THE ANALYSIS OF TRACE/FRAPTRAN IN ULTIMATE RESPONSE GUIDELINE FOR LUNGMEN ABWR NUCLEAR POWER PLANT

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ABSTRACT

There is more concern for the safety of NPPs in Taiwan after the Fukushima nuclear power plant (NPP) disaster occurred. Therefore, Taiwan Power Company developed an additional ultimate measure category, ultimate response guideline (URG), to prevent and mitigate Taiwan NPPs from encountering core damage for events beyond design basis. The main actions of URG are the depressurization and low pressure water injection of reactor and containment venting. Lungmen NPP is the first ABWR NPP in Taiwan. In this study, we focus on the thermal-hydraulic and fuel rod performance analysis for the URG study of Lungmen NPP. Therefore, TRACE/FRAPTRAN model of Lungmen NPP was developed in order to estimate the URG efficiency under Fukushima-like conditions. TRACE/FRAPTRAN analysis results show that the URG can keep the PCT below the criteria 1088.7 K under Fukushima-like conditions.

KEYWORDS
TRACE, URG, ABWR, safety analysis, FRAPTRAN.

1. INTRODUCTION

There are more concerns for the safety of the NPPs in Taiwan after Fukushima NPP disaster. In general, there are four categories for the NPP operating state, which involve normal operation, abnormal events/transients, accidents and severe accidents. For each operating state, there are corresponding procedures to follow to secure NPPs safety and integrity. Fig. 1 shows the correspondent relationship between NPP operating states and procedures. The first level is operating procedures (OPs) which focus on the NPP operation within an acceptable range. The second level is abnormal operating procedures (AOPs) which aim at restoring the function of NPP systems that could impact the NPP operating margins. The third level is emergency operating procedures (EOPs) which 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). Uncertainties may exist in both NPP status and in the outcome of actions for severe accidents. Therefore, SAMPS propose a range of possible actions and should allow for additional evaluation and alternative actions. However, EOP or SAMP is generally the symptom-based procedures to mitigate transients/accidents consequence and restore the NPP, depending on the real-time operational parameters of the NPP. For the compound severe accidents, such as Fukushima NPP disaster, its impact to NPP is relatively broad, rather than focus on one system or one area influence. Therefore, with regard to this fact, Taiwan Power Company developed an additional URG to prevent BWR, PWR and ABWR from encountering core damage for events beyond design basis [1]-[3].

The aim of this study is to use multiple computer codes to evaluate the URG effectiveness for Lungmen ABWR NPP. Lungmen NPP is the first ABWR NPP in Taiwan. 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 reactor internal pumps (RIP) in the reactor vessel, capable of providing 111% rated core flow at the nominal operating speed of 151.84 rad/sec. U.S. NRC has developed the advanced thermal-hydraulic code named TRACE for NPP thermal hydraulic analysis. According to the TRACE's user manual [4], 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. 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. According to the user and assessment manual [4]-[5], TRACE also provides greater simulation capability than the previous codes (TRAC-P, TRAC-B, RELAP5 and RAMONA), especially for events like LOCA. FRAPTRAN is a Fortran language computer code that calculates the transient performance of light-water reactor fuel rods during reactor transients and hypothetical accidents such as loss-of-coolant accidents, anticipated transients without scram, and reactivity-initiated accidents [6]. Additionally, a graphic user interface program, SNAP [7], which processes inputs, outputs, and animation models for TRACE and FRAPTRAN, is also developed by U.S. NRC.

There were three main steps in this study. First, Lungmen NPP TRACE model was established in this research. Second, by using the above TRACE model, the URG simulation and analysis under Fukushima-like conditions was performed. In this step, the no URG case was also performed. Subsequently, we compared the results of these two cases in order to evaluate the URG effectiveness for Lungmen NPP. Third, in order to confirm the mechanical property and integrity of fuel rods, FRAPTRAN analysis was also performed in this study.

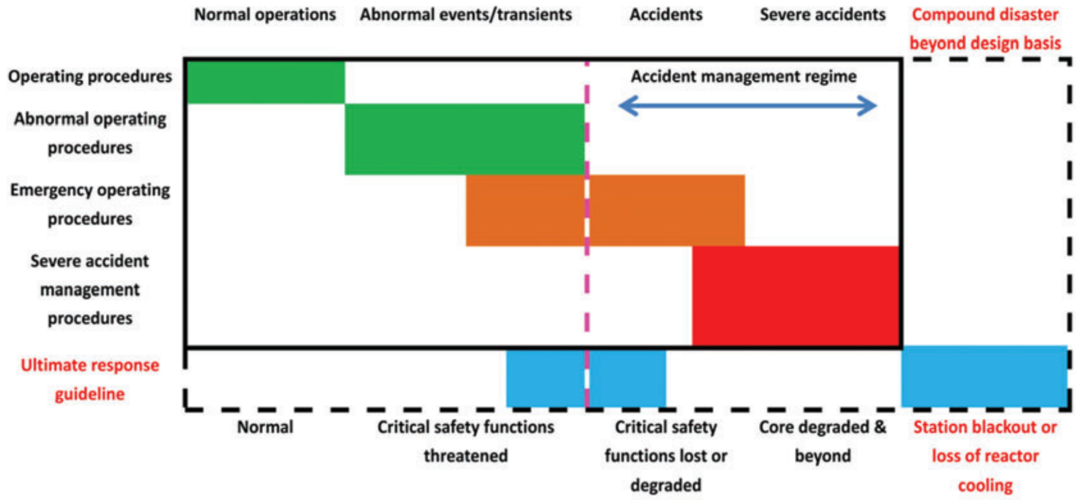


Figure 1. Correspondent Relation Between NPP Operating States and Operating Procedures.

