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Kuosheng BWR Decommissioning SBO Analysis with RELAP5/MOD 3.3

Prepared by:
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ABSTRACT

The Taiwan Power Company and the Nuclear Safety Commission (formerly the Atomic Energy Commission) of our country have, since 2004, engaged in research projects under the Taiwan-U.S. Civil Nuclear Cooperation Agreement, signed with the U.S. Nuclear Regulatory Commission (U.S.NRC) through the representative office in the United States. The collaboration involves the Code Application and Maintenance Program (CAMP), focusing on the application and maintenance of thermal-hydraulic codes (RELAP5 and TRACE) for nuclear power plants. The technical research outcomes are published in the NUREG/IA series reports. The CAMP international collaboration initiative was initiated by the U.S. Nuclear Regulatory Commission to ensure the safe operation of nuclear power plants, promote international information exchange, cooperation, and experience feedback in the nuclear field. In addition to ongoing experiments and simulation program development related to safety, active efforts are made to seek international experiences and feedback. Therefore, it is essential for our country to continue participating in the CAMP cooperation agreement, contributing research analysis and assessment results through international collaborative projects, and publishing NUREG reports for information and experience exchange with international organizations.

Aligned with the national energy policy, this project will be responsible for analyzing the decommissioning planning and operational safety of Taiwan Power Company's nuclear power plants. Over the four-year project period, analysis will be conducted using the SNAP/RELAP5 program. The current project aims to establish a model for the decommissioning transitional phase of Kuosheng Nuclear Power Plant using SNAP/RELAP5, supplemented by heat flow formula calculations and TRACE analysis for validation and comparison [1]. This effort will assist Taiwan Power Company in conducting assessments related to the decommissioning transitional phase of Kuosheng NPP and other associated tasks.

FOREWORD

RELAP5 is a thermal hydraulic analysis code and has been designed to perform best-estimate analysis of LOCA, operational transients, and other accident scenarios for Nuclear Power Plants. Traditionally, RELAP5 models were developed by ASCII files, which was not intelligible for the beginners of computer analysis. A graphic input interface code-SNAP is developed by Applied Programming Technology Inc. and can process the establishment of the RELAP5 models more conveniently.

Taiwan and the United States have signed an agreement on CAMP to obtain the authorization of these codes. NTHU is the organization in Taiwan responsible for the application RELAP5 and SNAP in safety analysis of nuclear power plants. Hence, the RELAP5/SNAP model of Kuosheng BWR NPP has been developed. The Unit 1 reactor at the Kuosheng NPP entered the decommissioning phase in 2021 due to insufficient storage space in the spent fuel pool, while Unit 2 entered the decommissioning phase after the expiration of its operating license in 2023 [2]. This study focuses on the safety issues related to the temporary storage of spent nuclear fuel in the reactor pressure vessel during the decommissioning transition phase of Kuosheng NPP A thermal-hydraulic analysis model for the decommissioning transition phase of Kuosheng NPP was developed using the RELAP5 program, and a case study and safety assessment of a loss of cooling water accident were conducted.

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EXECUTIVE SUMMARY

RELAP5 which is MOD3.3 Patch05 code was developed by Idaho National Engineering Laboratory for light water reactor transient analysis. RELAP5 can simulate the operation of NPPs under normal operations and transients, provide an accurate and rapid analysis pattern for NPP systems, and provide transients analysis results to NPPs and regulatory commission. RELAP5/MOD3.3 code is featured with nonhomogeneous and non-equilibrium model for the two-phase system and is a one-dimensional thermal hydraulic analysis code which uses Semi-Implicit method numerical scheme. RELAP5/MOD3.3 code also includes some models to deal with some particular phenomenon, such as critical flow model, reflooding model, metal-water reaction model etc.

SNAP which is developed by Applied Programming Technology, Inc. is a graphic interface code and different from the traditional input deck in ASCII files. SNAP can help users to easily build the RELAP5 models in a graphic interface. Furthermore, SNAP has the animation function to present RELAP5 analysis results. Hence, RELAP5/MOD3.3 and SNAP codes were used in this study.

The decommissioning plan for Kuosheng Nuclear Power Plant is divided into four stages, with a duration of 25 years each: the decommissioning transition phase, the decommissioning dismantling phase, the site final condition detection phase, and the site restoration phase. This study primarily simulates the scenario described in Chapter 5, Section 2 of the decommissioning plan, titled "Period with Fuel Remaining in the Core [2]." During this period, spent nuclear fuel still remains in the reactor core and due to insufficient storage space in the spent fuel pool, some spent nuclear fuel needs to be temporarily stored within the reactor core. During this period, it is necessary to continue providing power supply, maintaining cooling water replenishment measures, and other support systems to facilitate the removal of residual heat from the spent nuclear fuel.

The research method will first establish the SNAP/RELAP5 model of the decommissioning transition phase of Kuosheng Nuclear Power Plant. Then, combined with the decay heat data provided by Taiwan power company for 1 to 3 years, the SBO case is analyzed by this SNAP/RELAP5 model.

ABBREVIATIONS AND ACRONYMS

CAMP	Code Applications and Maintenance Program
NRC	Nuclear Regulatory Commission
NTHU	National Tsing Hua University
SBO	Station Blackout
NPP	Nuclear Power Plant
FSAR	Final Safety Analysis Report
SNAP	Symbolic Nuclear Analysis Program
BWR	Boiling Water Reactor
TSS	Transient simulation steady state
EPRI	Electric Power Research Institute
TAF	Top Active Fuel

1 INTRODUCTION

Kuosheng NPP utilizes the General Electric's sixth-generation Boiling Water Reactor (BWR/6) paired with the Mark III containment vessel. The space above the reactor pressure vessel is referred to as the reactor cavity. During the decommissioning transitional phase at the Kuosheng NPP, the reactor's upper cover will be opened to establish communication with the spent fuel pool. When modeling, considerations are given to the program's computational capabilities and the complexity of model establishment, leading to simplifications in certain area configurations.

During the initial phase of decommissioning at Kuosheng NPP, known as the transition phase, the reactor core temporarily stores the most recent batch of spent nuclear fuel while awaiting the activation of dry storage. The decay heat of this spent nuclear fuel decreases with longer shutdown periods. However, the decay heat of the spent fuel temporarily stored in the reactor core remains relatively high. Therefore, this study aims to assess the impact of the decay heat of spent nuclear fuel in the reactor core during the early stage of shutdown on the development of accidents.

The study's simulation conditions are based on input from relevant sources such as the "Taiwan Power Company Nuclear Backend Operations Division, Kuosheng NPP Decommissioning Plan, 2021," operational cycle assessment reports, and monitoring records during decommissioning [3]. Initial conditions such as power, decay heat versions, and other necessary parameters are considered. Additionally, insights from case analysis reports on the decommissioning transition phases of Kuosheng NPP and Chinshan Nuclear Power Plant, conducted by Tsinghua University using the TRACE analysis model, are incorporated.

Once the model is established, it is compared with calculations from heat flow formulas and supplemented with data from the TRACE program for analysis. The credibility of the SNAP/RELAP5 model's open mode is verified, followed by refinement of subsequent case simulations to evaluate the development of scenarios after the loss of cooling water by SBO. This evaluation includes determining the available time for implementing rescue measures by power plants to prevent fuel exposure and ensure the plant's safety.

2 MODEL AND METHODOLOGY DESCRIPTION

2.1 Kuosheng RELAP5/SNAP Model Description

During the decommissioning transitional phase of the Kuosheng NPP, the reactor core still contains 624 bundles of ATRIUM-10 used nuclear fuel from the 28th cycle [4]. The estimation of decay heat is based on the Fission Product Decay Heat and Heavy Element Decay Heat, referencing the U.S. Nuclear Regulatory Commission review plan NUREG-0800 ASB 9-2 [5]. However, the NRC does not recommend using this as a basis for storing used nuclear fuel pools. Additionally, its suitable calculation range for post-shutdown days is from 0 to 107 seconds (115 days), which differs from the actual scenario at the Kuosheng NPP.

