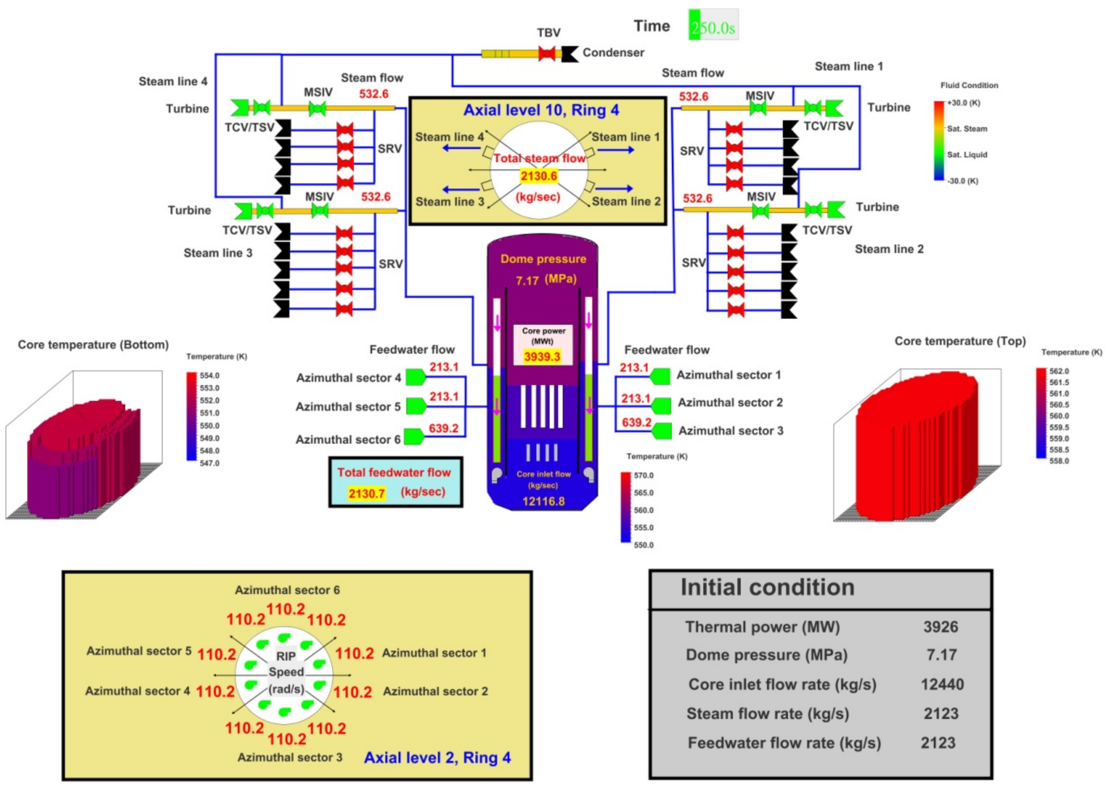

Figure 5 The initial condition and animation model of Lungmen

3.1 ARI Analysis

Table 1 shows the sequence of ARI analysis. The MSIV fully closure time is assumed to be 4sec. Figure 6~10 show the results of TRACE/PARCS analysis. After MSIVs close, the steam is kept in vessel, increasing the dome pressure to reach the scram signal setpoint 7.76MPaG (about 4sec). The normal scram system fails. Reactor is soon into ATWS transient and initiates the ARI signal. According to the data from Taiwan Power Company, it would need 25sec to let the control rod all-in: 15sec for initiating the Hydraulic Control Unit (HCU) to insert the control rod into core; 10sec for control rod insertion. For simulation, ARI (10sec all-in) is assumed to be inserted 15sec later (about 19sec) after system receives the high pressure signal. The control rods are all-in about 29sec. In Figure 6, compared with the dotted line, representing the core power without control rod, the solid line (with control rod) tends to decline about 20sec. It reveals that the core power decrease because of the control rods insertion. And the reactor is bought to a safe shutdown condition (the core power < 6% rated power) about 28sec. Moreover, the peak dome pressure is 9.12MPaG, which is below the 10.342MPaG limit. Figure 10 shows the maximum average cladding temperature. The peak average cladding temperature is 309.5℃, which is below the 1204℃ limit. The oxidation under this temperature is insignificant. Therefore, the primary system criteria and the fuel integrity criteria of 10CFR50.46 are met.

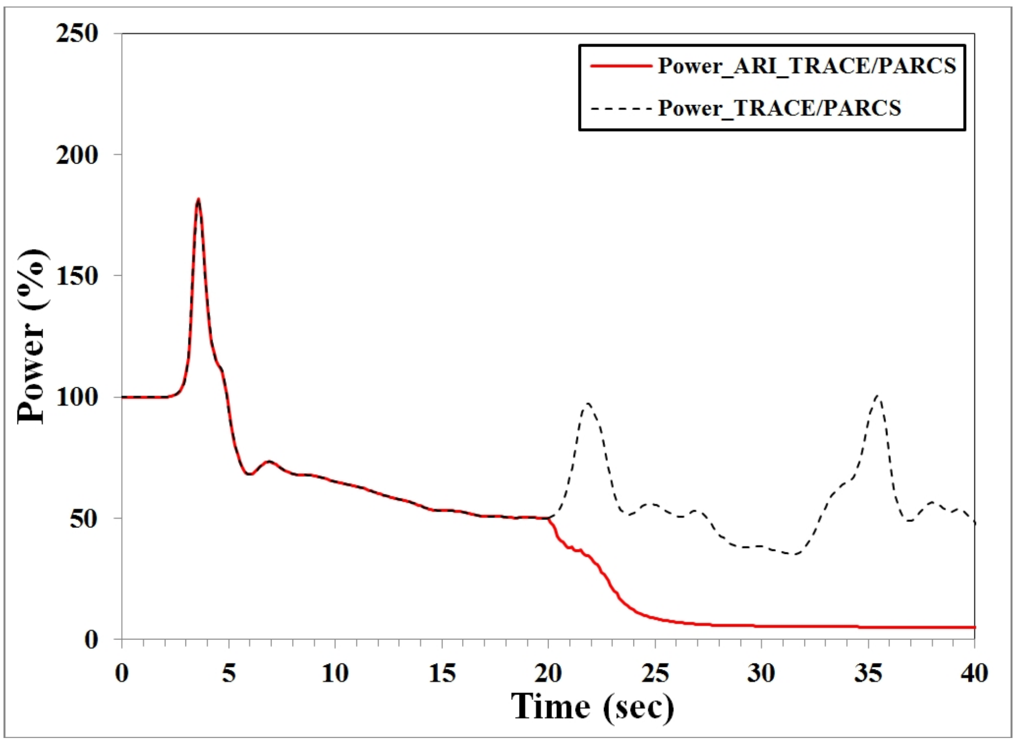

Figure 6 The core power (ARI)