2. ULTIMATE RESPONSE GUIDELINE (URG)

According to URG [1]-[3], the core concept is treating compound disaster beyond design basis (blue blocks in Fig. 1). When Lungmen NPP meets a Fukushima-like accident (the accident with loss of all AC power or reactor cooling conditions), EOP/SAMP and URG will be initiated at the same time. The main difference among EOP, SAMP and URG is that when the NPP status does not recovery in time, URG must be executed without most information of NPP. EOP and SAMP focus on maintaining the reactor core cooling, preventing the release of radioactive material, and protecting the property of NPP. However, 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 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 NPP encounters the Fukushima-like accident, URG will be activated to prevent reactor core from being damaged. Once entering the procedure of URG, the NPP reactor will be depressurized first, and if the electrical power cannot be recovered before passive reactor core isolation cooling (RCIC) becomes inoperable, any water available will be injected into the reactor vessel. Fig. 2 depicts 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) or TBV (turbine bypass vale) when the NPP meets the situation 3 + 1 or 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 NPP critical status cannot be restored before 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.

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

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

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.

- AC-Independent Water Addition System (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. According to the URG, RCIC/ADS/ACIWA are used in this procedure.

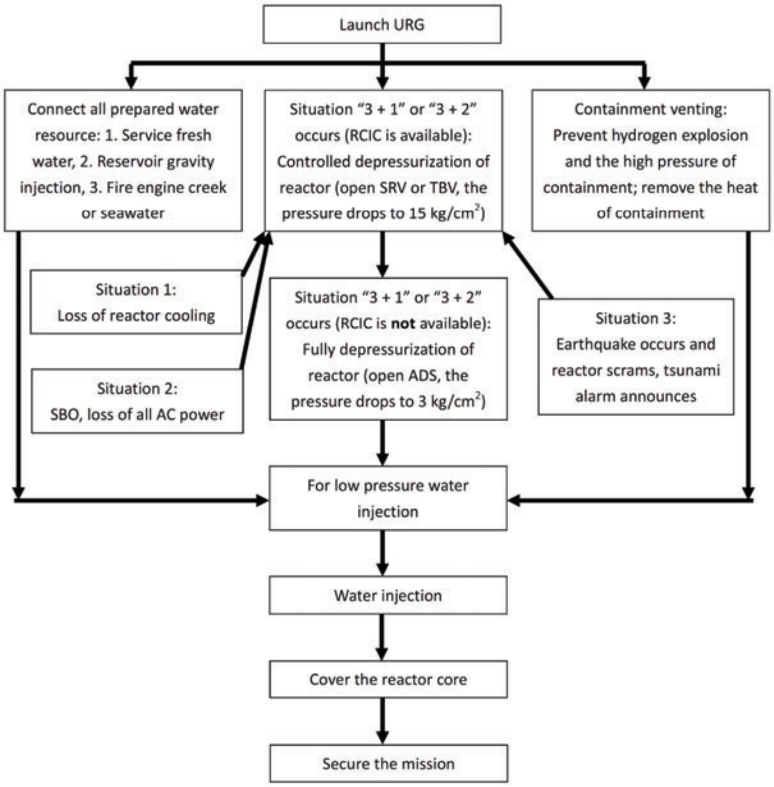


Figure 2. URG Flowchart.

3. TRACE AND FRAPTRAN MODELING OF LUNGMEN NPP

In this study, we established Lungmen NPP TRACE model by using TRACE v 5.0 patch 4 and SNAP v 2.2.9. The process is shown in Fig. 3. First, the system and operating data, startup tests and FSAR data of Lungmen NPP were collected [1], [8-17]. Second, several important control systems such as RIPs control system, pressure control system and feedwater control system etc. were established by using SNAP and TRACE. Third, other necessary components (e.g., RPV (Reactor pressure vessel) and main steam piping) were added into the TRACE model. Fourth, the TRACE model was verified by FSAR data under the steady state and transients conditions. In this step, MSIV closure and loss of feedwater flow transient data of FSAR were used to compare with the results of TRACE. Next, we used the TRACE model to simulate the URG procedure under Fukushima-like conditions. Finally, by using the results of TRACE, we established FRAPTRAN model of Lungmen NPP and performed the analysis to confirm the mechanical property and integrity of fuel rods.