Therefore, for subsequent model refinement cases, the decay heat results will be replaced by those from RG3.54 [6]. RG3.54 is suitable for simulating the period covering the current situation at the Kuosheng NPP (1 to 110 years), and it encompasses a more diverse range of decay heat contributing factors. The model establishment refers to the initial version's startup test of the thermal-hydraulic flow pattern. It largely maintains the complete core thermal-hydraulic flow region components, including the downflow region, recirculation system, and internal geometric configurations, to retain the basic pattern of the thermal-hydraulic flow. Subsequently, adjustments are made to the boundary conditions of inlet water injection (card number 400, see Figure 2-1) and outlet gas discharge pressure (card number 549, see Figure 2-2), both set to 1 atmosphere. Furthermore, the power reduction values are modified to match the decay heat described in the decommissioning report, time step and water injection settings are shown in Figure 2-3 and Figure 2-4.

To minimize debugging procedures, the connectivity at the inlet and outlet is also modified while preserving the original components and modifying their initial conditions where possible. For example, in the case of communication between the upper pool outlet and atmosphere, an existing steam pipe pathway is repurposed to create a set of pipes and valves to simulate overflow cooling water and communication with the outside for gas discharge.

Regarding used nuclear fuel and decay heat, the original Heat Structure is utilized to introduce thermal energy into the central 4 sets of Pipe components as POWER links. The axial power settings are also kept consistent with the startup test model of the Kuosheng NPP. In practice, different batches of fuel rods exist within the reactor core, each with varying thermal energy. To simulate this, some fuel components are set to have no heat source while others are set to have a heat source, representing the water rods, control rods, and actual heat-generating fuel components, see Figure 2-5, Figure 2-6 and Figure 2-7.

The total water storage volume is set to 1555.72 $m^{3,}$ with the upper pool volume pre-set at 1178.5 m^3 (including approximately 50 m^3 for the reactor top). Finally, the method of coolant water injection is modified by adjusting the feeding water pathways, varying flow rates and water temperatures to match actual on-site conditions.

2.2 Analysis Methodology Description

The reference decommissioning plan and TRACE program report were used to establish the base case mode [7]. The power output of the Kuosheng NPP during the decommissioning period was set according to different shutdown days: 7 days at 9.1141 MWt, 30 days at 5.0568 MWt, 60 days at 3.5043 MWt, 90 days at 2.8115 MWt, 180 days at 1.8215 MWt, and 365 days at 1.026 MWt, as referenced. To verify the credibility of the SNAP/RELAP5 program, a comparison between the results obtained from formula calculations and TRACE program simulations will be conducted for parameters such as void fraction, pressure, and temperature variations.

The simulation scenario is set for a 1-day cooling test, where continuous injection of cooling water is conducted to monitor the pressure and temperature variations of the entire pool, as Table 2-1. This ensures the proper functioning of the injection system and overflow gas discharge components. Once the data stabilizes, the injection is halted, as Table 2-2. Subsequently, a Station Blackout (SBO) event is simulated and allowed to continue until the end of the simulation period without any remedial actions to observe the subsequent temperature rise and changes in water level, see Figure 2-8 to Figure 2-12.

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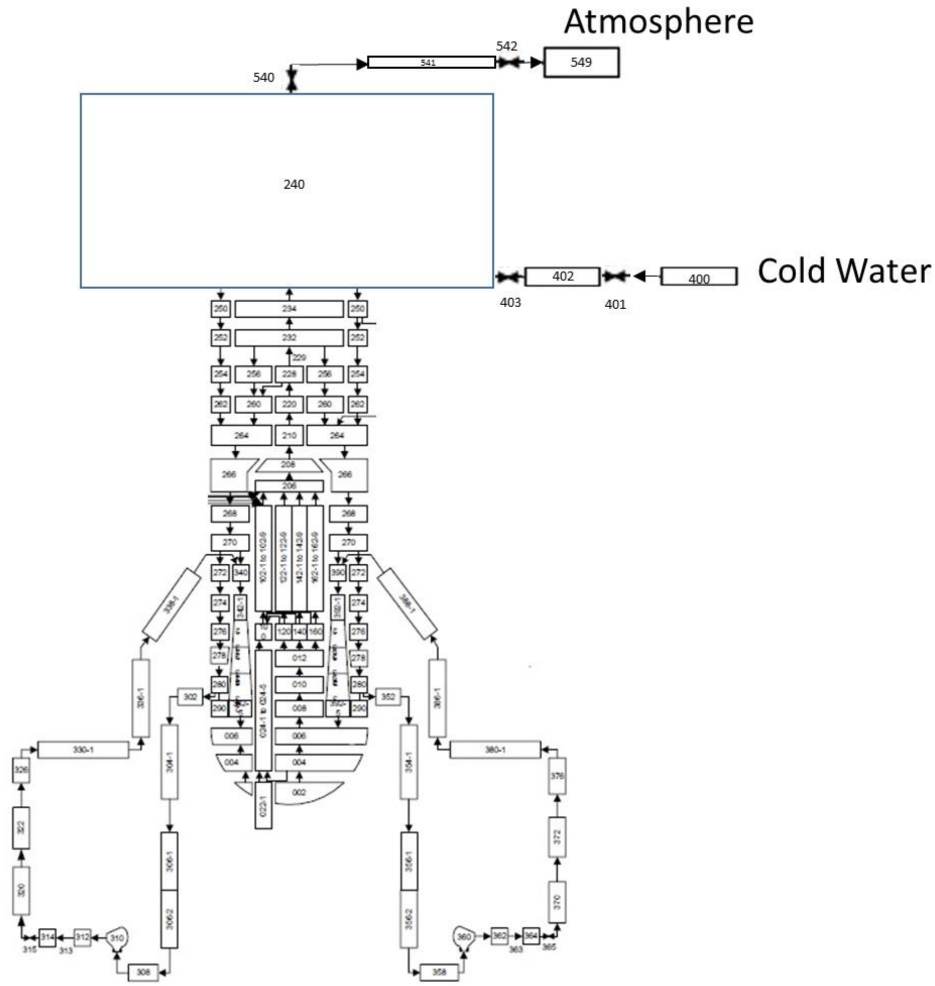


