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International Agreement Report

The Ultimate Response Guideline Simulation and Study for Lungmen (ABWR) Nuclear Power Plant Using RELAP5/SNAP

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ABSTRACT

The RELAP5/SNAP model for Lungmen ABWR nuclear power plant (NPP) was established for the simulation and study of the URG (ultimate response guideline). The main actions of the URG are the depressurization and low pressure water injection of the reactor and the venting of the containment. Therefore, this research focuses to assess the URG utility of Lunemgn NPP under Fukushima-like conditions. Two steps are in this study. The first step is the establishment of RELAP5/SNAP model using the system and operating data, startup tests reports and FSAR of Lungmen NPP. The second step is the simulation and study of the URG under Fukushima-like conditions by using the above RELAP5/SNAP model. In this step, the case without URG was also performed to evaluate the URG effectiveness for Lungmen NPP. According to RELAP5 analysis results, the URG can keep the peak cladding temperature (PCT) below the failure criteria (1088.7 K) under Fukushima-like conditions. It indicates that Lungmen NPP can be controlled in a safe situation.

FOREWORD

The U.S. NRC (United States Nuclear Regulatory Commission) has developed a thermal hydraulic analysis code-RELAP5. RELAP5 has been designed to perform best-estimate analysis of loss-of-coolant accidents (LOCAs), operational transients, and other accident scenarios in reactor systems. Models used include multidimensional two-phase flow, non-equilibrium thermo-dynamics, generalized heat transfer, reflood, level tracking, and reactor kinetics. Traditionally, the RELAP5 code analysis model was developed by ASCII file, which was not intelligible for the beginners of computer analysis. Fortunately, a graphic input interface, SNAP (Symbolic Nuclear Analysis Program) is developed by Applied Technology Incorporation Inc. and the model development process becomes more conveniently.

To obtain the authorization of these codes, Taiwan and the United States have signed an agreement on CAMP (Code Applications and Maintenance Program) which includes the development and maintenance of RELAP5 code. NTHU (National Tsing Hua University) is the organization in Taiwan responsible for the application RELAP5 and SNAP in thermal hydraulic safety analysis. To meet this responsibility, the RELAP5/MOD3.3 model of Lungmen nuclear power plant has been developed. This model was used to perform the URG analysis.

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EXECUTIVE SUMMARY

RELAP5/MOD3.3 Patch04 code, which was developed for light water reactor transient analysis at Idaho National Engineering Laboratory (INEL) for U.S. NRC, is applied in this research. This code is often performed to support rulemaking, licensing audit calculations, evaluation of accident, mitigation strategies, evaluation of operator guidelines, and experiment planning analysis. Same as other thermal hydraulic analysis codes, RELAP5/MOD3.3 is based on nonhomogeneous and non-equilibrium model for the two-phase system. However, calculations in this code will be solved by a fast, partially implicit numerical scheme to permit economical calculation of system transients. It can produce accurate transient analysis results in relatively short time.

SNAP is an interface of NPP analysis codes and developed by U.S. NRC and Applied Programming Technology, Inc. Different from the traditional input deck in ASCII files, the graphical control blocks and thermal hydraulic connections make researches comprehend the whole power plant and control system more easily. Due to these advantages, the RELAP5/MOD3.3 model for Lungmen NPP was established with SNAP interface in this research.

Lungmen NPP is the ABWR NPP in Taiwan. Two identical units are in Lungmen NPP. Each unit has 3,926 MWt rated thermal power 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 reactor internal pumps (RIPs) in the reactor vessel. The RIPs are capable of providing 111% rated core flow at the nominal operating speed of 151.84 rad/sec. Additionally, Lungmen NPP uses a defense-in-depth approach that meets the regulatory requirements to reduce the likelihood of an SBO (station blackout) and prevent it from evolving into a severe accident. This is accomplished using the following features:

- RCIC (Reactor Core Isolation Cooling)

The RCIC system can provide core cooling from a diverse power source (reactor steam) for an extended amount of time. The extended RCIC operation requires makeup water supply being switched from the condensate storage tank (CST) to the suppression pool (SP).

- ADS (Automatic Depressurization System)

The ADS provides a highly reliable means of depressurizing the reactor in the event of failure of the high pressure injection systems. This permits core cooling with low pressure systems, such as ACIWA, and avoids high pressure core melt sequences.

- ACIWA (AC-Independent Water Addition System)

The ACIWA provides diverse capability to supply water to the reactor in the event that either the AC power or RCIC is unavailable. The water sources of ACIWA are from outdoor fire trucks and fire protection water supply tanks. There are two fire protection water supply tanks in Lungmen NPP. The amount of water is 2300 m^3 in each tank.

There are two main steps in this study. First, the RELAP5/SNAP model was established in this research according to the system and operating data, startup tests and FSAR data of Lungmen NPP. Second, by using the above RELAP5/SNAP model, the study of URG under Fukushima-like conditions was performed. In this step, the case without URG was also performed. Subsequently, the results of these two cases were compared to confirm the URG effectiveness for Lungmen NPP. The analysis results of RELAP5 imply that the URG maintains the PCT below the criteria (1088.7 K) under Fukushima-like conditions. It depicts that Lungmen NPP is at the safe situation.

ABBREVIATIONS AND ACRONYMS

ACIWA	AC-Independent Water Addition System
ADS	Automatic Depressurization System
AOP	Abnormal Operating Procedure
BAF	Bottom of Active Fuel
CAMP	Code Applications and Maintenance Program
CST	Condensate Storage Tank
EOP	Emergency Operating Procedure
FSAR	Final Safety Analysis Report
INEL	Idaho National Engineering Laboratory
LOCA	Loss-Of-Coolant Accident
M/G	Motor Generator
NPP	Nuclear Power Plant
NTHU	National Tsing Hua University
OP	Operating Procedure
PCT	Peak Cladding Temperature
RCIC	Reactor Core Isolation Cooling
RIP	Reactor Internal Pump
SAMP	Severe Accident Management Procedure
SBO	Station Blackout
SNAP	Symbolic Nuclear Analysis Program
SP	Suppression Pool
TAF	Top of Active Fuel
URG	Ultimate Response Guideline
U.S. NRC	United States Nuclear Regulatory Commission

1 INTRODUCTION

After Japan Fukushima NPP disaster, there are more concerns for the safety of the NPPs in Taiwan. In general, the NPP operating states involve the normal operation, abnormal events/transients, accidents and severe accidents. And each operating state has corresponding procedures to follow to secure NPPs integrity and safety. Fig. 1 presents the correspondent relationship for the NPP operating states and procedures. The first level is operating procedures (OPs). OPs focus on the NPP operation within an acceptable range. The second level is abnormal operating procedures (AOPs). AOPs aim at restoring the function of NPP systems that could impact the NPP operating margins. The third level is emergency operating procedures (EOPs). EOPs focus on bringing the NPP to a safe and stable state by following a reactor trip or safety injection signal. The forth level is severe accident management procedures (SAMPs). SAMPS propose a range of possible actions and should allow for additional evaluation and alternative actions. However, EOPs or SAMPs are generally based on events refers NPP status and parameters to mitigate the events consequence. For the compound severe accidents, EOPs and SAMPs can't handle these accidents. Hence, with regard to this fact, Taiwan Power Company established the URG to prevent NPPs from encountering core damage for events beyond design basis [1]-[3].