Fig. 4 depicts the TRACE model of Lungmen NPP. In this model, the vessel was divided into 11 axial levels, four radial rings, and six azimuthal sectors (separated 36°, 36°, 108°, 36°, 36°, and 108° apart), and connected with four steam lines (connected to the 36° azimuthal sector of the vessel), six feedwater lines (connected to six azimuthal sectors separately, one for each sector), 18 channel components which were used to simulate the fuel region (one for each azimuthal sector in three inner radial rings), and 10 RIPs (connected to six azimuthal sectors separately, one for every 36°). The water rods and partial length rods were also simulated in the channels and each channel component presented some bundles (30 bundles × 6 channels + 40 bundles × 6 channels + 75 bundles × 4 channels + 76 bundles × 2 channels = 872 bundles in 18 channels). Each steam line has one MSIV, several SRVs, one turbine control valve (TCV) and one turbine stop valve (TSV). One valve component was used to simulate the bypass valve

(BPV) capability of Lungmen NPP in the TRACE model. The critical flow models for MSIVs, SRVs, TCVs, TSVs and BPV have been considered in our analysis. 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. When the water level reaches the level 2 setpoint, the RIPs of the first and second group will be tripped. The RIPs of the third group are tripped by one of the following conditions: 1. the water level reaches the level 3 setpoint; 2. the dome pressure reaches the high pressure setpoint; 3. TSV closure and the reactor scram occur; 4. TCV closure and the reactor scram occur.

Before the transient calculation of Lungmen TRACE model begins, it is necessary to carry out the steady state calculation to make sure that the system parameters are consistent with FSAR data [8]. The time step of this model was 0.01 sec and the steady state convergence was 1×10^{-4}. These system parameters include feedwater flow, steam flow, NRWL (Narrow Range Water Level), vessel dome pressure, etc. Table I shows the comparison of steady state results of FSAR and TRACE. It can be seen that TRACE results agree well with FSAR data. The differences of the steady state results between TRACE and FSAR were caused by the different calculation procedures, phenomenological modeling, and nodalization. In order to assess the system response of TRACE model, the MSIV closure and loss of feedwater flow transient of FSAR data were used to compare with the results of TRACE. The results and sequences of TRACE were similar to FSAR data. By the above compared results, it indicates that there is a respectable accuracy in Lungmen NPP TRACE model and it also shows that Lungmen NPP TRACE model is satisfying for the purpose of Lungmen NPP safety analyses with confidence.

ODYN is a GE transient analysis tool which is used in FSAR analysis of Lungmen NPP [18]. The overall ODYN model consisted of one reactor vessel, one steamline, RIP control system, feedwater control system, and liquid control system, etc. A comparison of TRACE and ODYN model of Lungmen NPP shows that the main differences between the simulations of TRACE and ODYN model are in the RPV and main steam lines (see Table II). The RPV of TRACE model was composed of one vessel component (3-D component). However, one 1-D vessel component was used to simulate the RPV of ODYN model, considering the axial direction of the RPV only. As for steam lines, there were four separate steam lines in TRACE model, which was identical to those in Lungmen NPP. However, these four steam lines were lumped to one steam line in the ODYN model.

A one-dimensional kinetic model and neutronics data were used for power calculations in the ODYN model, while in the TRACE model, the neutronics model was point kinetic model. Point kinetic parameters such as delay neutron fraction, Doppler reactivity coefficient, and void reactivity coefficient were provided as TRACE input for power calculations.

The geometry data of the fuel rod and the results of TRACE analysis (fuel rod power, coolant conditions, heat transfer coefficient) were inputted into FRAPTRAN to analyze the reliability of fuel rods. There were 12 axial nodes and 15 radial nodes in the FRAPTRAN model of Lungmen NPP (see Fig. 5).