Figure 2-1 Kuosheng NPP Decommissioning Model Node Graph

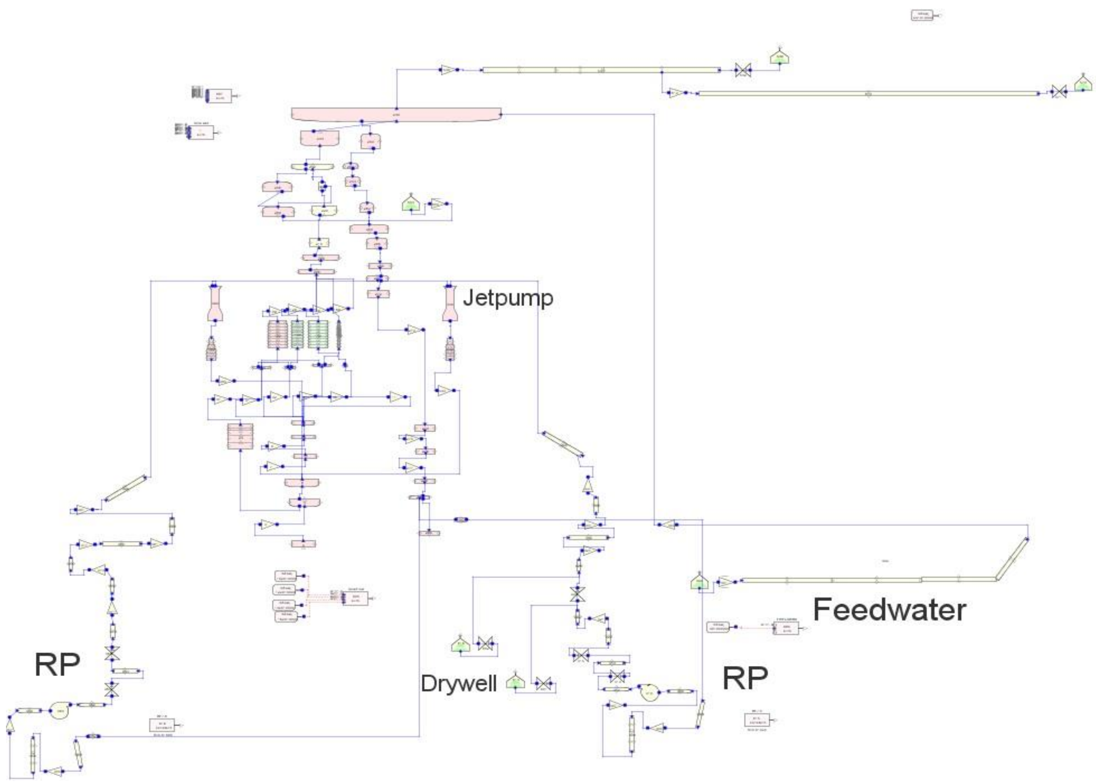
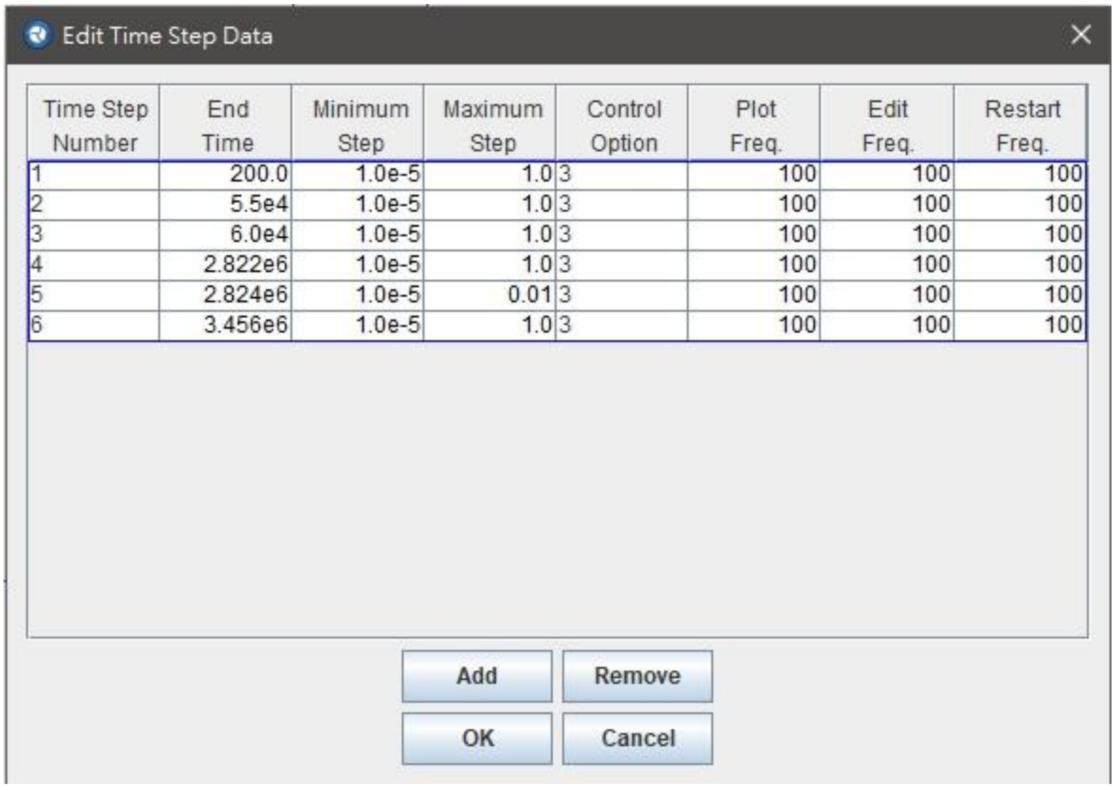
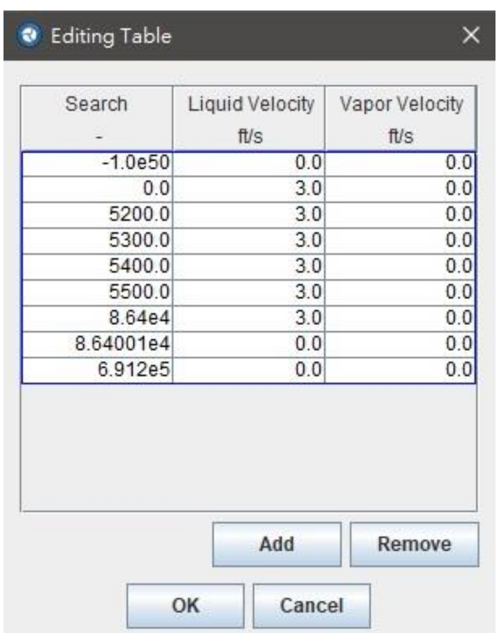


Figure 2-2 The RELAP5/SNAP of Kuosheng NPP Decommissioning Model



Time Step Number	End Time	Minimum Step	Maximum Step	Control Option	Plot Freq.	Edit Freq.	Restart Freq.
1	200.0	1.0e-5	1.0	3	100	100	100
2	5.5e4	1.0e-5	1.0	3	100	100	100
3	6.0e4	1.0e-5	1.0	3	100	100	100
4	2.822e6	1.0e-5	1.0	3	100	100	100
5	2.824e6	1.0e-5	0.01	3	100	100	100
6	3.456e6	1.0e-5	1.0	3	100	100	100

Figure 2-3 Simulation of Time Step



Search -	Liquid Velocity ft/s	Vapor Velocity ft/s
-1.0e50	0.0	0.0
0.0	3.0	0.0
5200.0	3.0	0.0
5300.0	3.0	0.0
5400.0	3.0	0.0
5500.0	3.0	0.0
8.64e4	3.0	0.0
8.64001e4	0.0	0.0
6.912e5	0.0	0.0