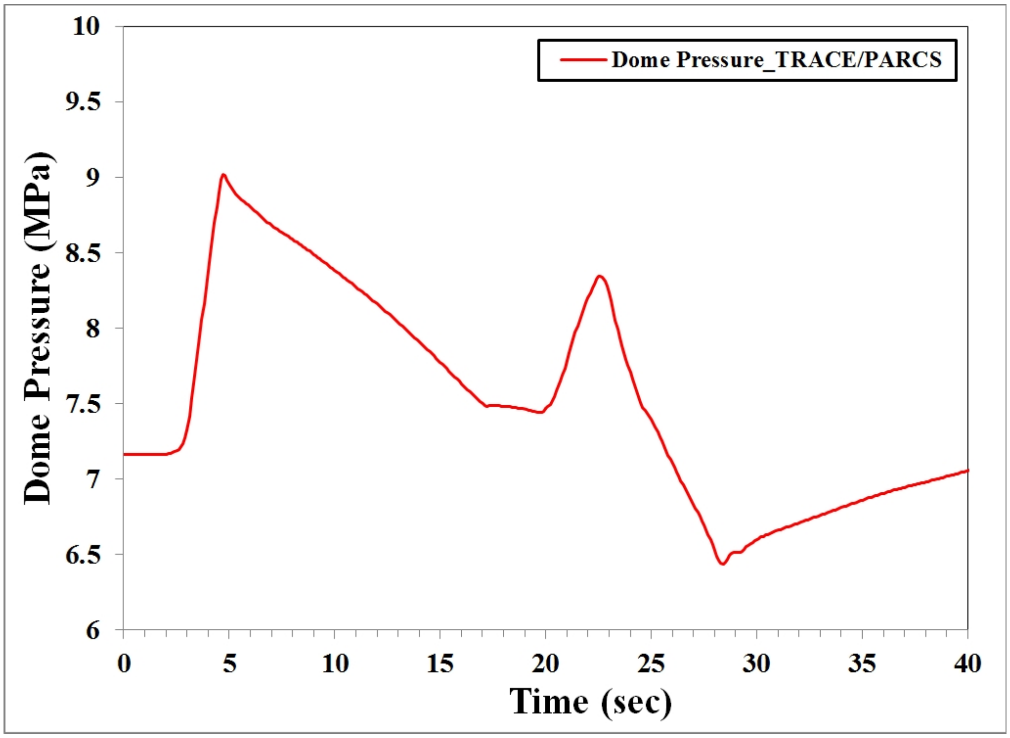

Figure 7 The dome pressure (ARI)

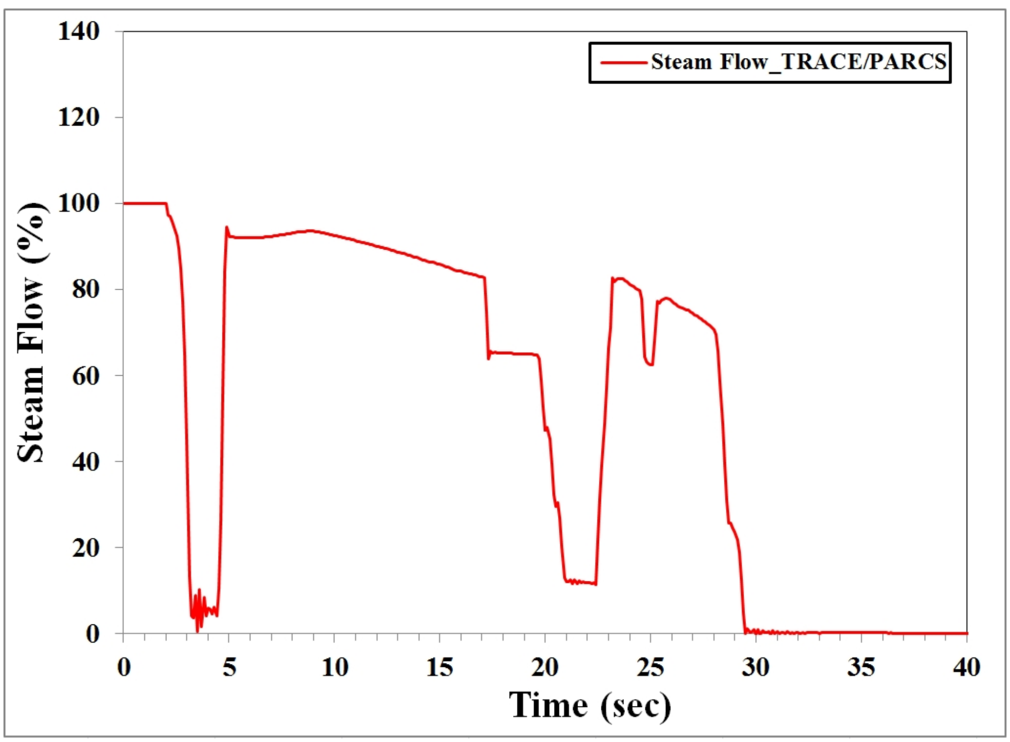

Figure 8 The steam flow (ARI)

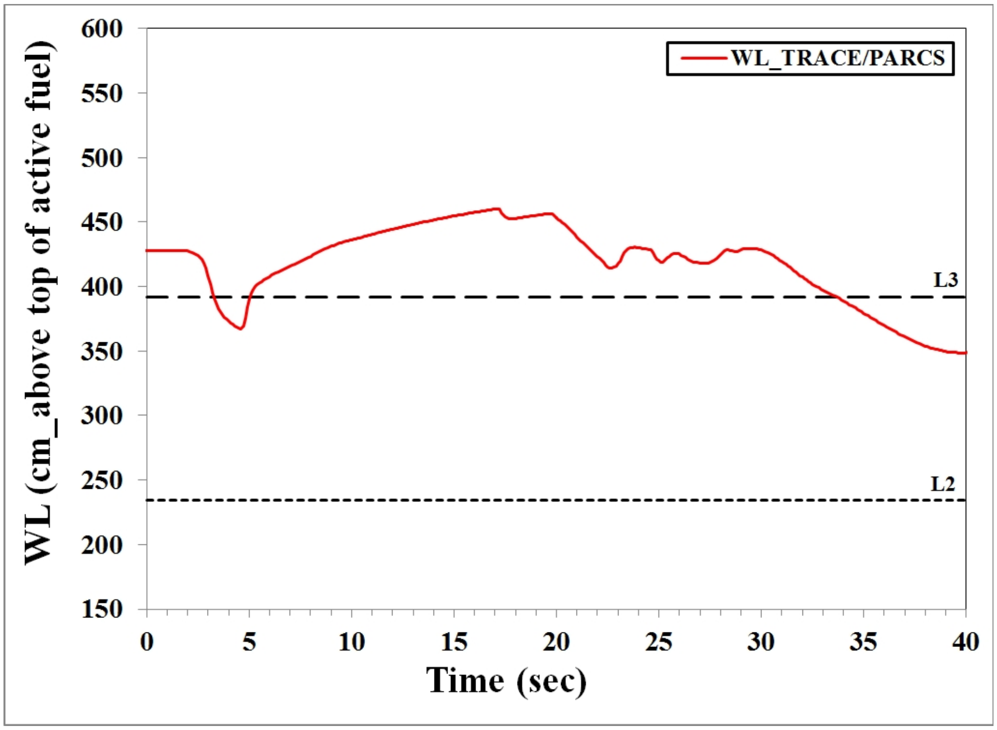

Figure 9 The water level (ARI)