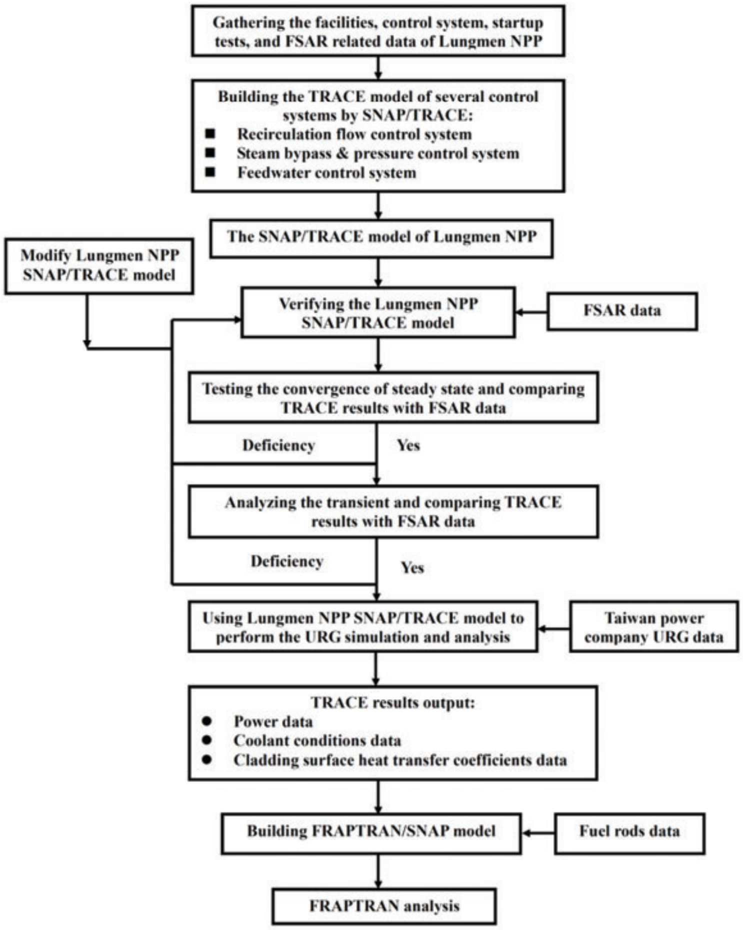


Figure 3. The Methodology of Lungmen NPP TRACE/FRAPTRAN Model.

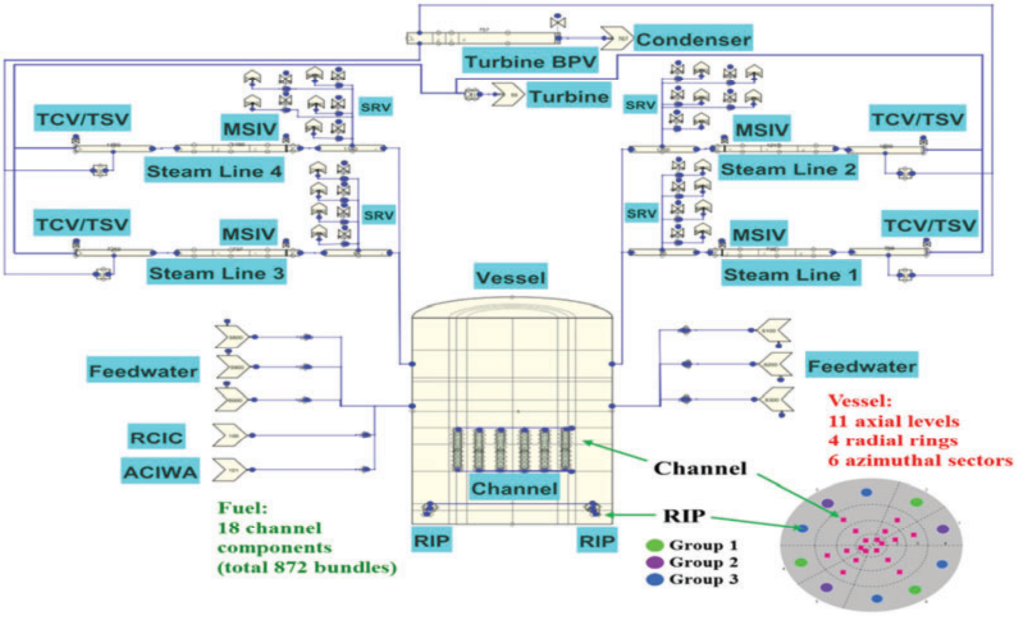


Figure 4. Lungmen NPP TRACE Model.

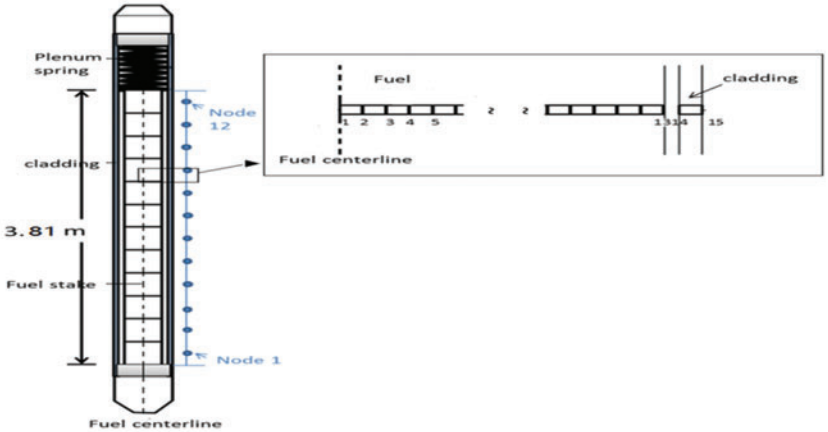


Figure 5. Lungmen NPP FRAPTRAN Model.