The aim of this research is to use RELAP5 to evaluate the URG effectiveness for Lungmen NPP. Lungmen NPP is the ABWR NPP in Taiwan. Two identical units are in Lungmen NPP. Each unit has 3,926 MWt rated thermal power 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. The RIPs are capable of providing 111% rated core flow at the nominal operating speed of 151.84 rad/sec. Additionally, Lungmen NPP uses a defense-in-depth approach that meets the regulatory requirements to reduce the likelihood of an SBO and prevent it from evolving into a severe accident. This is accomplished using the following features:

- RCIC

The RCIC system can provide core cooling from a diverse power source (reactor steam) for an extended amount of time. The extended RCIC operation requires makeup water supply being switched from the CST to the SP.

- ADS

The ADS provides a highly reliable means of depressurizing the reactor in the event of failure of the high pressure injection systems. This permits core cooling with low pressure systems, such as ACIWA, and avoids high pressure core melt sequences.

- ACIWA

The ACIWA provides diverse capability to supply water to the reactor in the event that either the AC power or RCIC is unavailable. The water sources of ACIWA are from outdoor fire trucks and fire protection water supply tanks. There are two fire protection water supply tanks in Lungmen NPP. The amount of water is 2300 m^3 in each tank.

RELAP5 code, which was developed for light water reactor transient analysis at Idaho National Engineering Laboratory (INEL) for U.S. NRC, is applied in this research. This code is often performed to support rulemaking, licensing audit calculations, evaluation of accident, mitigation strategies, evaluation of operator guidelines, and experiment planning analysis [4]. Same as other thermal hydraulic analysis codes, RELAP5 is based on nonhomogeneous and non-equilibrium model for the two-phase system. However, calculations in this code will be solved by a fast, partially implicit numerical scheme to permit economical calculation of system transients. It can produce accurate transient analysis results in relatively short time, which means large amounts of sensitivity or uncertainty analysis might be possible. The version of RELAP5 is MOD3.3 Patch04 which is used in this study.

SNAP is an interface of NPP analysis codes and developed by U.S. NRC and Applied Programming Technology, Inc. Different from the traditional input deck in ASCII files, the graphical control blocks and thermal hydraulic connections make researches comprehend the whole power plant and control system more easily. Due to these advantages, the RELAP5/MOD3.3 model for Lungmen NPP was established with SNAP interface in this research.

There are two main steps in this study. First, Lungmen NPP RELAP5/SNAP model was established in this research according to the system and operating data, startup tests and FSAR data of Lungmen NPP. Second, by using the above RELAP5/SNAP model, the study of URG under Fukushima-like conditions was performed. In this step, the case without URG was also performed. Subsequently, the results of these two cases were compared to confirm the URG effectiveness for Lungmen NPP.

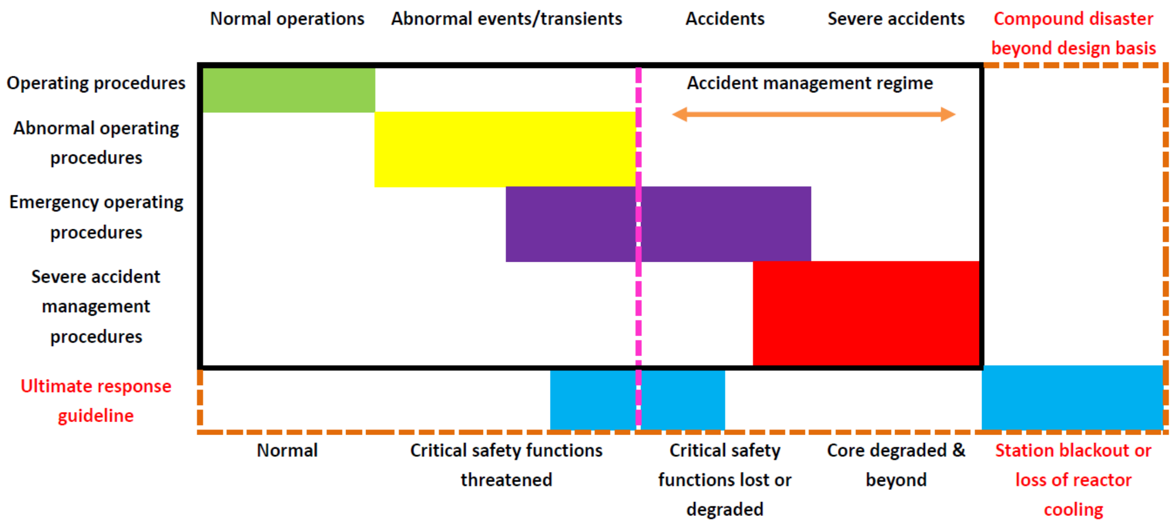

Figure 1 Correspondent Relation for the NPP Operating States and Operating Procedures

2 URG DESCRIPTION

According to the URG [1]-[3], the core concept is treating compound disaster beyond design basis (see Fig. 1, blue blocks). When Lungmen NPP meets a Fukushima-like accident (the accident with loss of all AC power or reactor cooling conditions), the EOP, SAMP and URG will be initiated at the same time. The main difference among the EOP, SAMP and URG is that when the NPP status does not recovery in time, the URG must be executed without most information of NPP. The EOP and SAMP focus on maintaining the reactor core cooling, preventing the release of radioactive material, and protecting the property of NPP. However, the URG may result in the permanent damage on the reactor of NPP and is an irreversible choice, so it needs the senior manager such as the vice president or the plant manager to make this decision. The following are the main objectives of the URG:

- Maintain the reactor core cooling.
- Maintain the monitoring functions of the control room.
- Prevent the release of radioactive material.
- Remove the amount of cumulated hydrogen in building.
- Maintain the spent fuel pool cooling and water level.

When Lungmen NPP encounters the Fukushima-like accident, the URG will be activated to prevent reactor core from being damaged. Once entering the procedure of the URG, the NPP reactor will be depressurized first, and if the electrical power cannot be recovered before RCIC becomes inoperable, any water available will be injected into the reactor vessel. Fig. 2 presents the URG procedure. The URG procedure includes several measures to be performed:

- Perform the controlled depressurization for the reactor to bring down the dome pressure to 15 kg/cm^2 by opening one SRV (safety/relief valve) when the NPP meets the situation 3 + 1 or 3 + 2 (RCIC is available).
- Prepare alternative water supply which might include service fresh water, reservoir gravity injection, fire engine creek, or sea water within the first hour.
- If the NPP status cannot be restored before the RCIC is unavailable, perform the fully depressurization to further lower down the dome pressure to 3 kg/cm^2 by opening all ADS. The set-up of alternative water supply must be finished before the fully depressurization is performed.
- Inject the low pressure water into the reactor vessel after the system fully depressurizes.
- Perform the containment venting if the containment pressure is beyond design to maintain containment integrity.