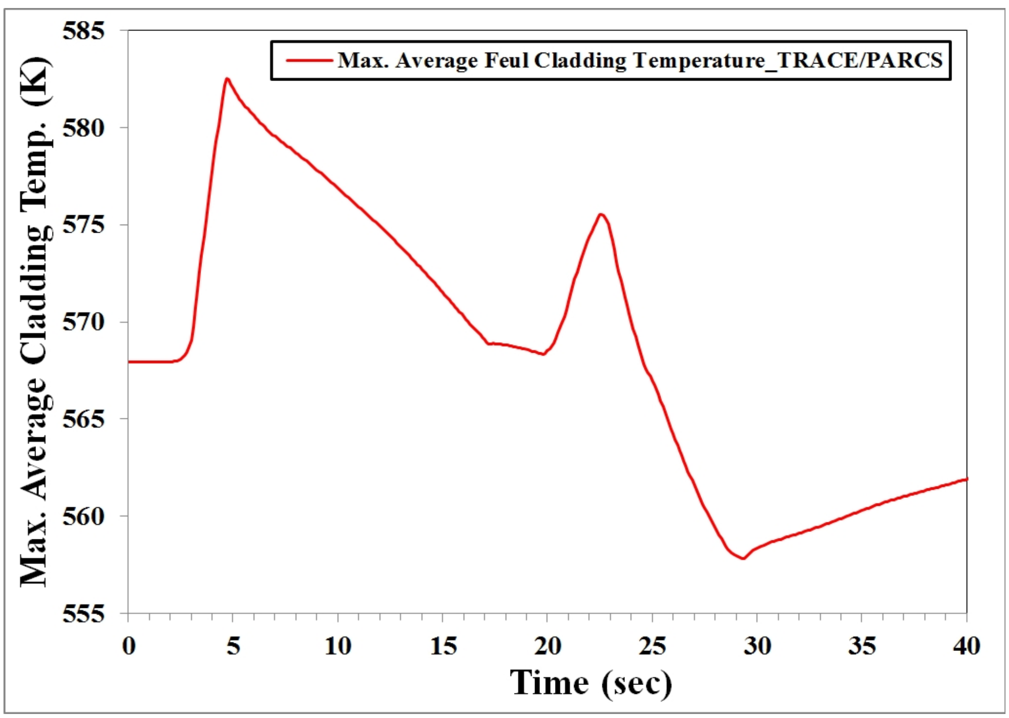

Figure 10 The maximum average cladding temperature (ARI)

Table 1 The transient sequences of ARI analysis

Time (sec)	
0	Transient starts
4	System reaches the high pressure setpoint (7.76MPaG): RIP3 (without M/G set) trips; RIP1 and RIP2 (with M/G set) runback (-5% rated speed) to minimum speed (47.12 rad/sec); ARI signal is initiated
19	ARI is initiated
29	Control rods are all-in.

3.2 FMCRD Run-In Analysis

Table 2 shows the sequence of FMCRD run-in analysis. The MSIV fully closure time is assumed to be 4sec. Figure 11~15 show the results of TRACE/PARCS analysis. After MSIVs close, the steam is kept in vessel, increasing the dome pressure to reach the scram signal setpoint 7.76MPaG (about 4sec). The normal scram system fails. Reactor is soon into ATWS transient and initiates the ARI signal. ARI is assumed to fail, and then system would initiate the FMCRD run-in signal. According to the data from Taiwan Power Company, it would need 120sec to let the control rod all-in. For FMCRD run-in analysis, because the control rods are driven by electric power, there is no need to wait for initiation. Thus, FMCRD run-in is initiated (20sec) instantaneously after ARI fail. The control rods are all-in about 140sec. In Figure 11, compared with the dotted line, representing the core power without control rod, the solid line (with control rod) tends to decline about 20sec. It reveals that the core power decrease because of the control rods insertion. And the reactor is bought to a safe shutdown condition (the core power < 6% rated power) about 104sec. Moreover, the peak dome pressure is 9.12MPaG, which is below the 10.342MPaG limit. Figure 15 shows the maximum average cladding temperature. The peak average cladding temperature is 309.5℃, which is below the 1204℃ limit. The oxidation under this temperature is insignificant. Therefore, the primary system criteria and the fuel integrity criteria of 10CFR50.46 are met.

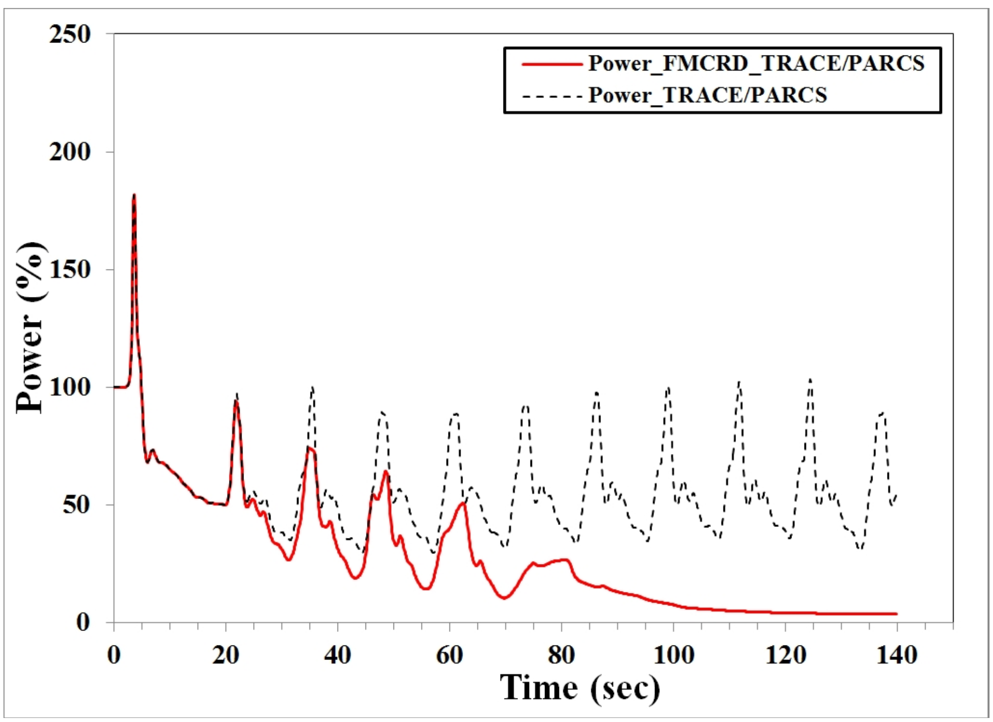

Figure 11 The core power (FMCRD run-in)