Figure 2-4 Cooling Water Setting

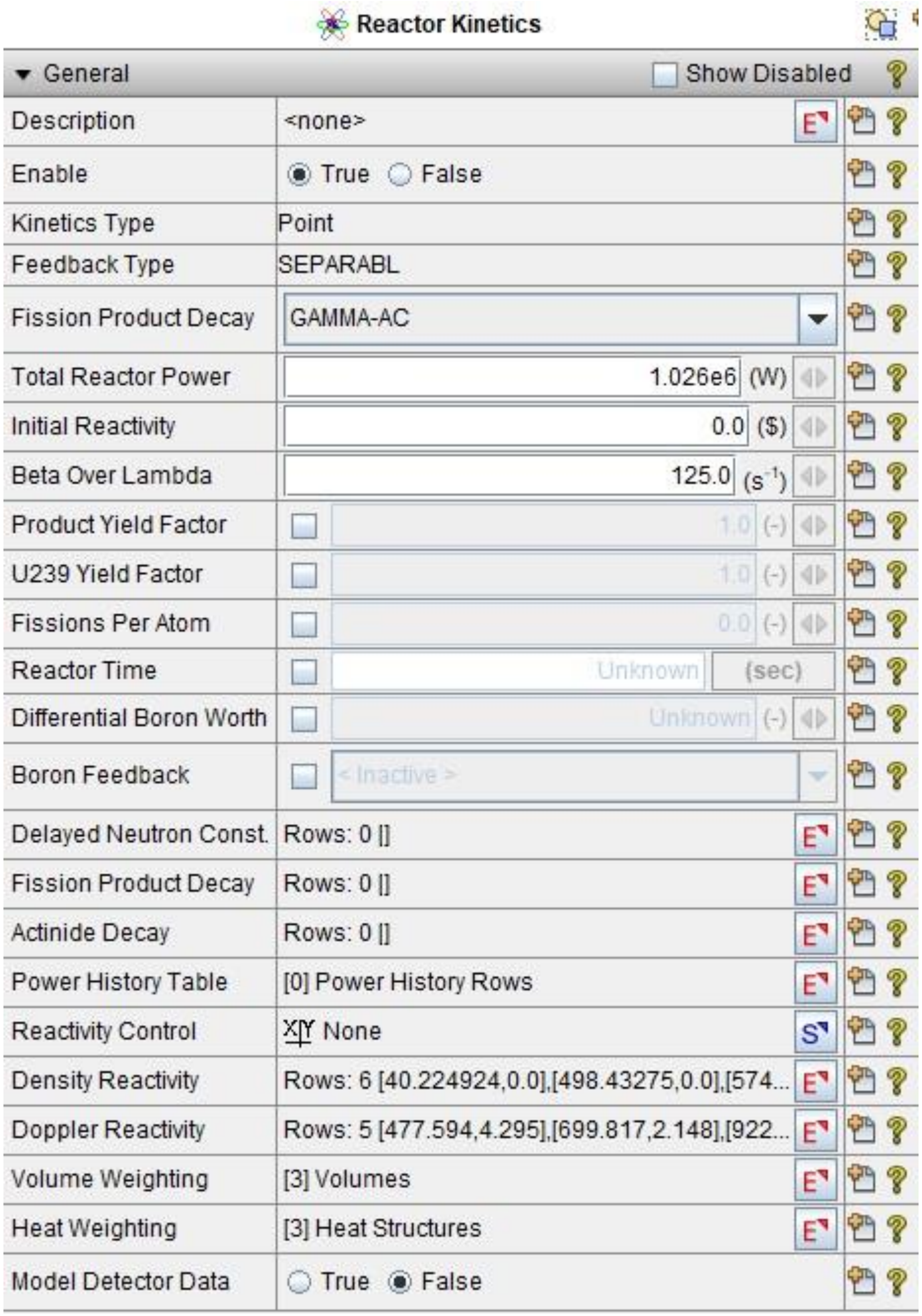


Figure 2-5 Decay Heat Setting Schematic Diagram

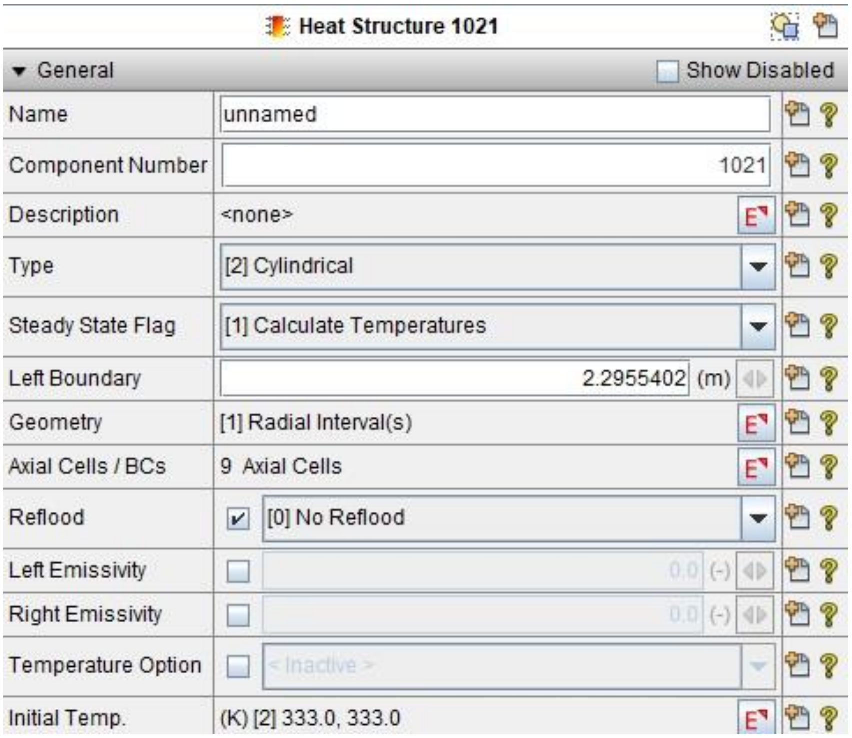


Figure 2-6 Heat Structure Without Reflood

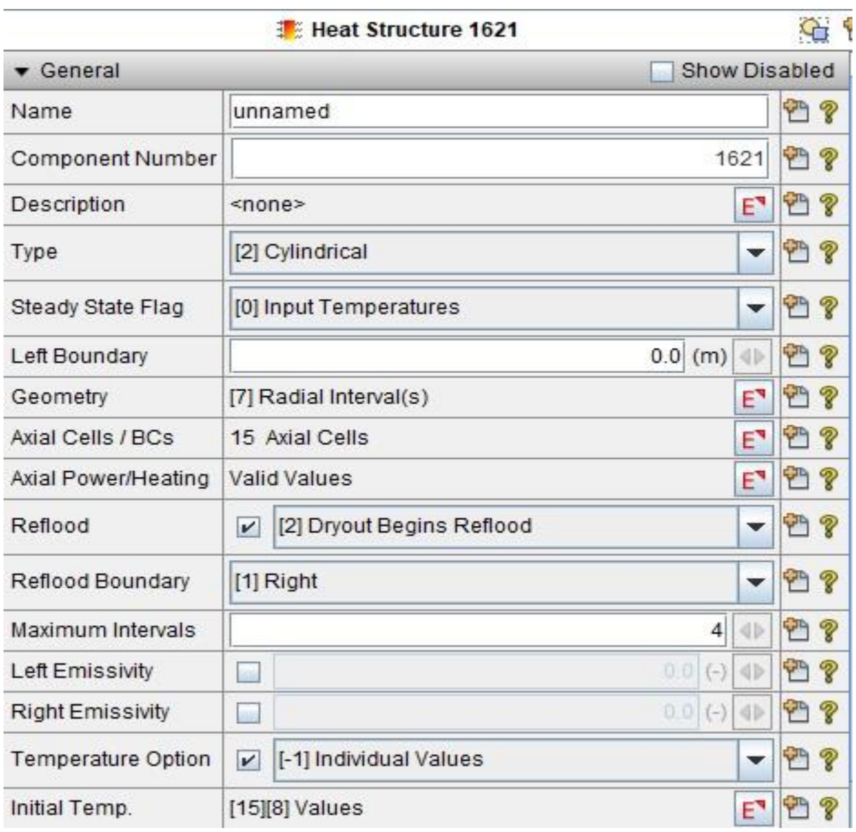


Figure 2-7 Heat Structure with Reflood

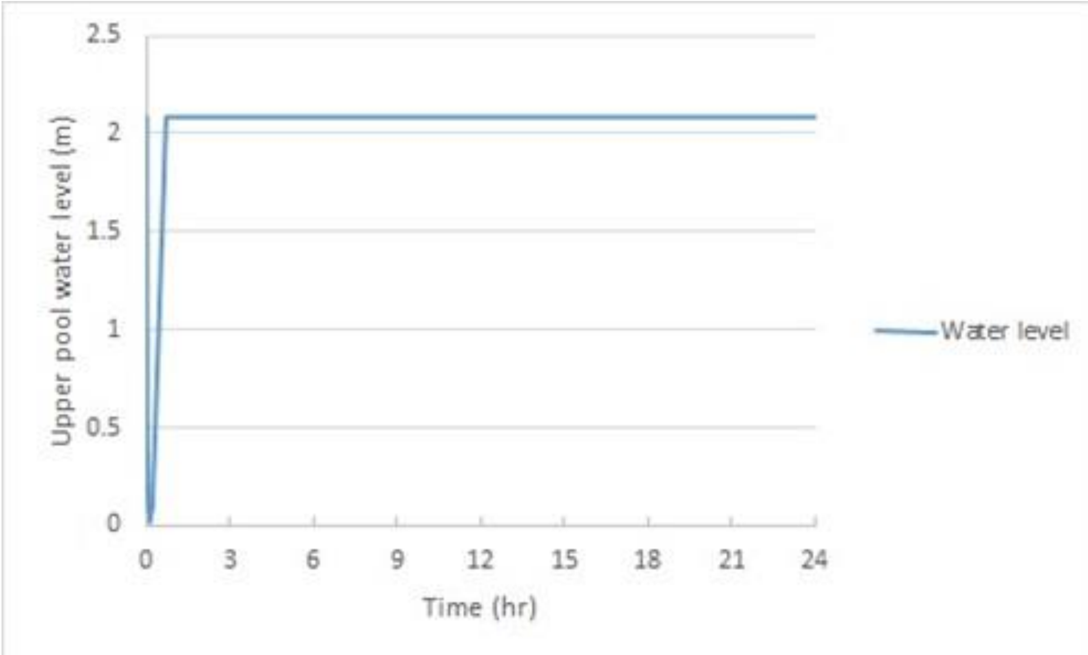


Figure 2-8 The Result of Decay Heat Power

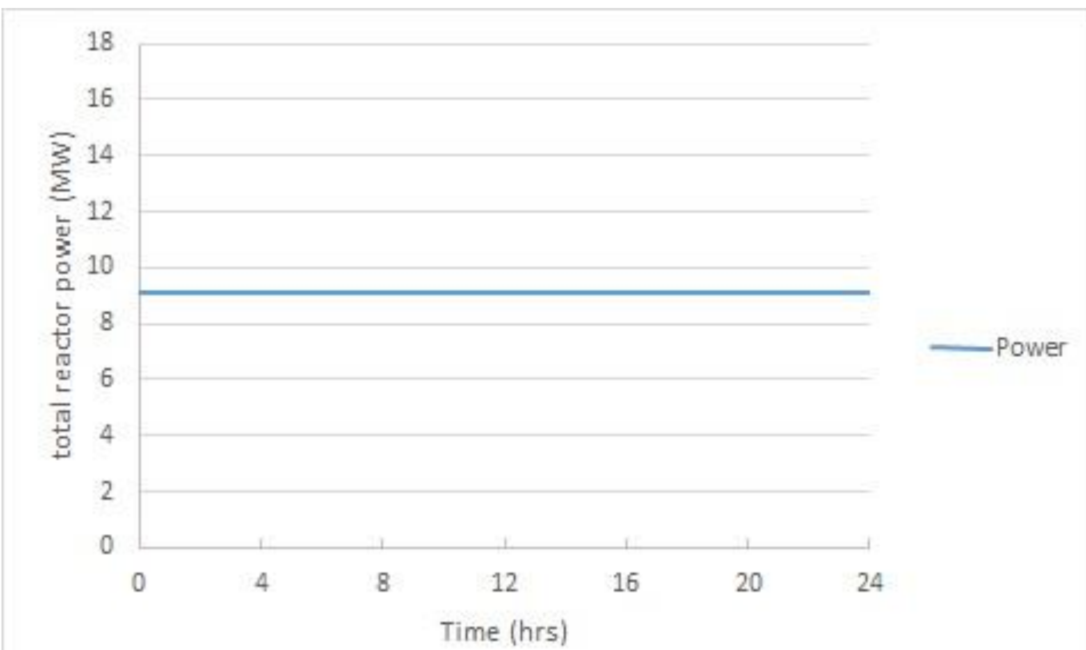


Figure 2-9 The TSS Result of Upper Pool Water Level

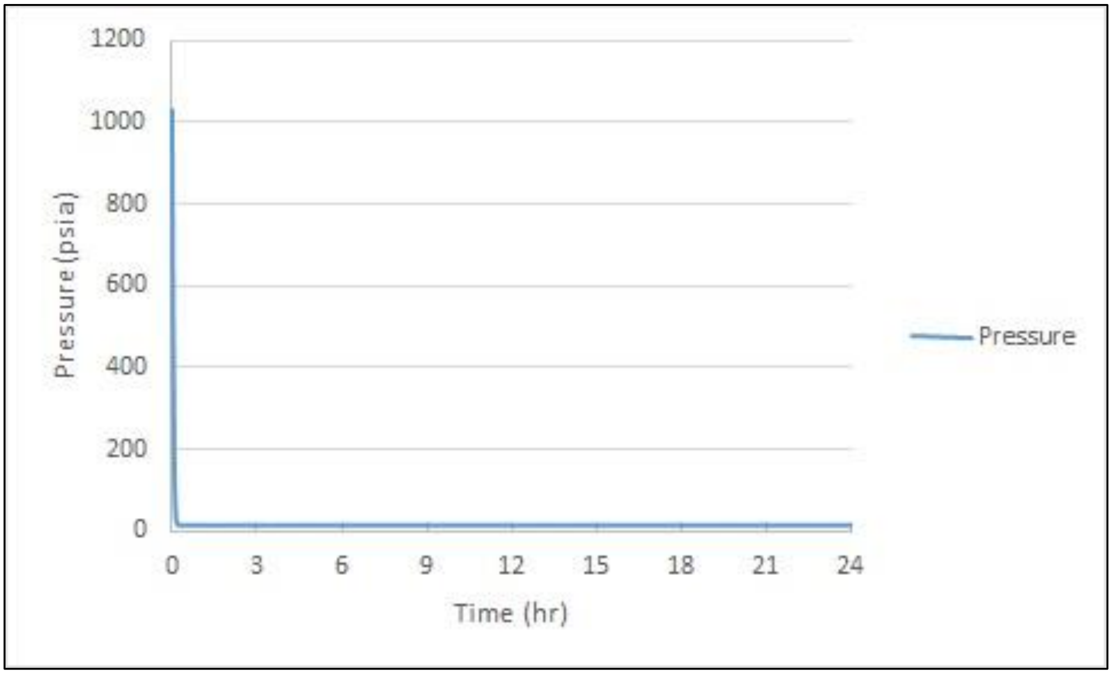


Figure 2-10 The TSS Result of Exit Pressure

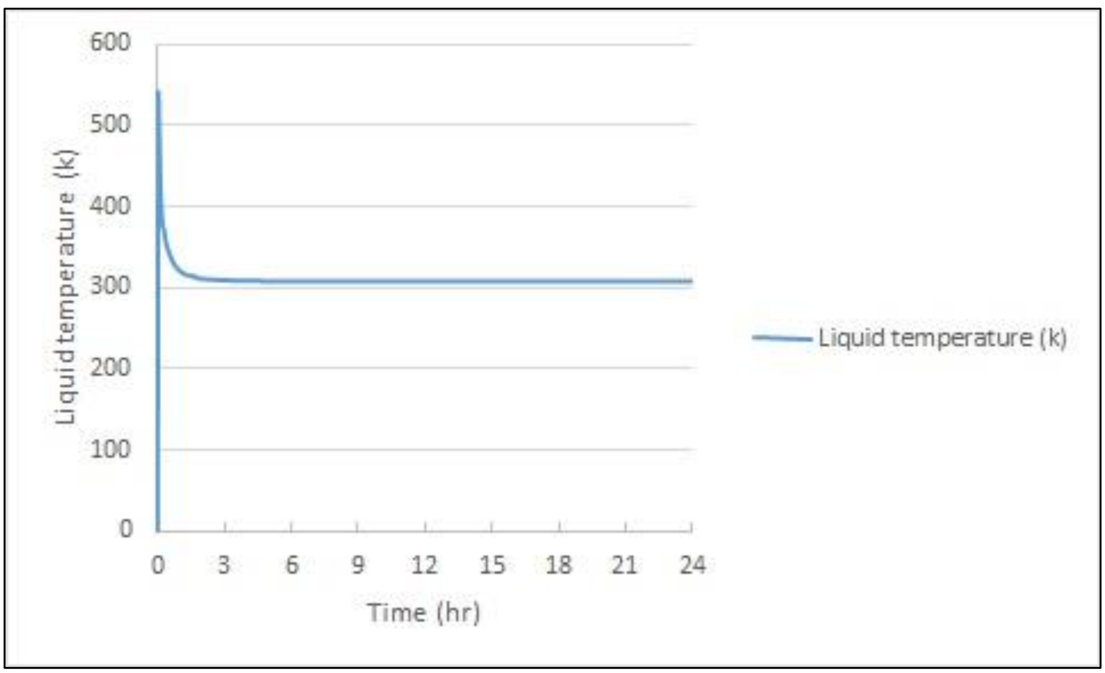


Figure 2-11 The TSS Result of Average Liquid Temperature

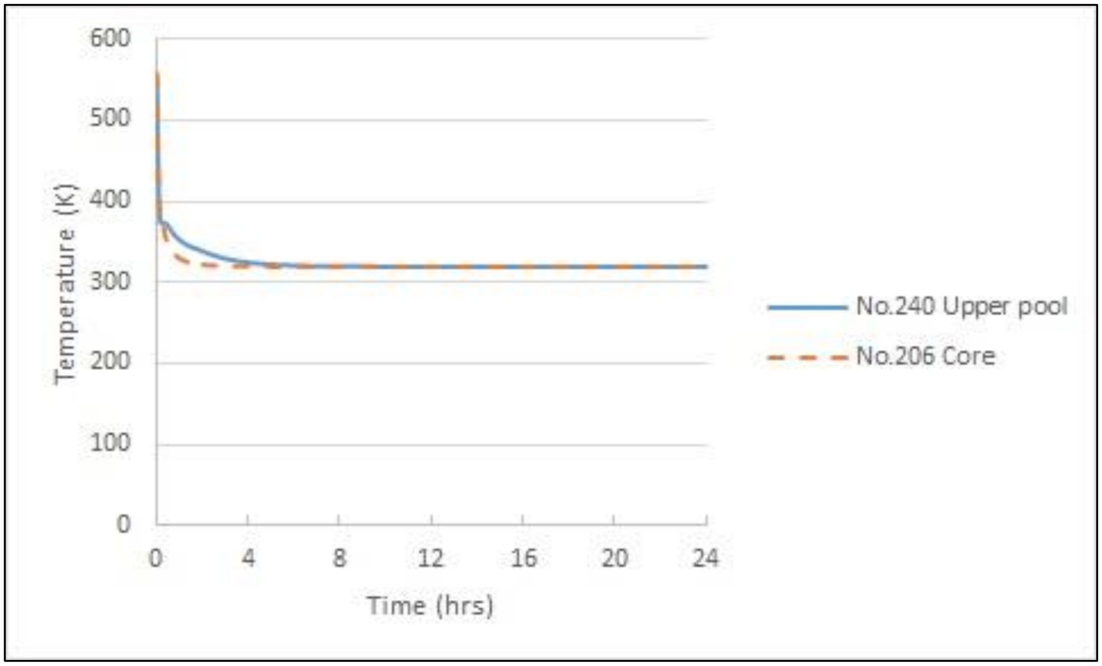


Figure 2-12 The TSS Result of Liquid Temperature Compare Upper Pool and Reactor Core

Table 2-1 Sequence of Events in Kuoshang Decommissioning SBO

Events	Time (sec)
0	Start injection, Release valve open
2,000	RCP trip
86,400	Stop injection
5,616,000 (65 day)	End of time

Table 2-2 The Steady State Results Between 100 Sec To 2200 Sec

Decay heat (MWt)	SNAP/RELAP5 transient 100 sec (Psi / K)	SNAP/RELAP5 transient 2200 sec Upper pool full (Psi / K)
9.1141	14.69/531	18.72/355
5.0586	14.69/530	18.66/353
3.5043	14.69/530	18.77/354
2.8115	14.69/530	18.84/354
1.8215	14.69/530	18.84/354
1.026	14.69/531	18.76/353

3 THE ANALYSIS RESULTS OF THE BASE CASES

3.1 Description of Energy Conservation Formula

The focus of this chapter is on temperature variations. Data comparison will involve applying thermal flux formulas to relevant data for validation reference. The data source is a report published by the Electric Power Research Institute (EPRI) in 2012 [8]. Using the principle of energy conservation, temperature variations after the loss of cooling in the spent fuel pools of the Fukushima Daiichi Nuclear Power Plant will be estimated, and these estimations will be compared with results obtained from the TRACE program.

$$Pt = V\rho s(100 - T_{init})$$

$$t = \frac{V\rho s(100-T_{init})}{P}$$

1. Using 100-T_{init} to represent the difference between the initial water temperature and the saturation temperature.
2. P represents the decay heat power of spent nuclear fuel, measured in kW/s.
3. t represents the time required to reach the saturation temperature, measured in seconds.
4. V represents the volume of cooling water that can be accommodated, measured in cubic meters; ρ represents the density of cooling water, measured in kg/m³.
5. $Tinit$ represents the initial cooling water temperature, measured in degrees Celsius.
6. S for unit conversion: 10 cubed.

3.2 The Results and Discussion