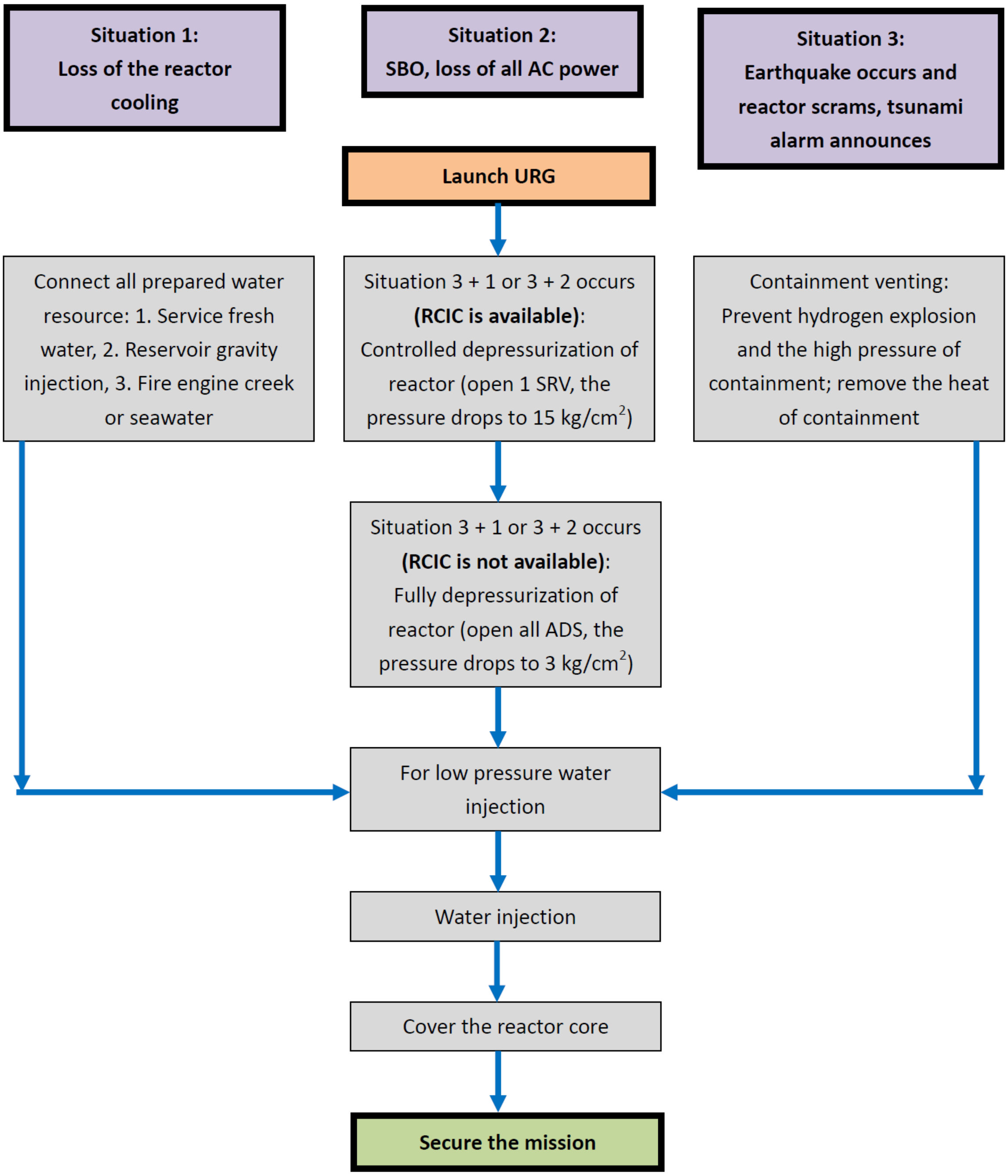

Figure 2 URG Flowchart

3 RELAP5/SNAP MODEL

The steps of the RELAP5/SNAP model for Lungmen NPP are as follows:

1. The system and operating data, startup tests reports, and FSAR of Lungmen NPP were collected [1], [5]-[10] for the establishment of the RELAP5/SNAP model.
2. Several important control systems such as RIPs control system, pressure control system and feedwater control system etc. were established by using SNAP and RELAP5.
3. Other necessary components (e.g., reactor pressure vessel and main steam piping) were added into the RELAP5/SNAP model.
4. This model was used to simulate the URG procedure under Fukushima-like conditions.

In addition, the initial conditions for this study are as follows:

- Power: 3926 MWt
- Core flow: 52.2 x10^6 kg/hr
- Dome pressure: 7.17 MPa
- Narrow range water level: 425 cm (above TAF)
- Steam flow: 7.66 x 10^6 kg/hr
- Feedwater flow: 7.66 x 10^6 kg/hr

Fig. 3 shows the RELAP5/SNAP model of Lungmen NPP. In this model, the reactor is in node 2~96. The dome of the reactor is in node 32, the upper plenum is in node 96, the stand pipe is in node 66, the core inlet is in node 4, and the downcomer is in node 20 and 18. Four steam lines are also simulated and are in node 100~200. Each steam line has one MSIV and several SRVs. These valves are simulated by the valve components of RELAP5. The 10 RIPs are classified into three groups in Lungmen NPP, three RIPs for each of the first and second groups, and four RIPs for the third group. The RIPs in the third group are not connected to the motor generator (M/G) set; the other six RIPs are connected to the M/G set. The RIPs are simulated by the pump components (node 10, 12, 14) of RELAP5. The time-dependent volume components of RELAP5 are used to simulate feedwater, RCIC, and ACIWA.

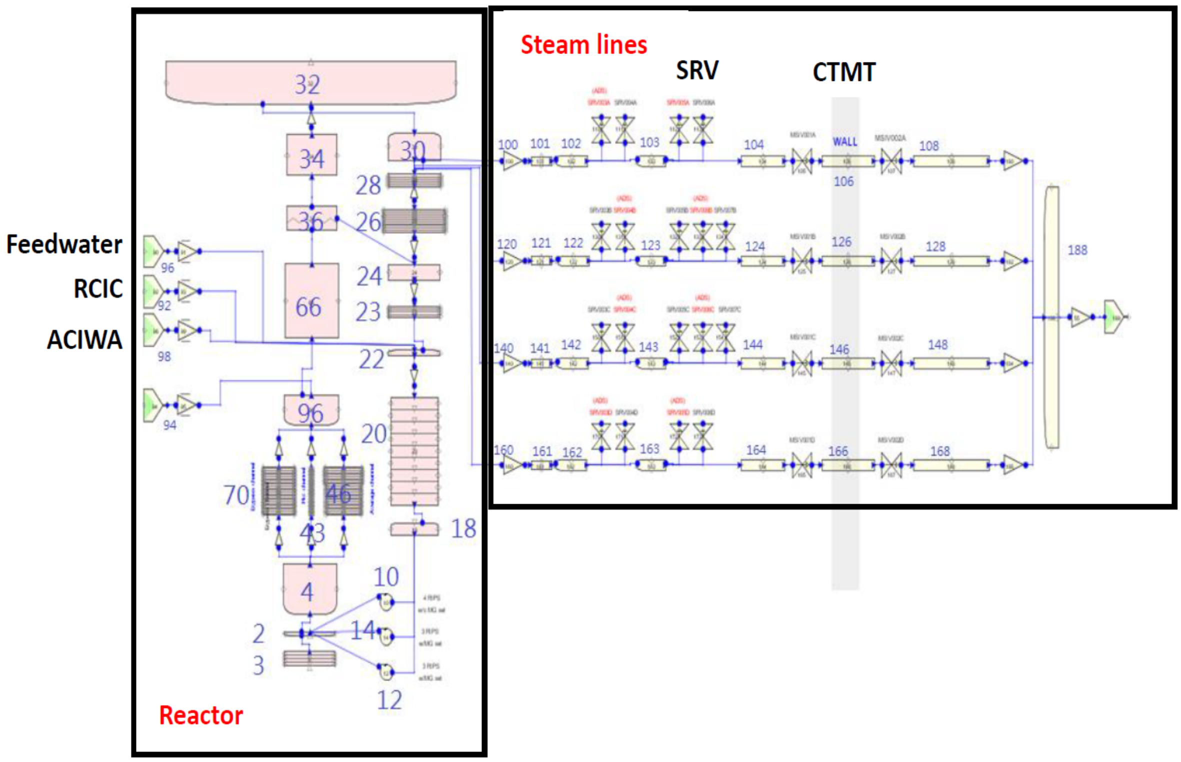

Figure 3 Lungmen NPP RELAP5/SNAP Model

4 RESULTS

According to the URG, the RCIC, ADS, and ACIWA are used in this procedure. In this study, there are two cases: URG case (Case 1) and no URG case (Case 2). In addition, there are some assumptions in these cases, including: (1) the simulation of steady state is performed during 0~300 sec; (2) the scram of reactor, all RIPs trip, feedwater flow trip, MSIV closure are performed at 300 sec; (3) the SRVs are activated in this transient; (4) the decay heat model ANS-1971 is used in the transients.