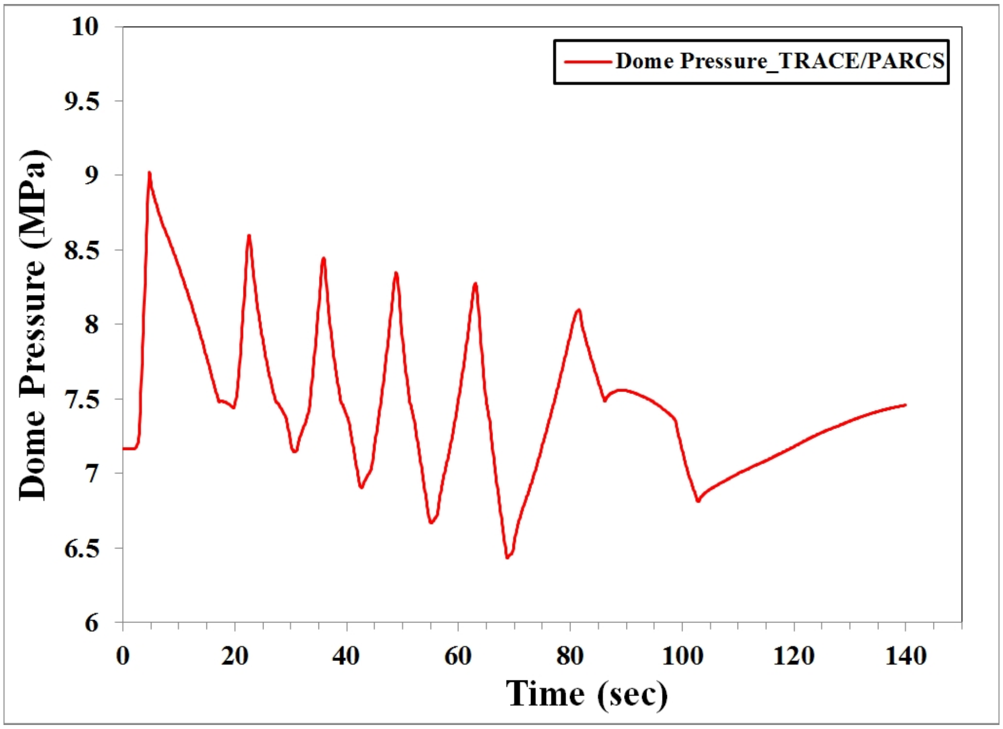

Figure 12 The dome pressure (FMCRD run-in)

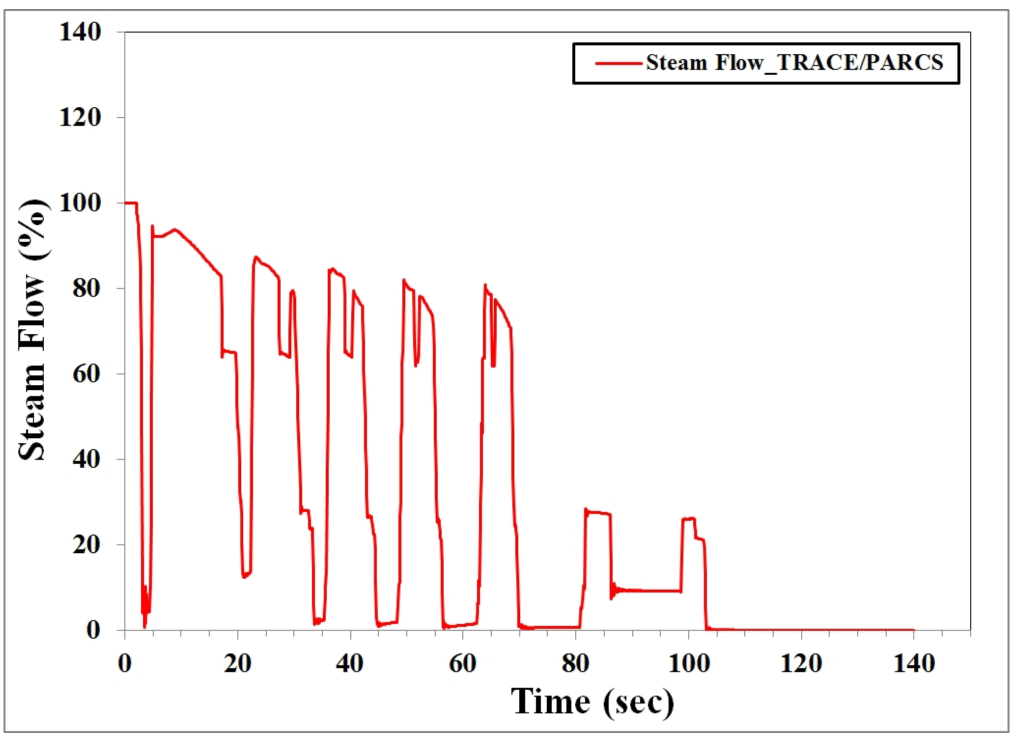

Figure 13 The steam flow (FMCRD run-in)

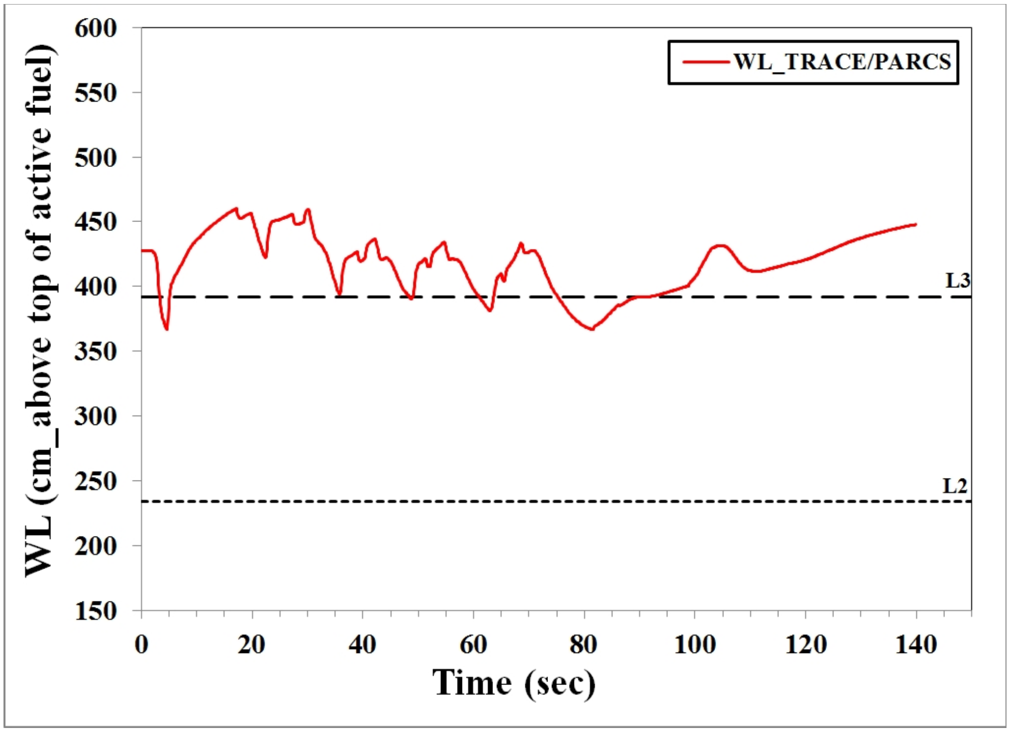

Figure 14 The water level (FMCRD run-in)