Before the Station Blackout (SBO) condition occurs, all important parameters have reached stable equilibrium conditions, including upper pool void fraction, outlet pressure, liquid temperature, and flow variations at the inlet and outlet ends.

To compare and validate with thermal flux formula calculations and TRACE program, Kuosheng decommissioning RELAP5 model scenario is established with the initial water temperature set at 60°C (139.73°F / 333K), slightly conservative compared to actual on-site conditions. The simulation results from SNAP/RELAP5 indicate that under 7 days of decay heat, saturation temperature is reached after 8.16 hours post-SBO. Similarly, for 30 days, it takes 15.02 hours, for 60 days, 21.83 hours, for 90 days, 27.33 hours, for 180 days, 42.44 hours, and for 365 days, 75.77 hours.

From the comparison results Table 3-1, it is evident that in SNAP/RELAP5's open pool mode, the time taken for the overall pool water temperature to reach saturation temperature of 100°C from the initial 60°C is generally delayed across various decay heat calculations [9]. The data differences for decay heat ranging from 7 days to 180 days remain within an acceptable range. However, as the decay heat decreases to its lowest value of 1.026 MWt at 365 days, a considerable discrepancy emerges, this is due to the imperfect connection between the reactor core top and the upper pool. In the RELAP5 model, the upper pool structure is simplified, represented only by a single BRANCH component instead of accurately reflecting the actual situation.

Table 3-1 Table of Time to Reach Saturation Temperature

After reactor shut down （d）	Decay heat （MW）	Formula (h)	TRACE (h)	RELAP5 (h)
7	9.1141	7.8	7.57	8.16
30	5.0586	14.06	14.09	15.02
60	3.5043	20.29	20.21	21.83
90	2.8115	25.3	25.06	27.33
180	1.8215	39.04	37.99	42.44
365	1.026	69.32	64.48	75.77

4 THE ANALYSIS RESULTS OF THE CASES

Considering the differences in the results of the core hot water flow discussed in previous chapters and the possibility that the horizontal partitioning of the upper pool may not adequately assess the horizontal flow; the model is further refined. The first step is to adjust the components surrounding the original steam-water separator, merging them and modifying the flow rates. The second step involves further dividing the upper pool longitudinally into three regions and horizontally into five layers, using SNGLJUN connections to allow flow between the partitions, as referenced in Figure 4-1 and Figure 4-2.

Table 4-1, where the data source is the heat supplied within time t equaling the heat required to raise a fixed volume of water to the saturation temperature, the formula can be derived as follows:

$$Wt \times 3600 \times 0.23884 = V \times \rho \times 10^3 \times 1 \times (100-T)$$

Given that 1J = 0.23884 cal, the density of water at 30℃ is 995.65 Kg/m³, and setting the pool water volume to 1128.5 m³, with an input of 1year decay heat of 0.7867 MW, it can be calculated that water level takes approximately 36.04 days to reach the upper pool dry out, and takes 44.83 days to TAF.

The temperature changes in each layer also follow the expected trend without any abnormal conditions. Level 5, being connected to the outside, almost always maintains a temperature close to saturation, while the temperatures of Level 4 and other layers slightly exceed saturation due to receiving more heat transfer from the reactor core. This can be observed in Figure 4-3, Figures 4-4, and Figures 4-5 depict the cumulative changes in outlet pressure and outlet flow rate. The pressure data is extracted from the pipe component (card number 541) just before the boundary conditions. From the resulting curves, it can be observed that the pressure values fluctuate between 14.699 to 14.701 psia. Although there are some minor fluctuations later on (up to around 15 psia), a closer examination of the data shows that these occur just before the water level approaches the TAF. The final water level decrease, as shown in Figure 4-6, exhibits a smoother decline after refinement, without the abrupt drops seen previously. However, there is little difference in the overall trend, with only a slight delay in the changes.

Table 4-2 using the decay heat simulation computation based on the corresponding RG3.54 version after one year of shutdown at the Kuosheng NPP as an example, regarding the water level changes: in the event of an SBO scenario, the overall water temperature is expected to reach saturation around 164.88 hours (approximately 6.87 days), the entire upper pool is projected to be completely dried out after approximately 867.6 hours (around 36.15 days), and the TAF position is estimated to be reached at 1,075 hours (approximately 44.83 days). Before reaching saturation temperature, the longitudinal and transverse flow rate data between the upper pool waters show positive values, indicating that the flow direction is consistent with the direction set by the junction. It means that the flow is moving from left to right. As the fluid decreases, the overall fluctuation amplitude also decreases, see Figure 4-7.

After removing the oscillation peak values, the longitudinal flow rate data all show negative values. This is because the initial flow direction set in the model is upward, indicating that the fluid is flowing downward in the reverse direction.