Table I. The comparison of initial conditions (100% rated power/100% rated core flow) of FSAR and TRACE

Parameters	FSAR	TRACE	Difference (%)
Power (MWt)	3926	3926	0
Dome pressure (MPa)	7.17	7.17	0
Narrow range water level (m)	1.19	1.19	0
Steam flow (kg/sec)	2122	2113	-0.4
Feedwater flow (kg/sec)	2122	2113	-0.4
Core flow(kg/sec)	12314.8	12343.63	0.2

Table II. The comparison of Lungmen NPP ODYN model and TRACE model

	ODYN model	TRACE model
The simulation of RPV	One 1-D vessel component (axial)	One 3-D vessel component
The simulation of main steam lines	Four main steam lines lumped to one main steam line	Four main steam lines
The calculation of power	One-dimensional kinetic model	Point kinetic model
Fluid field equations	Five equations	Six equations

4. RESULTS

In this research, there are two cases: URG case (case 1) and no URG case (case 2). There are some assumptions in these two 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-73 is used in this transient.

Table III shows the sequences of URG case with RCIC/ADS/ACIWA available. The flow rate of RCIC is 50 kg/sec and the flow rate of ACIWA is 60 kg/sec in this case. We assume that Lungmen NPP meets situation 3 first (see Fig. 2). The scram of reactor and SBO happens at the same time. Because situation 3 and 1 occurs, the controlled depressurization of reactor 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. RCIC maintains the water level of the reactor between level 2 and 8 during 300~3900 sec. According to FSAR, 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 TRACE, we assume that RCIC only runs one hour in this case. 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. 6 and 7 show the results of TRACE for URG case. Fig. 6 depicts the water level (based on the bottom of dryer skirt) result. The MSIVs were closed and feedwater was tripped which resulted in the decrease of water level during 300~380 sec. Subsequently, the controlled depressurization of reactor was performed at 380 sec and the water level dropped at the same time. When the water level dropped lower than level 2, RCIC started to inject water to the reactor. Therefore, the water level went up during 700~3900 sec. The dome pressure dropped to 15 kg/cm^2 and was kept to nearly this level in this period (see Fig. 6). Next, RCIC failed and the fully depressurization of reactor was performed at 3900 sec, so the water level and dome pressure decreased again. However, ACIWA was activated at 4700 sec, so the water level increased again. According to the URG [1], PCT should be lower than 1088.7 K. Fig. 7 presents the PCT result of TRACE. After the scram of reactor, the controlled depressurization and RCIC activated, PCT decreased during 300~3900 sec. The PCT went down again after the fully depressurization and ACIWA activated. Additionally, the PCT was always lower than 1088.7 K. It indicates that the zirconium-water reaction does not happen in this case.

Table IV presents the sequences of no URG case with RCIC/ACIWA unavailable. We also assume that Lungmen NPP meets situation 3 first. The scram of 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 SRVs were opened which resulted in the decrease of water level for no URG case (see Fig. 6, green curve). In Fig. 6 and 7, the oscillation occurred during 300~1400 sec which was caused by the open and close action of the SRVs. When the water level dropped to the TAF (top of active fuel), we assume that all ADS were manually opened at this time. After all ADS were activated, the water level and dome pressure dropped sharply (shown in Fig. 6). Because the ADS were opened, larger amount of the steam was passed from the reactor which resulted in the decrease of PCT (see Fig. 7). However, in this case, RCIC and ACIWA are unavailable, therefore, the PCT went up after 1750 sec and reached 1088.7 K at 3200 sec.

Fig. 6 and 7 also depict the comparison of URG (case 1) and no URG (case 2) case. For the controlled depressurization of URG, it may lead to the water level lower than TAF. Therefore, the PCT increased at 600 sec. However, RCIC injected the water to the reactor in this period, so the water level went up and covered the fuels. The PCT decreased after the water injection of RCIC. If the controlled depressurization of URG and RCIC were not performed, the water level went down slowly (see Fig. 6, 300~1400 sec, case 2). It indicates that the water level may be lower than TAF at 1100 sec (1400-300 = 1100) after the transient occurs. 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. 6, 1400~2000 sec, case 2; 3900~4500 sec, case 1). 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. 7, case 2). The PCT reached 1088.7 K at 3200 sec and it implied that the PCT was over this limit at 1800 sec (3200-1400 = 1800) after the fully depressurization started. In summary, TRACE analysis results show that the URG can keep the PCT below the criteria 1088.7 K under Fukushima-like conditions. It indicates that Lungmen NPP is at the safe status under these conditions. According to the above results of the comparison, the following essential features are worth to be noted:

- If Lungmen NPP performs the controlled depressurization of the reactor, RCIC should be available.
- If RCIC is not available at any time, the set-up of ACIWA must be finished as fast as possible. Then, after the fully depressurization of the reactor is performed, the low pressure water can be injected to the reactor.

- The controlled depressurization should be performed first. This procedure can mitigate the dropping of the water level when the fully depressurization starts.