Table 1 presents the sequences of URG case. The RCIC, ADS, and ACIWA are available in this case. The flow rate of the RCIC is 50 kg/sec and the flow rate of the ACIWA is 60 kg/sec. We assume that Lungmen NPP meets situation 3 first (see Fig. 2). Additionally, the scram of reactor and SBO happens at the same time. Because situation 3 and 2 occurs, the controlled depressurization is performed at 380 sec. In this step, in order to let the dome pressure drop to 15 kg/cm^2, one SRV is manually opened. The RCIC maintains the water level of the reactor between level 2 and 8 during 300~3900 sec. According to the FSAR, the RCIC can run 8 hours. But the URG requests that the alternative water supply must be ready within one hour. Therefore, in order to decrease the analysis time of RELAP5, we assume that the RCIC only runs one hour in this case. The RCIC fails at 3900 sec and fully depressurization is performed at the same time. All ADS are manually opened in this step. After the dome pressure drops to 3 kg/cm^2, the low pressure water (ACIWA) is injected to the reactor at 4700 sec.

Fig. 4~8 illustrate the results of RELAP5 for the URG case. Fig. 4 shows the water level results. The MSIVs were closed and feedwater was tripped which resulted in the decrease of water level during 300~380 sec. When the water level dropped lower than level 2, the RCIC started to inject water to the reactor (see Fig. 6) during 339~3900 sec. Subsequently, the controlled depressurization was performed at 380 sec and the water level dropped at the same time. Due to the water injection of the RCIC, the water level went up during 2000~3900 sec. The dome pressure dropped to 15 kg/cm^2 and was maintained to nearly this level in this period (see Fig. 5). Next, the RCIC failed and the fully depressurization was performed at 3900 sec, so the water level and dome pressure decreased again. However, the ACIWA was activated at 4930 sec, so the water level increased again. According to the URG (Ref. 1), the PCT should be lower than 1088.7 K. Fig. 8 presents the PCT result of RELAP5. After the scram, the controlled depressurization and the RCIC activated, the PCT decreased during 300~3900 sec. The PCT went down again after the fully depressurization and ACIWA activated. In addition, the PCT was always lower than 1088.7 K. It indicates that the zirconium-water reaction does not happen in this case.

Table 2 presents the sequences of no URG case. The RCIC and ACIWA are unavailable in this case. We also assume that Lungmen NPP meets situation 3 first. The scram of the reactor and SBO also happens at the same time. In order to simulate the more severe conditions, the fully depressurization is performed at 1400 sec. All ADS are manually opened in this step.

The MSIVs were closed, feedwater flow was tripped, and the SRVs were opened which resulted in the decrease of water level for no URG case (see Fig. 9). In Fig. 9, the oscillation occurred during 300~1400 sec which was caused by the open and close actions of the SRVs. Additionally, we assume that all ADS are manually opened at 1400 sec. After all ADS were activated, the water level and dome pressure dropped sharply (shown in Fig. 10). Because the ADS were opened, larger amount of the steam was passed from the reactor which resulted in the decrease of PCT (see Fig. 11). However, in this case, the RCIC and ACIWA are unavailable. Therefore, the PCT went up and reached 1088.7 K at 2350 sec.

Fig. 9~11 also depict the comparison of URG (Case 1) and no URG (Case 2) case. If the controlled depressurization of URG and RCIC were not performed, the water level went down slowly (see Fig. 9, 300~1400 sec, Case 2). It indicates that the water level may be lower than TAF after the fully depressurization. For the fully depressurization of URG, it also results in the dropping of water level. If the controlled depressurization was not performed before the fully depressurization started, the dropping of the water level was rapid (see Fig. 4 and 9). In addition, if the ACIWA was not performed after the fully depressurization, the water level would be lower than BAF (bottom of active fuel) and the PCT would increase (see Fig. 11). The PCT reached 1088.7 K at 2350 sec and it implied that the PCT was over this limit at 950 sec (2350-1400 = 950) after the fully depressurization started.