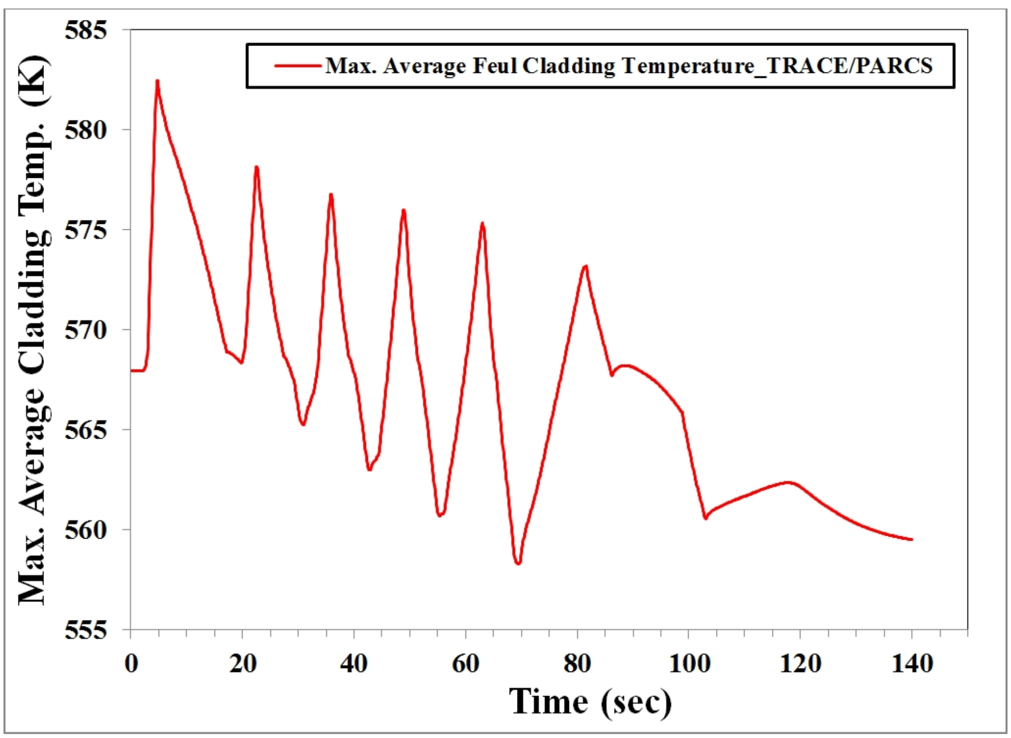

Figure 15 The maximum average cladding temperature (FMCRD run-in)

Table 2 The transient sequences of FMCRD run-in analysis

Time (sec)	
0	Transient starts
4	System reaches the high pressure setpoint (7.76MPaG): RIP3 (without M/G set) trips; RIP1 and RIP2 (with M/G set) runback (-5% rated speed) to minimum speed (47.12 rad/sec); ARI signal is initiated
19	ARI initiation failed. FMCRD starts to run-in after 1sec delay.
140	Control rods are all-in.

3.3 SLCS Initiation Analysis

Table 3 shows the sequence of SLCS initiation analysis. The MSIV fully closure time is assumed to be 4sec. Figure 16~22 show the results of TRACE analysis. After MSIVs close, the steam is kept in vessel, increasing the dome pressure to reach the scram signal setpoint 7.76MPaG (about 4sec). The normal scram system fails. Reactor is soon into ATWS transient. Both ARI and FMCRD run-in are assumed to fail. The reactor is at high pressure and SRNM (Startup Range Neuron Monitor) ATWS permissive for 180sec. After a 180sec delay, Standby boron liquid is rejected to bring the reactor shutdown. According to the data from Taiwan Power Company, it would need 96sec to inject the boron liquid. Thus, for SLCS initiation analysis, the standby boron liquid is assumed to be injected 276sec (180sec ATWS signal delay time and 96sec boron injection time) later after receiving the scram signal.

Figure 19 shows the void fraction feedback reactivity. Before boron injection (0~300sec), the high dome pressure, because of MSIV close, leads RVs to open, decreasing the dome pressure and increasing the void fraction. The increase of void fraction, then, gives the negative reactivity feedback to decrease the core power. Conversely, RV close leads the dome pressure to increase, decreasing the void fraction and increasing the core power. About 148sec, the water level, as shown in Figure 20, drops to low water level L2 because the feedwater pump trips, initiating RIP1 and RIP2 trip. It causes the increase of void fraction and gives another negative reactivity feedback to the core power. Thus, the peak reactor power, in this region, would still be controlled by pressure, RVs, void fraction and RIP rotation speed. Note that according to the design of Lungmen ABWR, the steam-driven feedwater pump would loss the power and trip immediately after MSIVs close. For ATWS analyses, we used the conservative assumption that the feedwater pump won’t trip until 120sec after receiving the scram signal. After boron injection (300~800sec), standby boron liquid absorbs the neutron, gives the reactivity feedback more negative, and brings the reactor to shutdown.

The peak dome pressure is 9.40MPaG, which is below the 10.342MPaG limit. Figure 22 shows the maximum average cladding temperature. The peak average cladding temperature is 591.78℃, which is below the 1204℃ limit. The oxidation under this temperature is insignificant. Therefore, the primary system criteria and the fuel integrity criteria of 10CFR50.46 are met.