In order to study the mechanical property and integrity of fuel rods, FRAPTRAN analysis was performed in this study. In this step, we only analyzed the no URG case. The URG case is not considered in this step because its PCT is lower than 1088.7 K. Fig. 8 and 9 show the results of FRAPTRAN for no URG case. FRAPTRAN output file depicted the fuel rod burst in the axial node 5 at 3200 sec. Hence, Fig. 8 and 9 only present the results of the axial node 5 in this paper. Fig. 8 depicts the cladding hoop strain result of FRAPTRAN and it shows that the strain goes up when PCT rises. NUREG-0800 Standard Review Plan [17] clearly defines fuel cladding failure criteria. For the uniform strain value, it is limited not to exceed 1%. The cladding hoop strain went up sharply after 2800 sec and was larger than this limit. The cladding hoop stress is shown in Fig. 8. As presented in Fig. 6, the pressure of the reactor affected the variation of cladding hoop stress. Because the pressure of the reactor went up, the cladding hoop stress decreased during 300~1400 sec. The stress increased sharply during 1400~3200 sec due to the pressure of the reactor decreased. However, the stress dropped to zero and kept this level after 3200 sec. Therefore, the cladding hoop strain and stress results indicated that the integrity of fuel rod was not able to be kept. Fig. 9 depicts the zirconium-water reaction energy and oxide thickness results of FRAPTRAN. According to FRAPTRAN results, the zirconium-water reaction occurred at 3100 sec and the oxide thickness of cladding started to increase after 3100 sec. The zirconium-water reaction energy and oxide thickness went up sharply after 3300 sec. According to 10 CFR 50.46 rules [19], the increasing oxide thickness of cladding should be less than 17%, Fig. 9 shows the cladding oxide thickness is over this critical value (0.11 mm). It also presented that the cladding burst in this case. In addition, the animation of Lungmen NPP TRACE model is presented by using the animation function of SNAP and TRACE analysis results. As shown in Fig. 10, the variation of no URG case can be observed in this animation model.

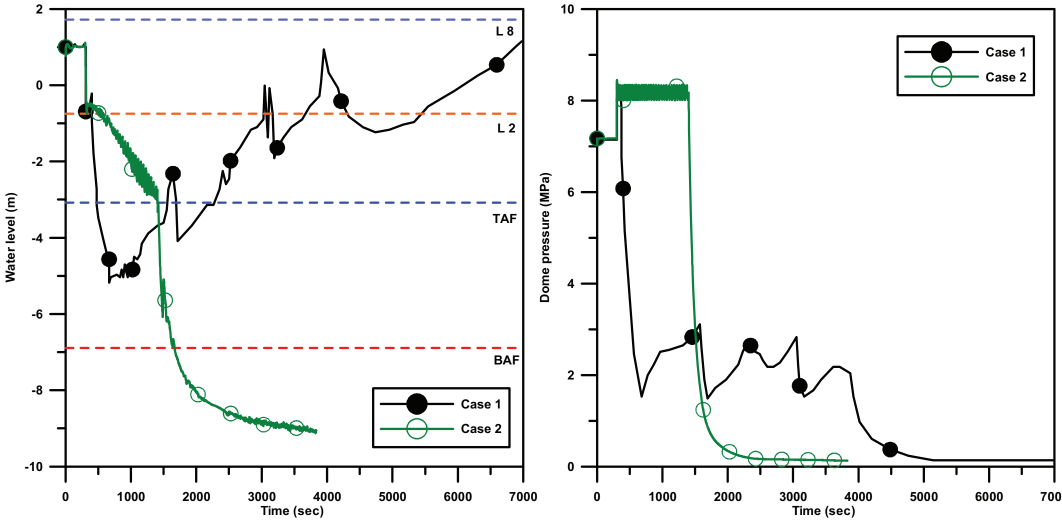


Figure 6. The Water Level and Dome Pressure Comparison of Case 1 and 2.

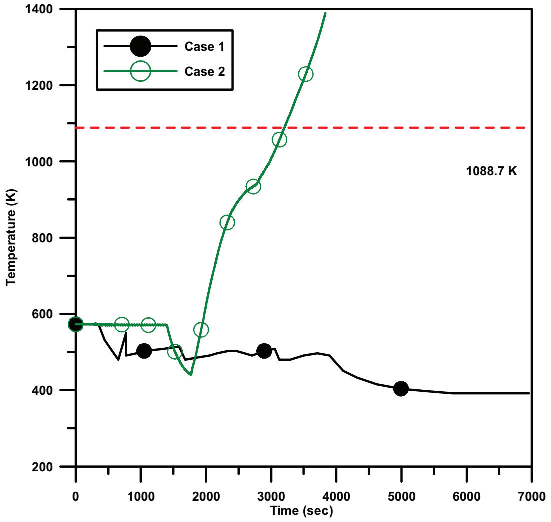


Figure 7. The PCT Comparison of Case 1 and 2.