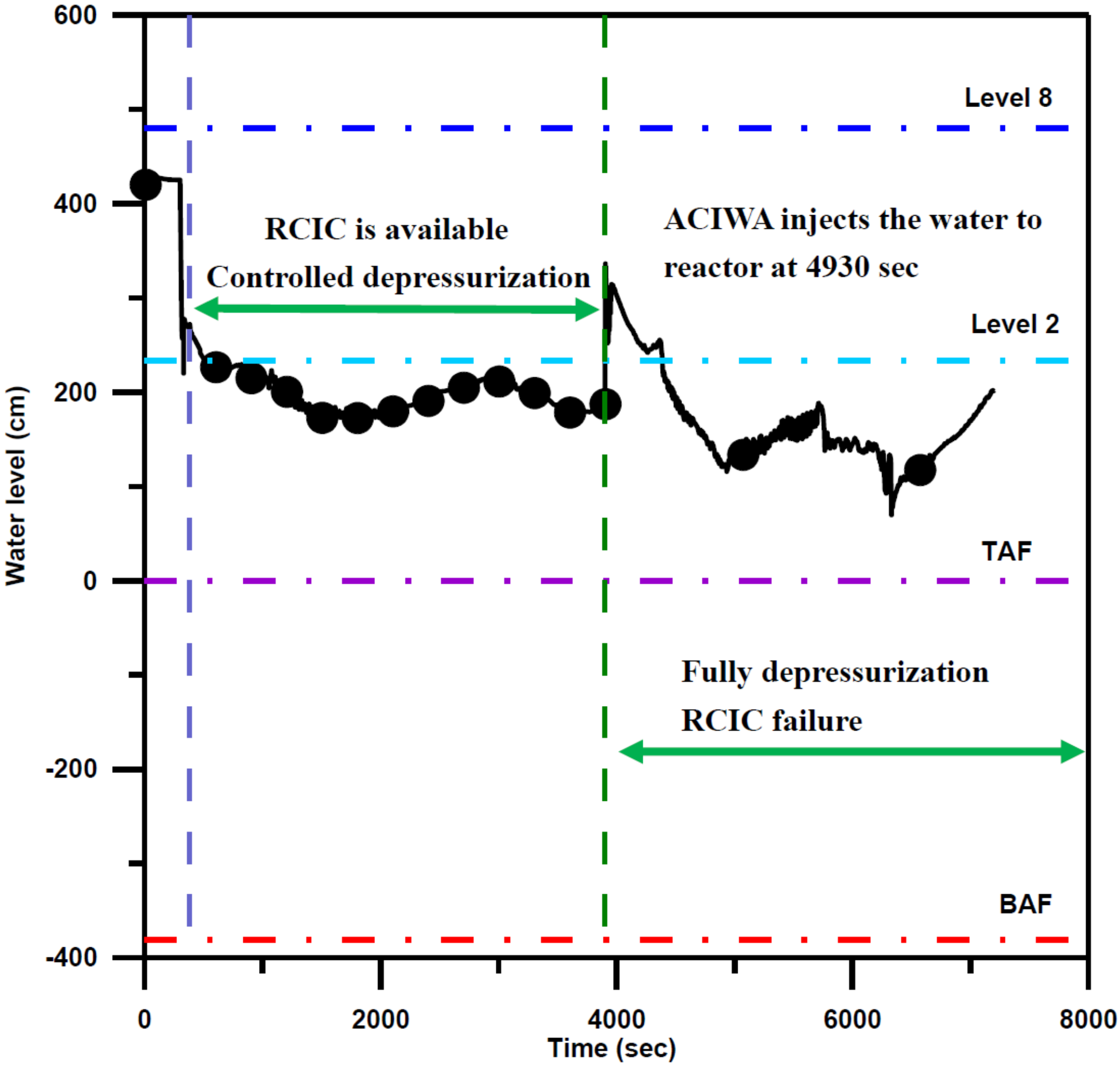

Figure 4 The Water Level Result for URG Case

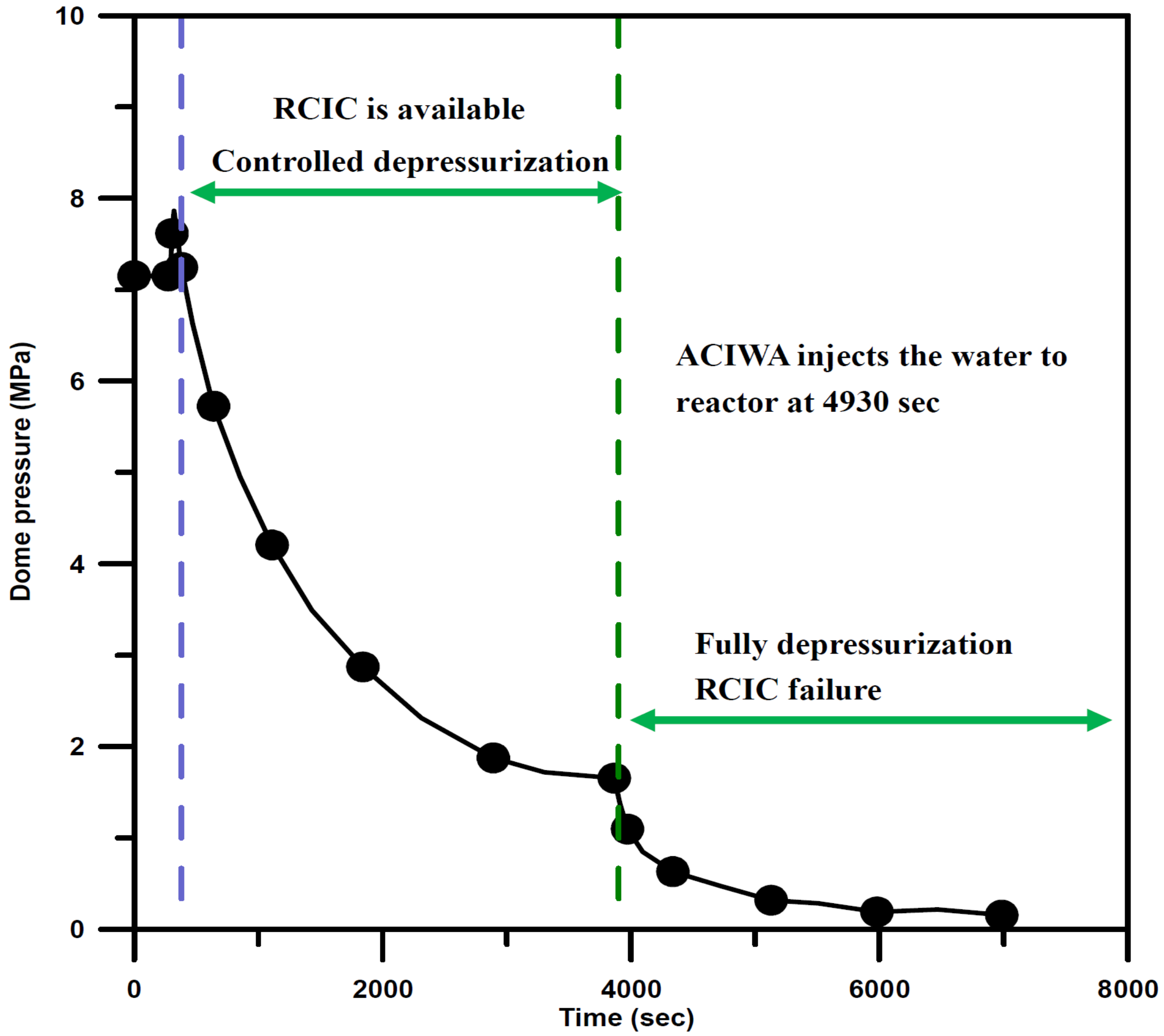

Figure 5 The Dome Pressure Result for URG Case

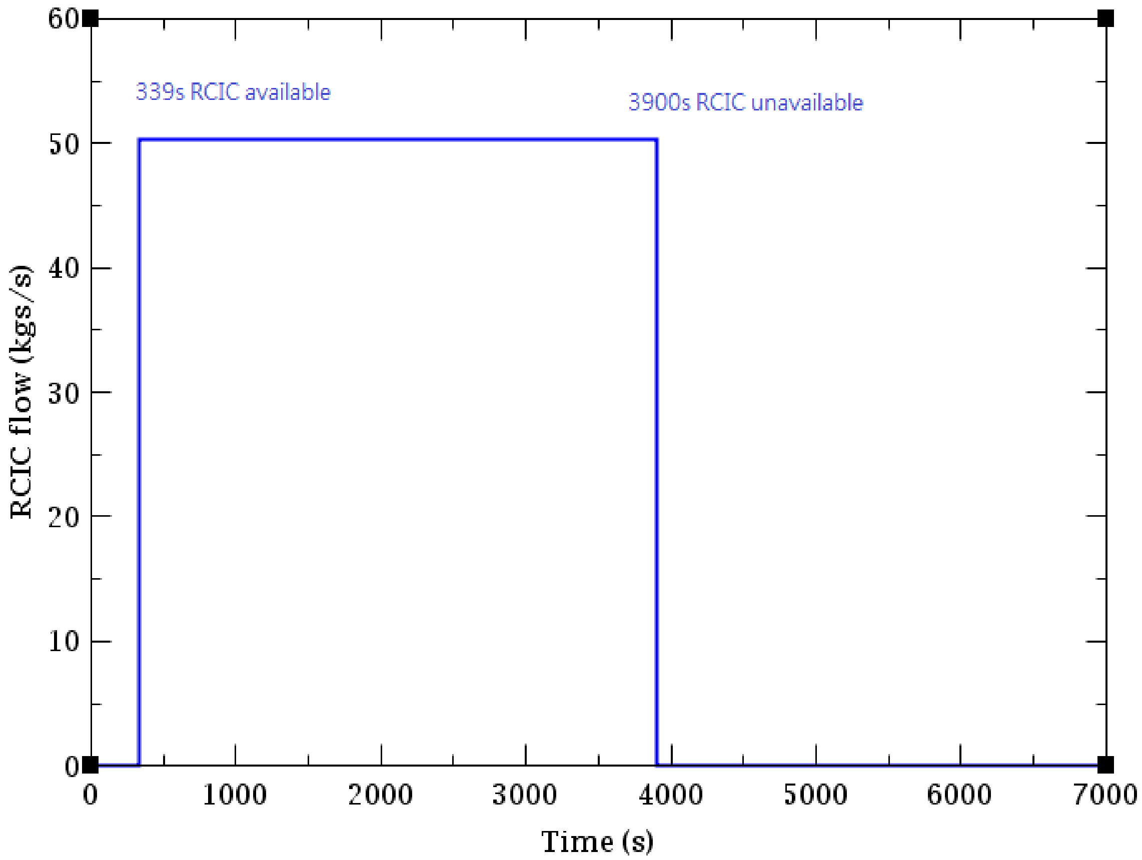

Figure 6 The RCIC Flow for URG Case

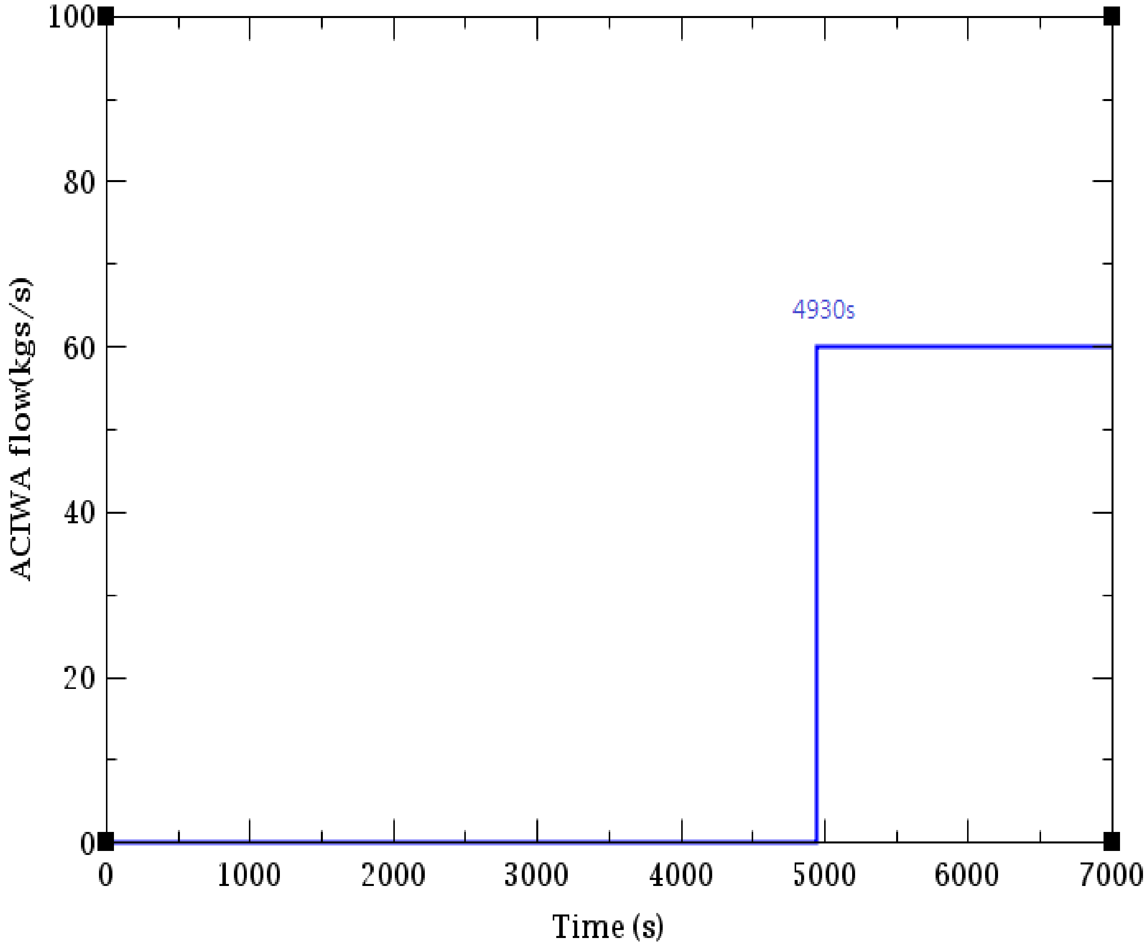

Figure 7 The ACIWA Flow for URG Case

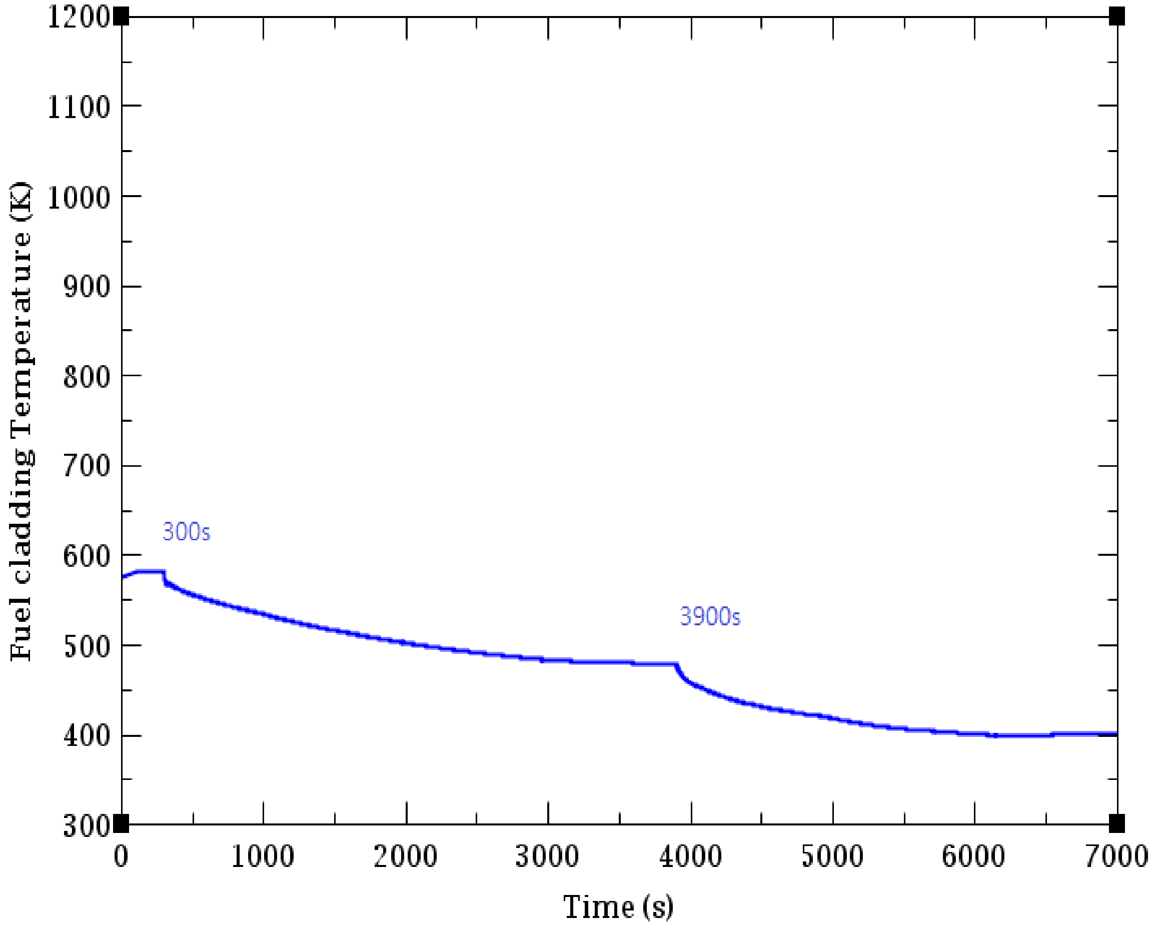

Figure 8 The PCT Result for URG Case

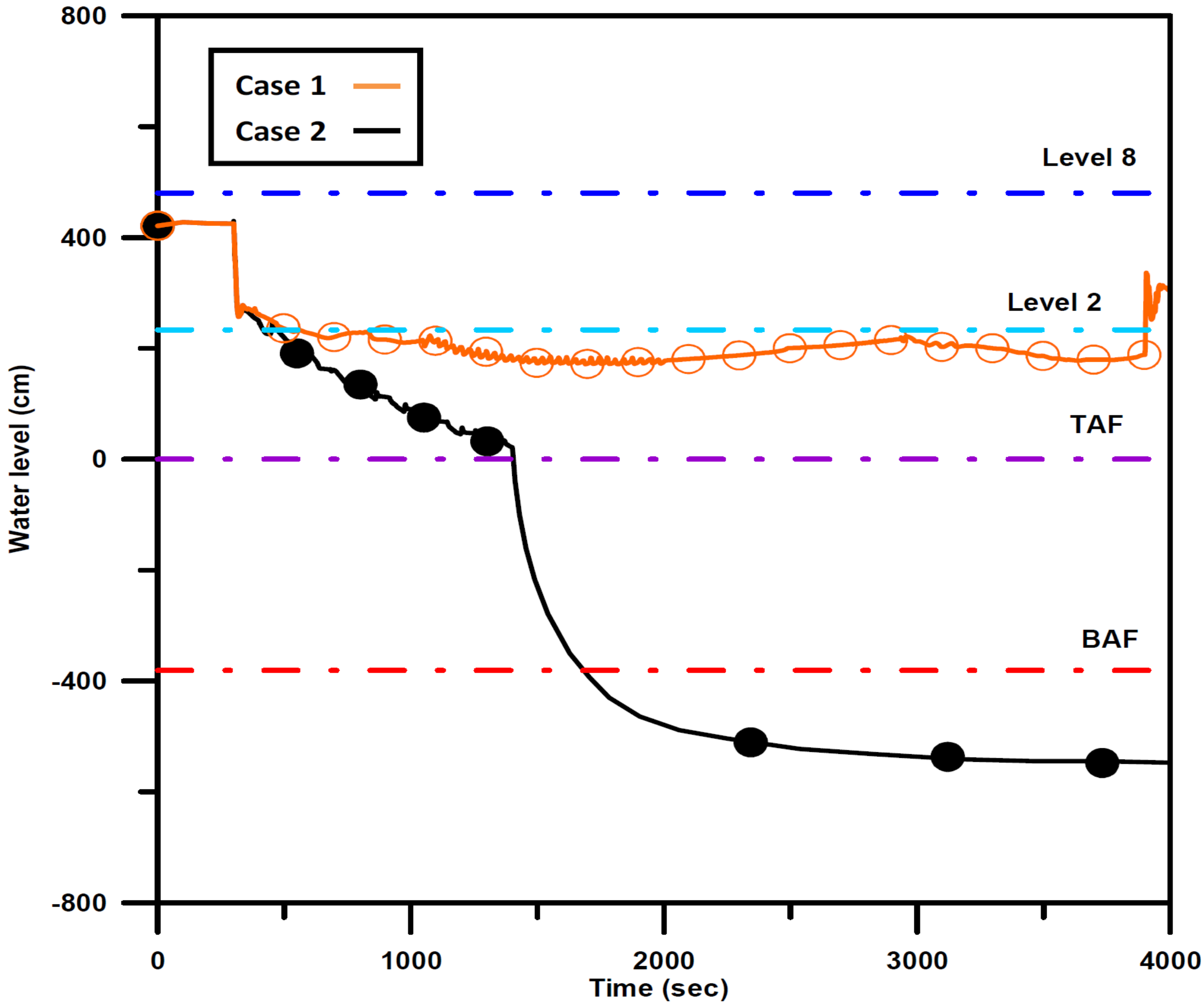

Figure 9 The Comparison of Water Level

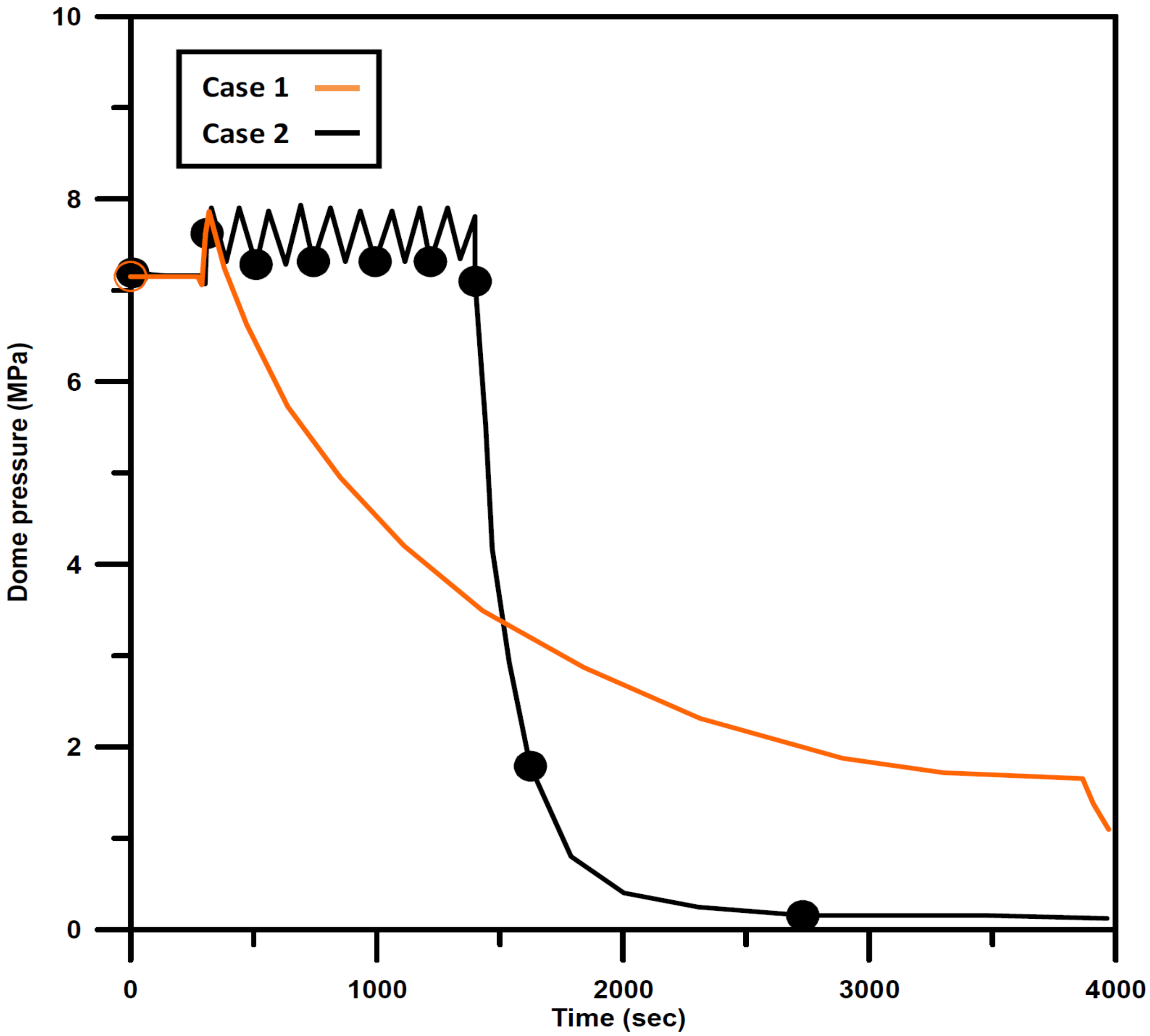

Figure 10 The Comparison of Dome Pressure

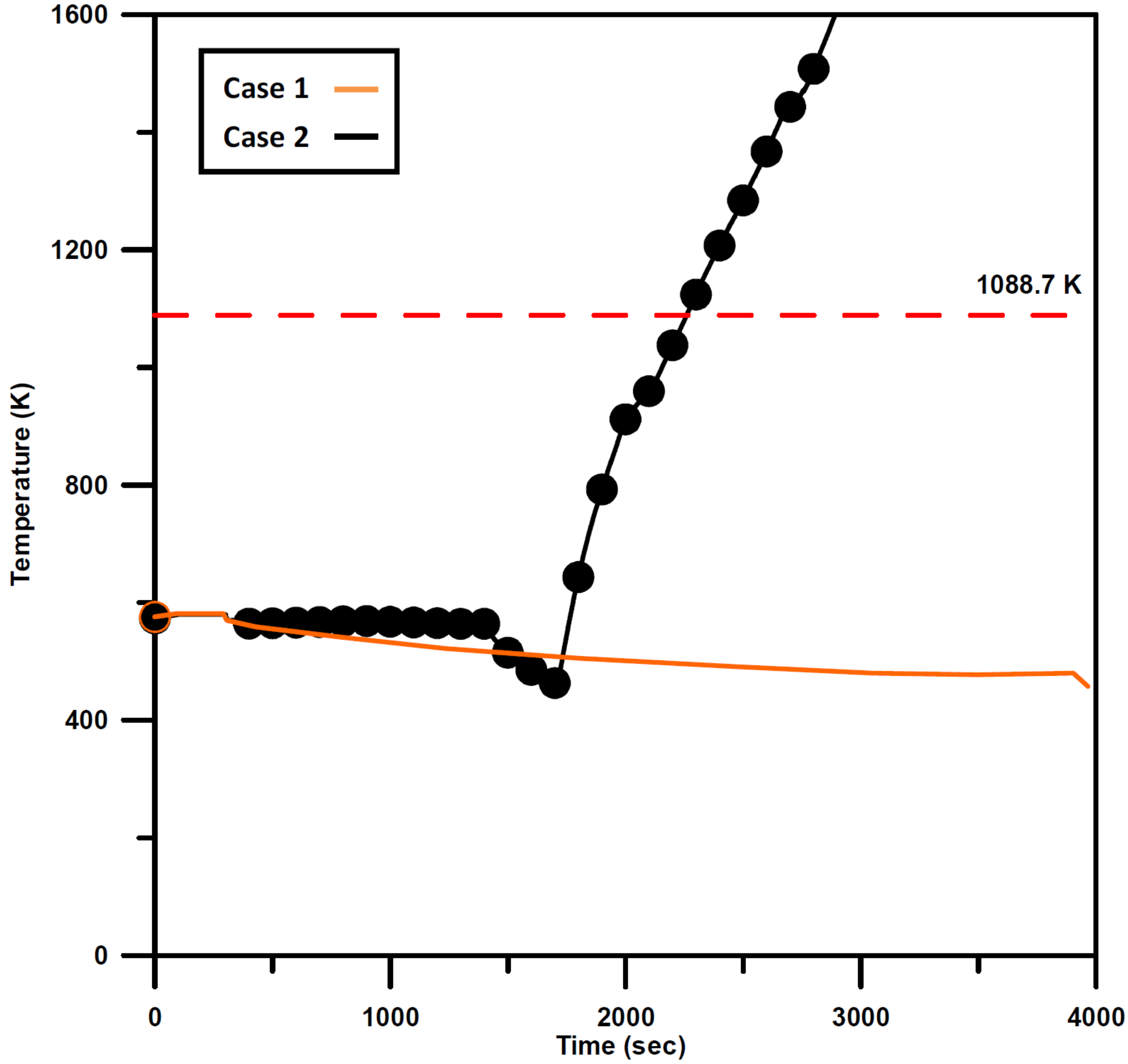

Figure 11 The Comparison of PCT

Table 1 The Sequences of URG Case (Case 1)

Action	Time* (sec)
Start	0
Reactor scrams (because earthquake occurs and tsunami alarm announces), SBO (loss of all AC power) occurs, MSIV closes, all RIPs and feedwater pumps trip, RCIC is available	300
Controlled depressurization of reactor (open 1 SRV, the pressure drops to 15 kg/cm2)	380