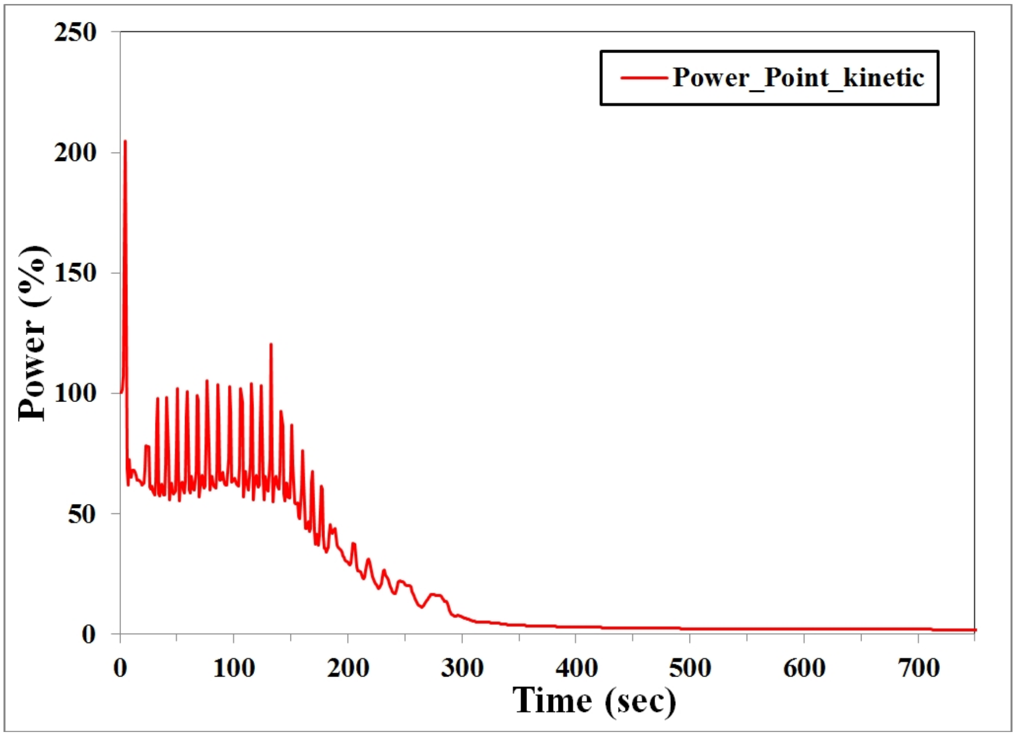

Figure 16　The core power (SLCS initiation)

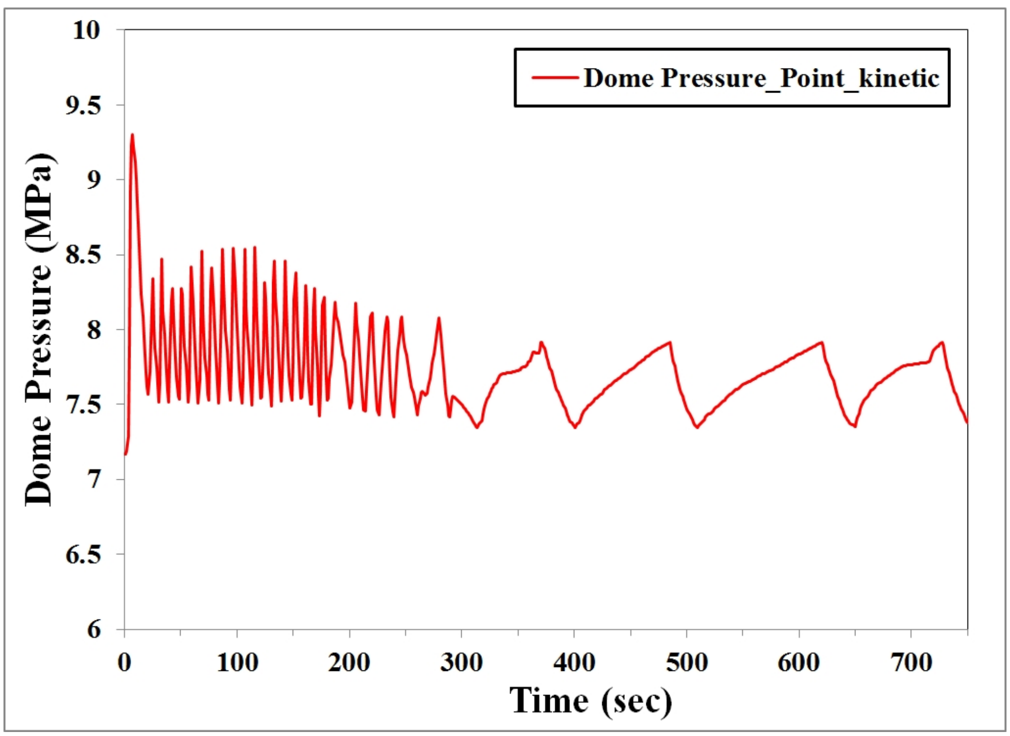

Figure 17　The dome pressure (SLCS initiation)

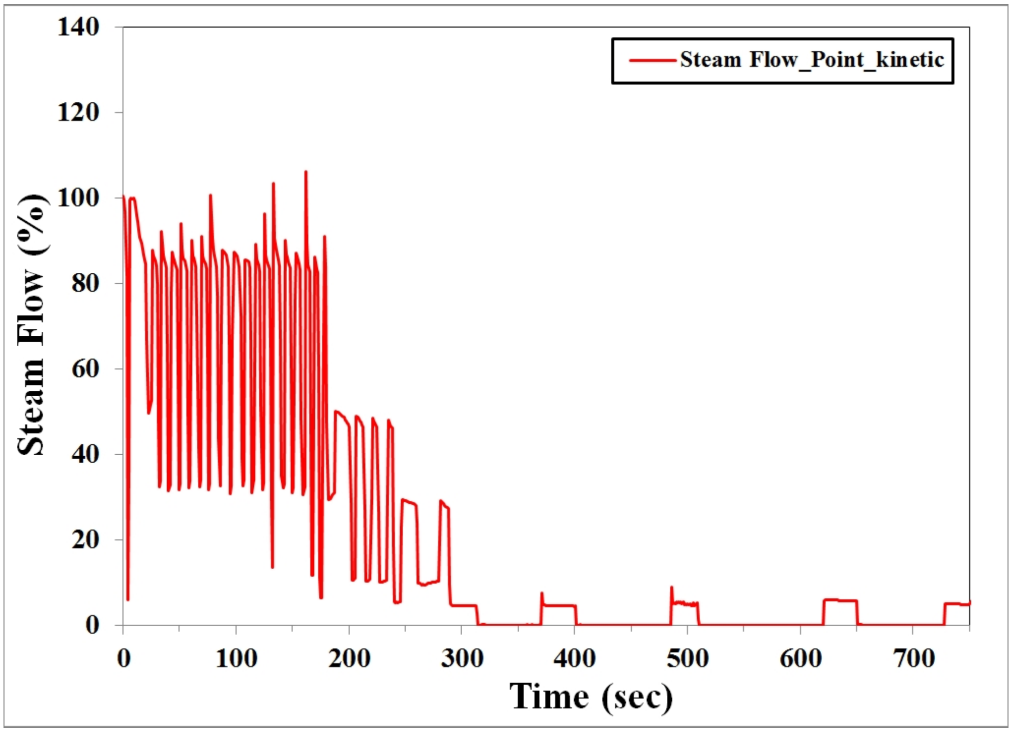

Figure 18 The steam flow (SLCS initiation)