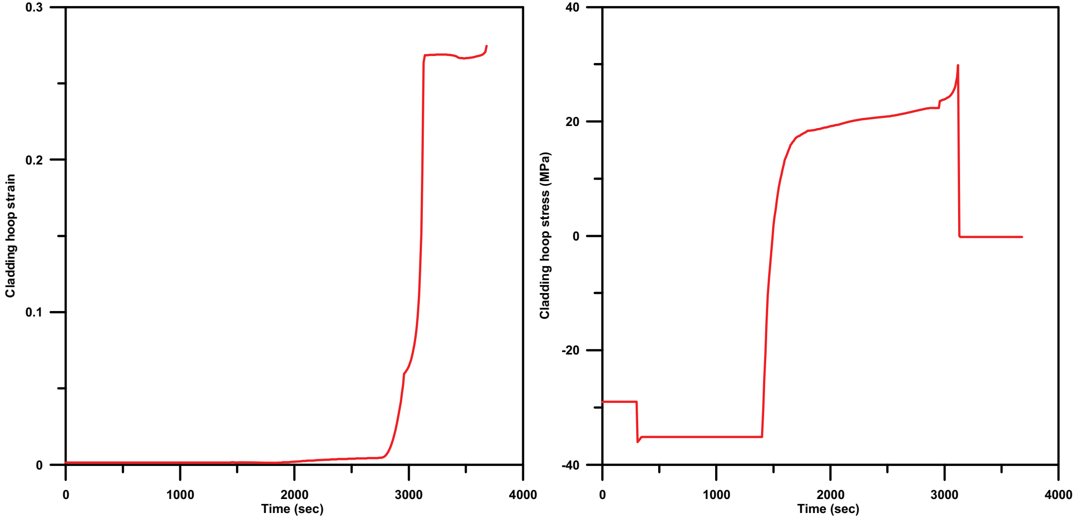


Figure 8. The Cladding Hoop Strain and Stress Result of FRAPTRAN for No URG Case.

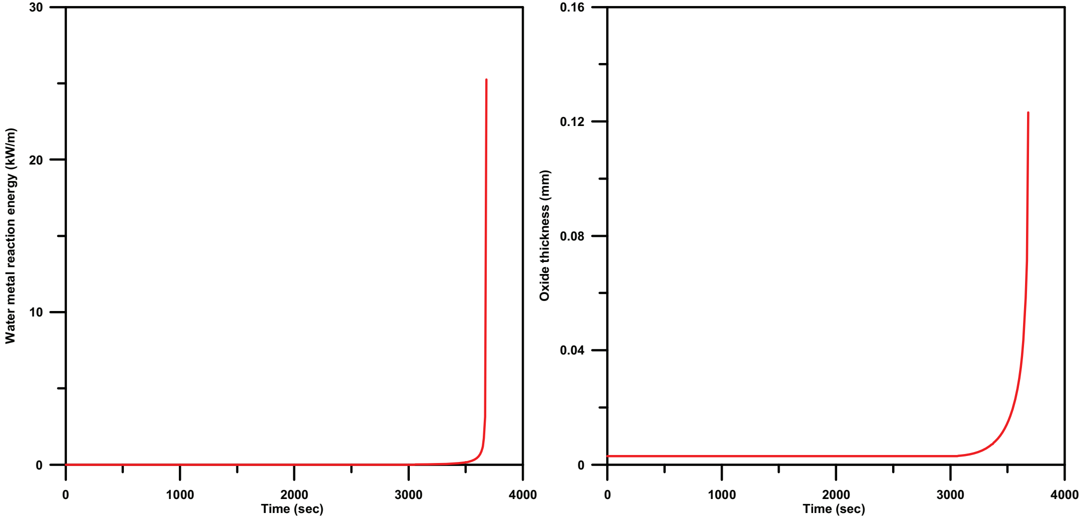
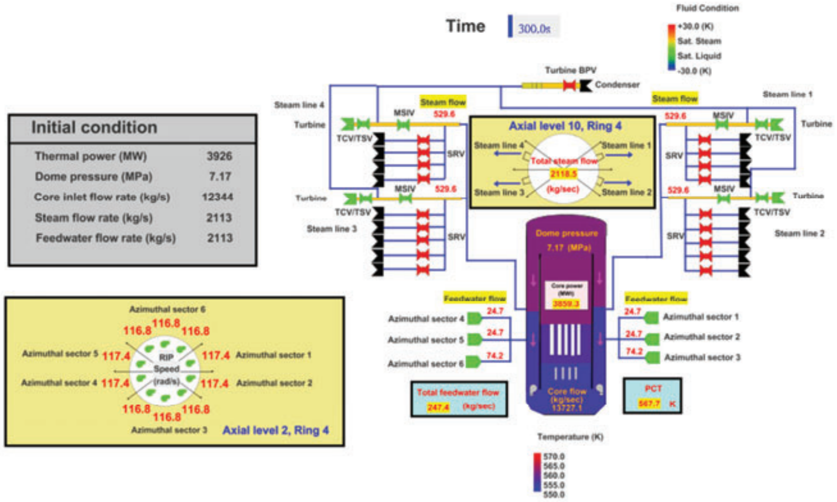
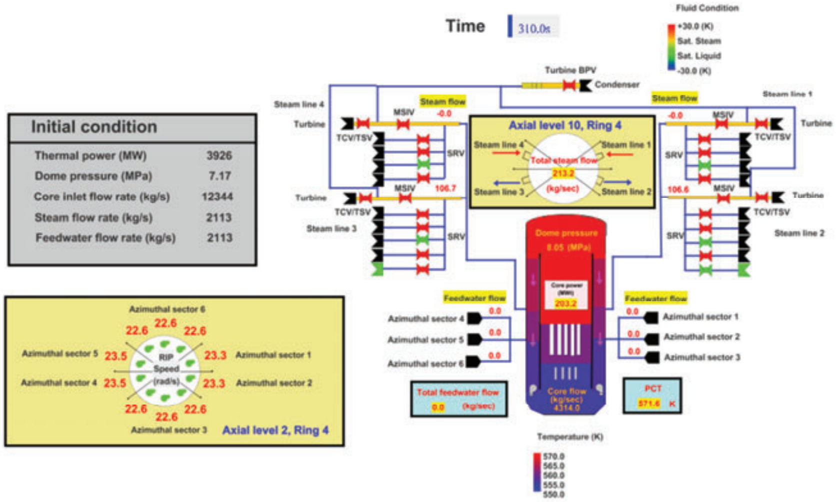