RCIC is not available, Fully depressurization of reactor (open all ADS, the pressure drops to 3 kg/cm2),	3900
Low pressure water injection (ACIWA)	4930
End	7000

***All are assumed values**

Table 2 The sequences of no URG case (Case 2)

Action	Time* (sec)
Start	0
Reactor scrams (because earthquake occurs and tsunami alarm announces), SBO (loss of all AC power) occurs, MSIV closes, all RIPs and feedwater pumps trip, RCIC is not available	300
Fully depressurization of reactor (open all ADS, the pressure drops to 3 kg/cm2),	1400
End	4000

*** All are assumed values**

5 CONCLUSIONS

This research established the RELAP5/SNAP model to confirm the effectiveness of URG for Lungmen NPP. The analysis results of RELAP5 indicate that the URG can maintain the PCT below the failure criteria (1088.7 K) under Fukushima-like conditions. It depicts that Lungmen NPP is at the safe situation. However, the following essential features are worth to be noted when the Lungmen NPP performs the URG:

- When the controlled depressurization of the reactor is performed, the RCIC should be available.
- The set-up of the ACIWA must be finished as fast as possible. Hence, Lungmen NPP can perform the fully depressurization of the reactor and inject the low pressure water to the reactor if the RCIC is unavailable.
- The controlled depressurization should be performed before the fully depressurization. It can mitigate the dropping of the water level when the fully depressurization is performed.

On the other hand, if Lungmen NPP meets Fukushima-like conditions (Case 2) and does not perform the URG, the water level may be lower than the TAF. If the fully depressurization is tripped by some mistakes under Fukushima-like conditions, the PCT may rise over 1088.7 K after 950 sec (based on the beginning time of the fully depressurization) which means a safety issue about the fuels may be generated.

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11. ABSTRACT (200 words or less)

The RELAP5/SNAP model for Lungmen ABWR nuclear power plant (NPP) was established for the simulation and study of the URG (ultimate response guideline). The main actions of the URG are the depressurization and low pressure water injection of the reactor and the venting of the containment. Therefore, this research focuses to assess the URG utility of Lungmen NPP under Fukushima-like conditions. Two steps are in this study. The first step is the establishment of RELAP5/SNAP model using the system and operating data, startup tests reports and FSAR of Lungmen NPP. The second step is the simulation and study of the URG under Fukushima-like conditions by using the above RELAP5/SNAP model. In this step, the case without URG was also performed to evaluate the URG effectiveness for Lungmen NPP. According to RELAP5 analysis results, the URG can keep the peak cladding temperature (PCT) below the failure criteria (1088.7 K) under Fukushima-like conditions. It indicates that Lungmen NPP can be controlled in a safe situation.

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