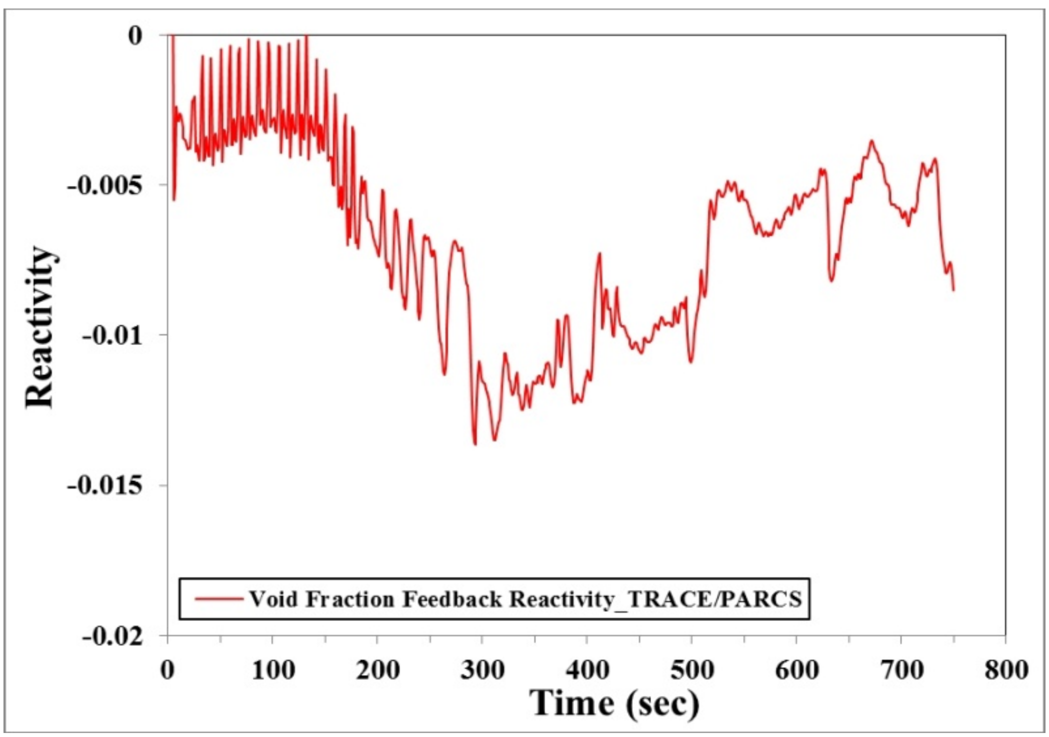

Figure 19 The void fraction feedback reactivity (SLCS initiation)

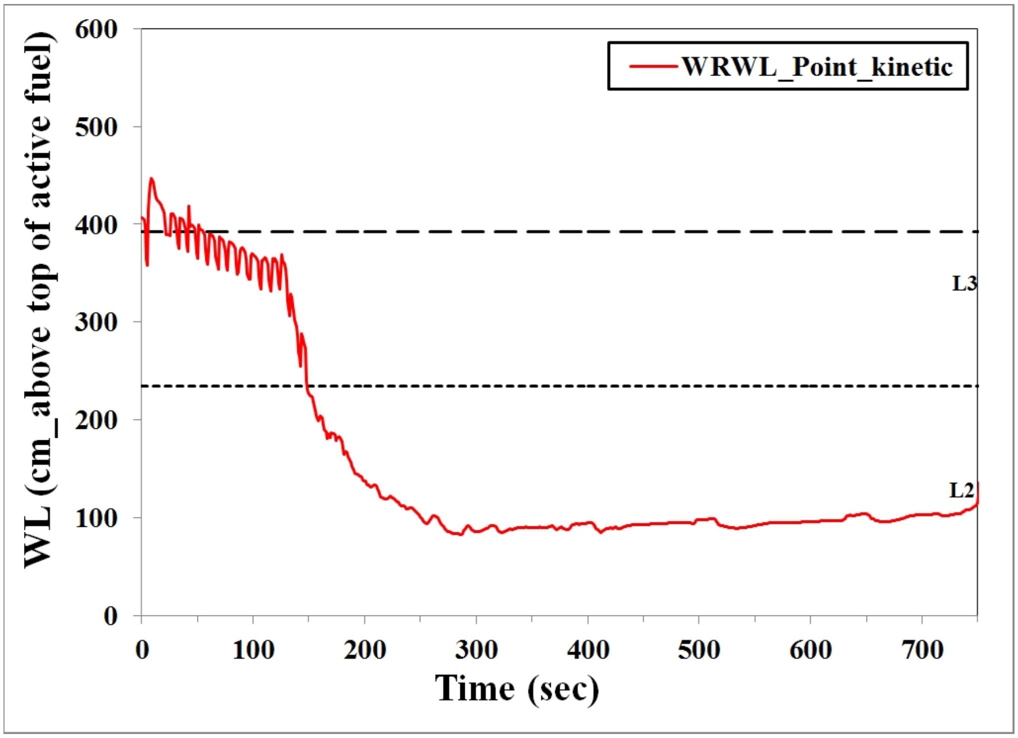

Figure 20　The water level (SLCS initiation)

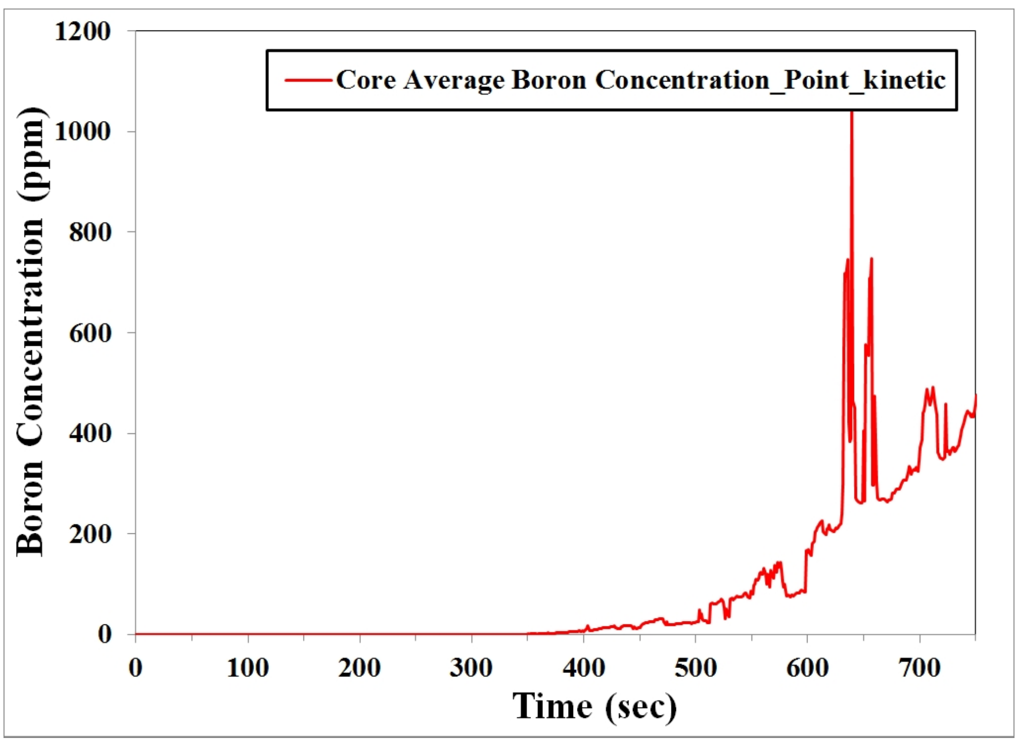

Figure 21　The core average boron concentration (SLCS initiation)