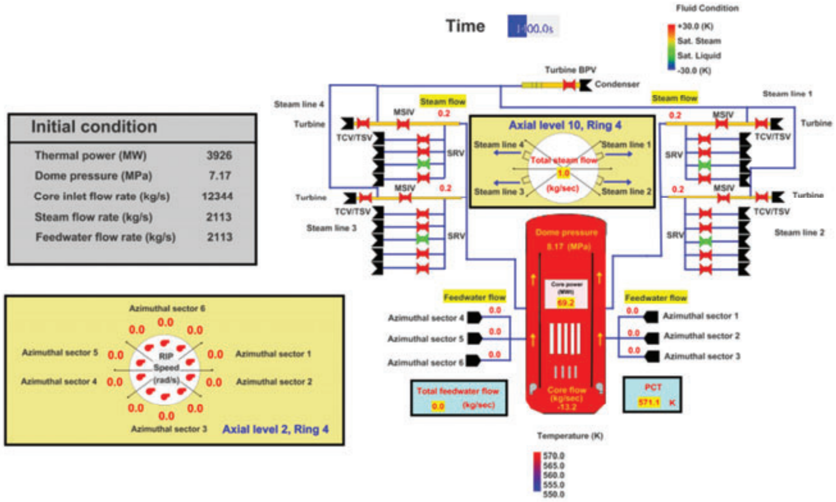
Figure 9. The Zirconium-Water Reaction Energy and Oxide Thickness Result of FRAPTRAN for No URG Case.



(a) 300 sec



(b) 310 sec



(c) 1400 sec

Figure 10. The Animation Model of Lungmen NPP (No URG Case).

Table III. The sequences of URG case

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/cm^2)	380
RCIC is not available, Fully depressurization of reactor (open 8 ADS, the pressure drops to 3 kg/cm^2),	3900
Low pressure water injection (ACIWA)	4700
End	7000

Table IV. The sequences of no URG case

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 8 ADS, the pressure drops to 3 kg/cm^2),	1400
End	4000

*ACIWA is not available

5. CONCLUSIONS

By using SNAP and TRACE, this study has developed the model to estimate the effectiveness of URG for Lungmen NPP. TRACE analysis results implied that the URG kept the PCT below the criteria 1088.7 K under Fukushima-like conditions. It indicated that Lungmen NPP was at the safe status. However, the following essential features are worth to be noted when the Lungmen NPP performs the URG:

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

On the other hand, if Lungmen NPP meets Fukushima-like conditions (case 2) and do not perform the URG, the water level may be lower than TAF after 1100 sec. If the fully depressurization is tripped by some mistakes under Fukushima-like conditions, the PCT may rise over 1088.7 K after 1800 sec (based on the beginning time of fully depressurization) which means a safety issue about the fuel rods may be generated. FRAPTRAN analysis results show that the cladding burst at 3200 sec and also depict the integrity of fuel rods cannot be kept under these conditions.

NOMENCLATURE

ACIWA	AC-Independent Water Addition System
ADS	Automatic Depressurization System
AOP	Abnormal Operating Procedure
BAF	Bottom of Active Fuel
BPV	Bypass Valve
CST	Condensate Storage Tank
EOP	Emergency Operating Procedure
FSAR	Final Safety Analysis Report
LOCA	Loss-of-Coolant Accident
M/G	Motor Generator
MSIV	Main Steamline Isolation Valve
NPP	Nuclear Power Plant
NRWL	Narrow Range Water Level
OP	Operating Procedure
PCT	Peak Cladding Temperature
RCIC	Reactor Core Isolation Cooling
RIP	Reactor Internal Pump
RPV	Reactor Pressure Vessel
SAMP	Severe Accident Management Procedure
SBO	Station Blackout
SP	Suppression Pool
SRV	Safety/Relief Valve
TAF	Top of ACTIVE FUel
TBV	Turbine Bypass Vale
TCV	Turbine Control Valve
TSV	Turbine Stop Valve
URG	Ultimate Response Guideline

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