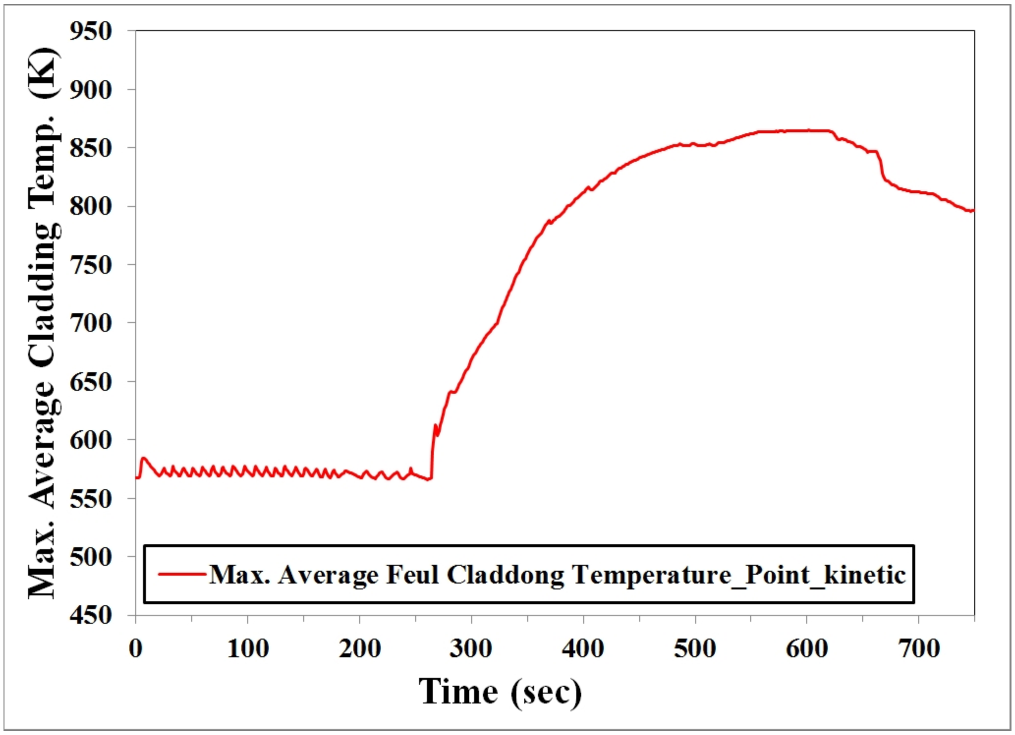

Figure 22 The maximum average cladding temperature (SLCS initiation)

Table 3 The transient sequences of SLCS initiation analysis

Time (sec)	
0	Transient starts
4	System reaches the high pressure setpoint (7.76MPaG): RIP3 (without M/G set) trips; RIP1 and RIP2 (with M/G set) runback (-5% rated speed) to minimum speed (47.12 rad/sec); ARI signal is initiated
19	ARI initiation failed. FMCRD starts to run-in after 1sec delay.
20	Control rod insertion is failed. Core power is maintained upon 6% rated power.
124	Feed water pump trips.
148	Water level decreases to low water level L2: initiating RIP1 and RIP2 trip signal (RIP1 trip instantaneously, and RIP2 trip 6sec later).
184	Automated initiation of ADS is inhibited; SLCS is initiated
280	Standby boron liquid is injected into core.

4. CONCLUSIONS

The objective of this paper is to analyse the MSIV closure ATWS transient for Lungmen ABWR. The analyses show the importance of control rod. Reactor power will decrease rapidly as control rod run-in, bringing the reactor to shutdown quickly (about 28sec and 104sec for ARI and FMCRD run-in respectively). If the ARI and FMCRD run-in fail simultaneously, the peak reactor power would still be controlled by pressure, RVs, void fraction and RIP rotation speed before boron injection (about 300sec). The reactor power would remain upon 6% rated power, and the reactor cannot be shutdown safely. However, the reactor core shutdown will then rely on the SLCS injection after 300sec. Moreover, the results of MSIV closure ATWS analyses are showed below:

(1) Fuel integrity: The peak cladding temperature is 309.5, 309.5, 591.78℃ respectively, which is below the 1204℃ limit. The oxidation under these temperatures is insignificant.

(2) Primary system: The peak pressure of ARI, FMCRD run-in, and SLCS initiation analyses is 9.12, 9.12, 9.40 MPaG respectively, which is below the 10.342 MPaG limit.

Therefore, the primary system criteria and the fuel integrity critria of 10CFR50.46 are met. The RRCS system has an ability of ATWS mitigation on MSIV closure ATWS transient.

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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-0438

2. TITLE AND SUBTITLE
ATWS Analysis of Lungmen ABWR for MSIV Closure Transient

3. DATE REPORT PUBLISHED

MONTH	YEAR
March	2014

4. FIN OR GRANT NUMBER

5. AUTHOR(S)
Jong-Rong Wang, Ai-Ling Ho*, 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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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
K. Tien, NRC Project Manager

11. ABSTRACT *(200 words or less)*

The objective of this report is to analyze the MSIV closure ATWS transient for Lungmen ABWR. There are three parts in ATWS analysis: ARI, FMCRD run-in and SLCS initiation. The ATWS analyses show that the TRACE/PARCS coupling model established in this report indeed have ability to analyze the ARI and FMCRD initiation transient. And the design (RRCS) of Lungmen ABWR is verified to have an ability to mitigate the ATWS transient. In addition, it also shows the importance of control rod. Reactor power will decrease rapidly as control rod run-in. If the ARI and FMCRD run-in fail simultaneously, the peak reactor power would still be controlled by pressure, RVs, void fraction and RIP rotation speed. However, the reactor core shutdown will then rely on the SLCS injection after 300sec. The peak pressure of ARI, FMCRD run-in, and SLCS initiation analyses is 9.12, 9.12, 9.40 MPaG respectively, which is below the 10.342 MPaG limit. And the peak cladding temperature is 309.5, 309.5, 591.78℃ respectively, which is below the 1204℃ limit. The oxidation under these temperatures is insignificant. Therefore, the primary system criteria and the fuel integrity critria of 10CFR50.46 are met.

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

Main Steam Isolation Valve (MSIV)
Taiwan Lungmen ABWR
Anticipated Transient without Scram (ATWS)
Code Application & Maintenance Program (CAMP)
INER (Institute of Nuclear Energy Research, Atomic Energy Council, R.O.C.)
Thermal hydraulic safety analysis
SNAP

13. AVAILABILITY STATEMENT
unlimited

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

15. NUMBER OF PAGES

16. PRICE

NRC FORM 335 (9-2004)

PRINTED ON RECYCLED PAPER

NUREG/IA-0438 ATWS Analysis of Lungmen ABWR for MSIV Closure Transient March 2014