An important feature utilized in this study is the animation mode of the SNAP program, which is a significant characteristic of SNAP. It transforms traditional numerical results into more vivid visuals, incorporating various symbols, color changes, and other techniques to vividly present the simulation process under the open-cover mode. This aids readers in quickly understanding our research project and its outcomes. Figure 4-8 demonstrates the progression of an SBO scenario over 3 years of decay heat shutdown using the SNAP animation feature.

Table 4-1 Table of Kuoshang Decommissioning SBO Decay Heat Power

After Reactor shutdown (y)	Decay Heat (MW)	SNAP/RELAP5 Total Reactor Power (MW)
1	0.7867	7.867e5
2	0.6464	6.44e5
3	0.5763	5.81e5

Table 4-2 Table of Kuoshang Decommissioning SBO Results

Event	After Reactor Shutdown (y)	Decay Heat (MW)	Formula (d)	RELAP5 (d)	Difference %
Upper pool dry out	1	0.7867	36.04	36.15	-0.3
	2	0.6464	43.83	43.21	1.41
	3	0.5763	49.20	47.95	2.54
Water level drop to TAF	1	0.7867	44.83	44.83	0
	2	0.6464	54.54	53.59	1.74
	3	0.5763	61.24	60.73	0.83

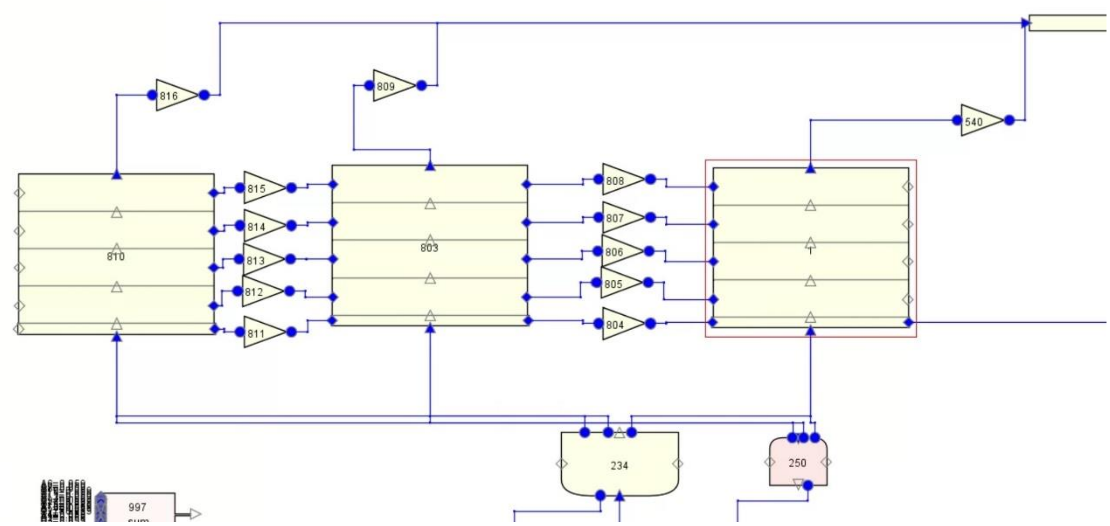


Figure 4-1 Upper Pool Vertical Splitting

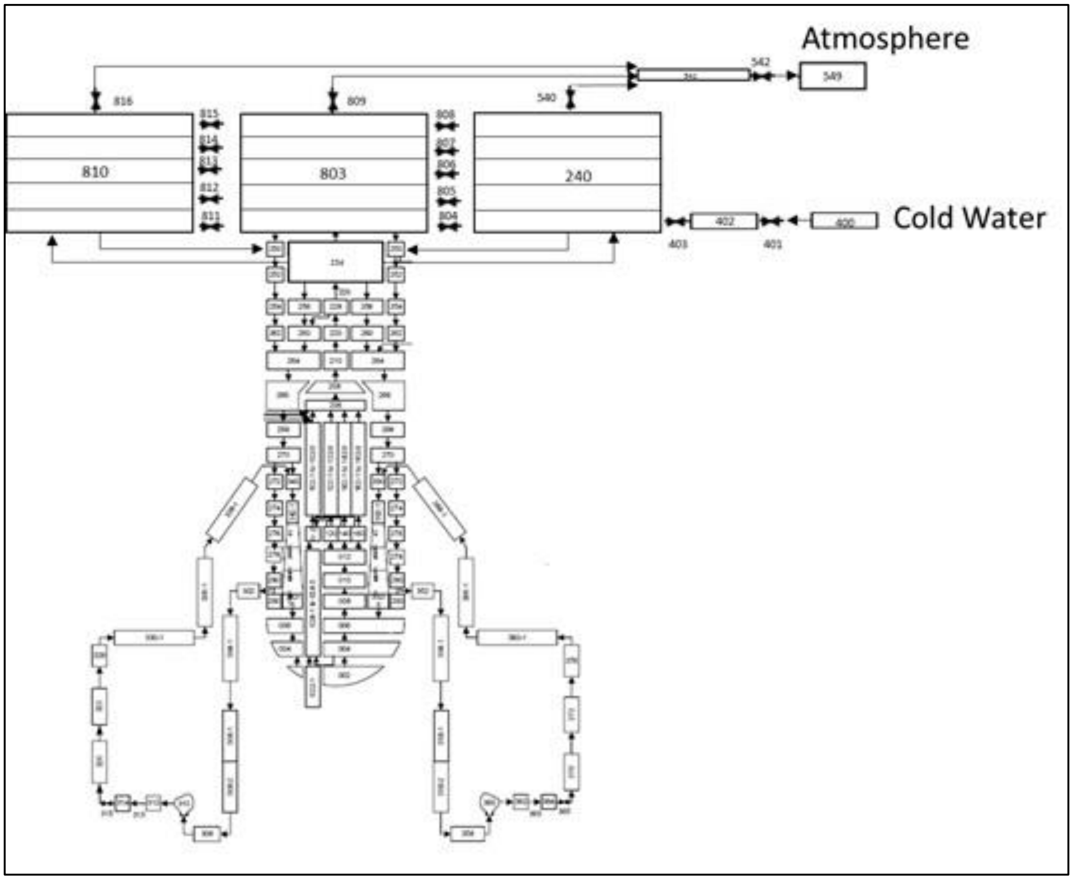


Figure 4-2 New Kuosheng Decommissioning Model Node Graph

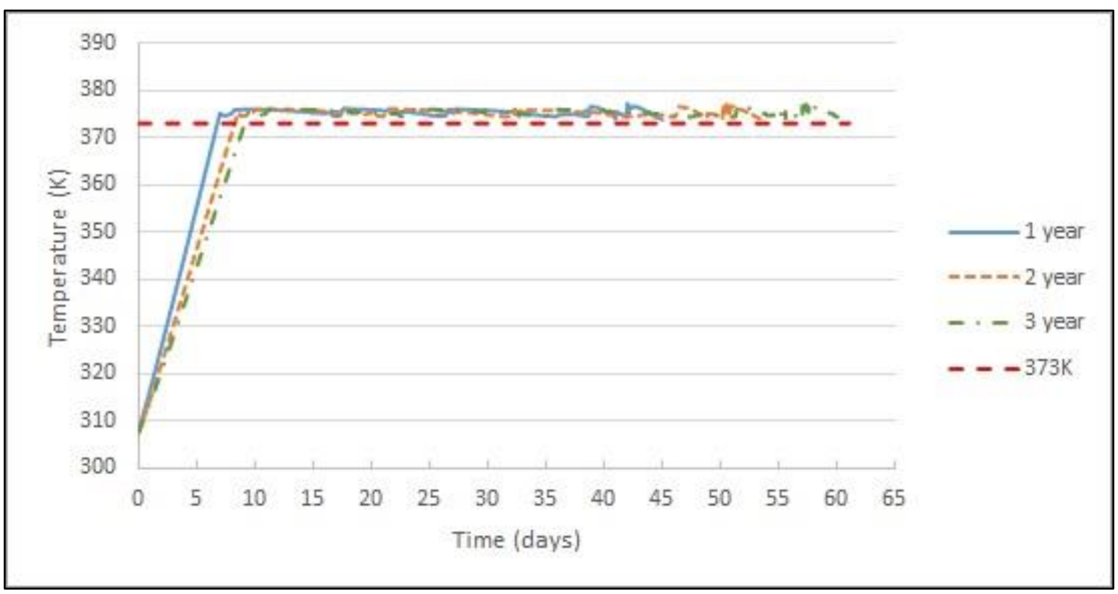


Figure 4-3 RG3.54 Temperature

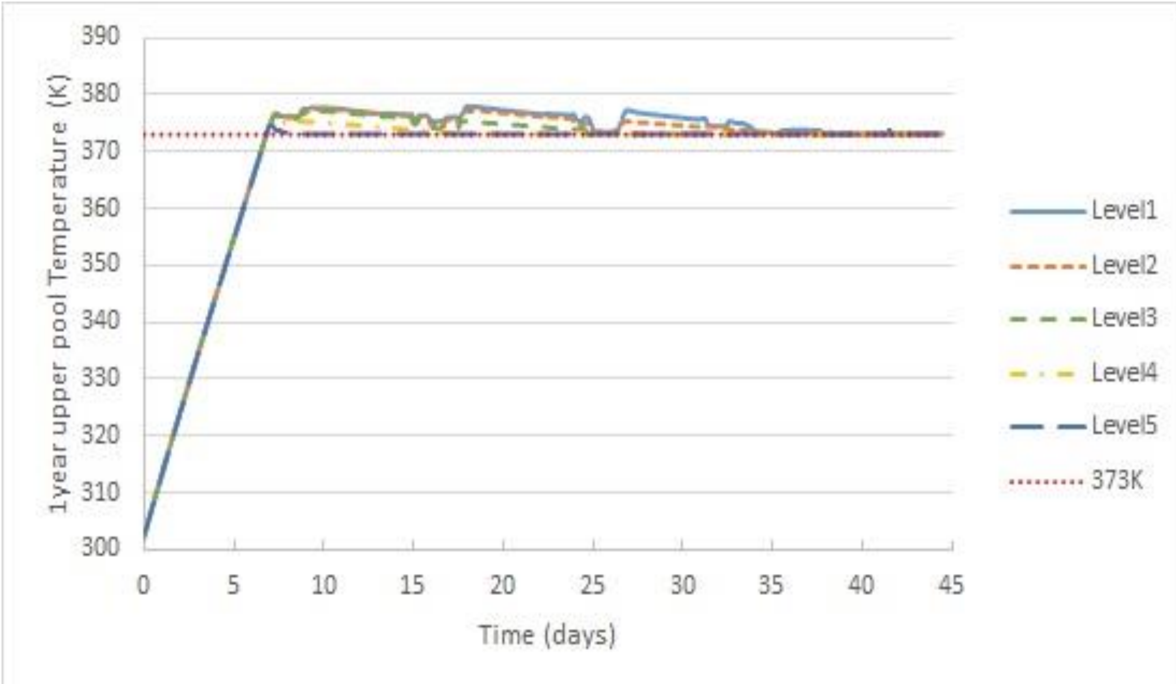


Figure 4-4 RG3.54 Upper Pool Temperature (1 year)

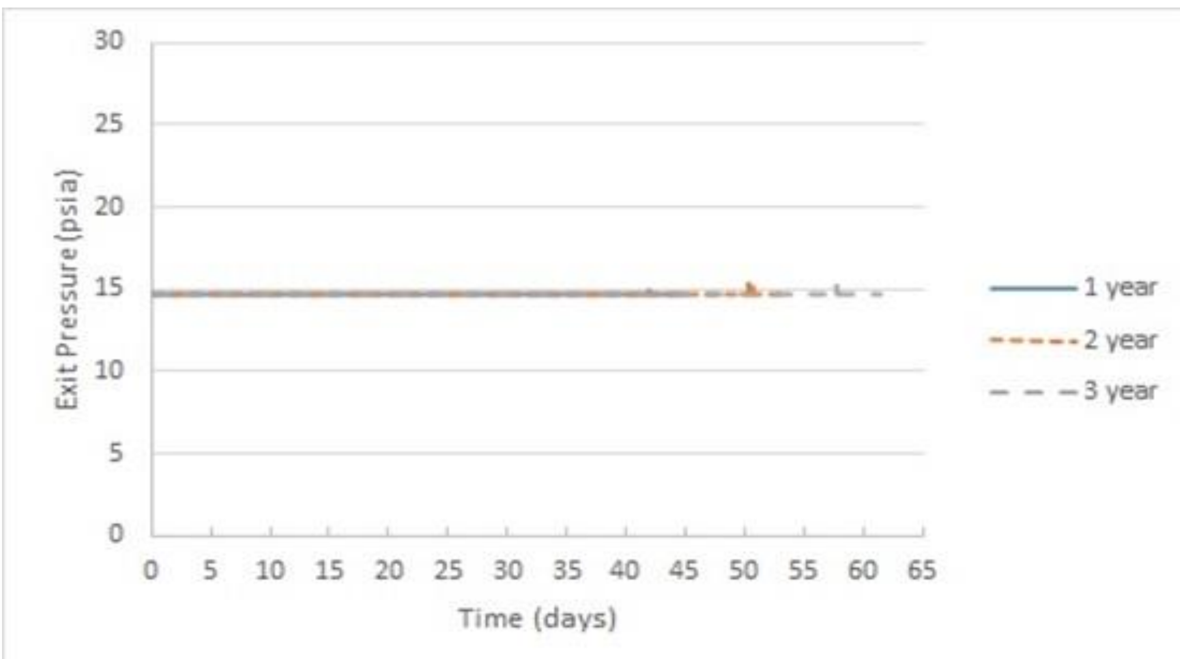


Figure 4-5 RG3.54 Exit Pressure

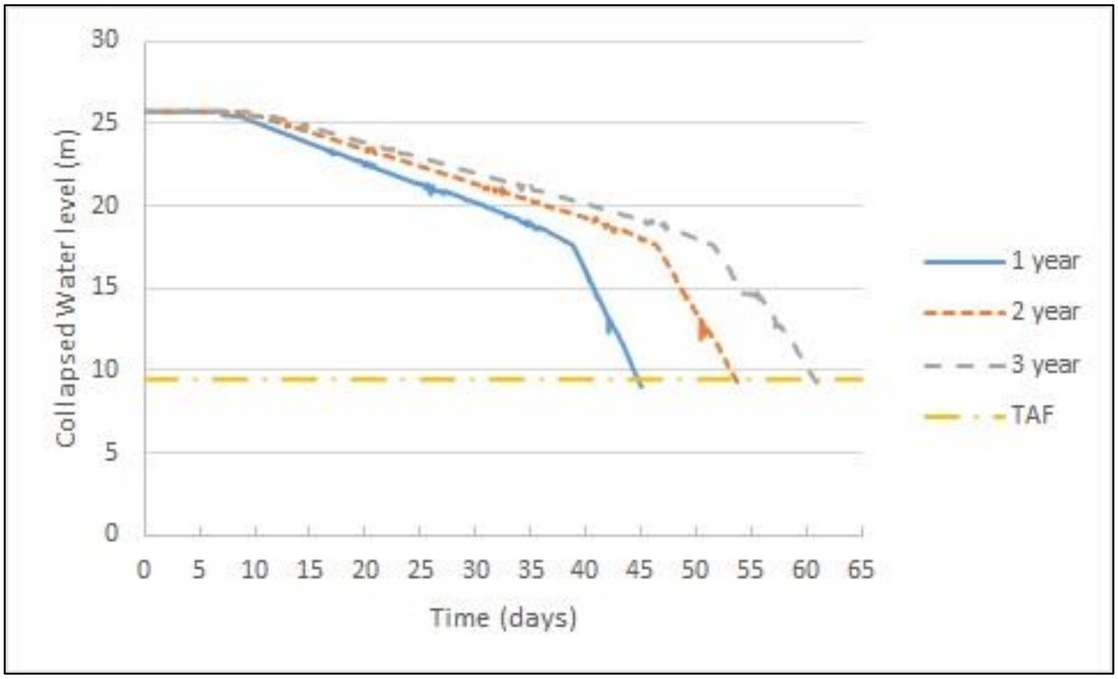


Figure 4-6 RG3.54 Total Water Level

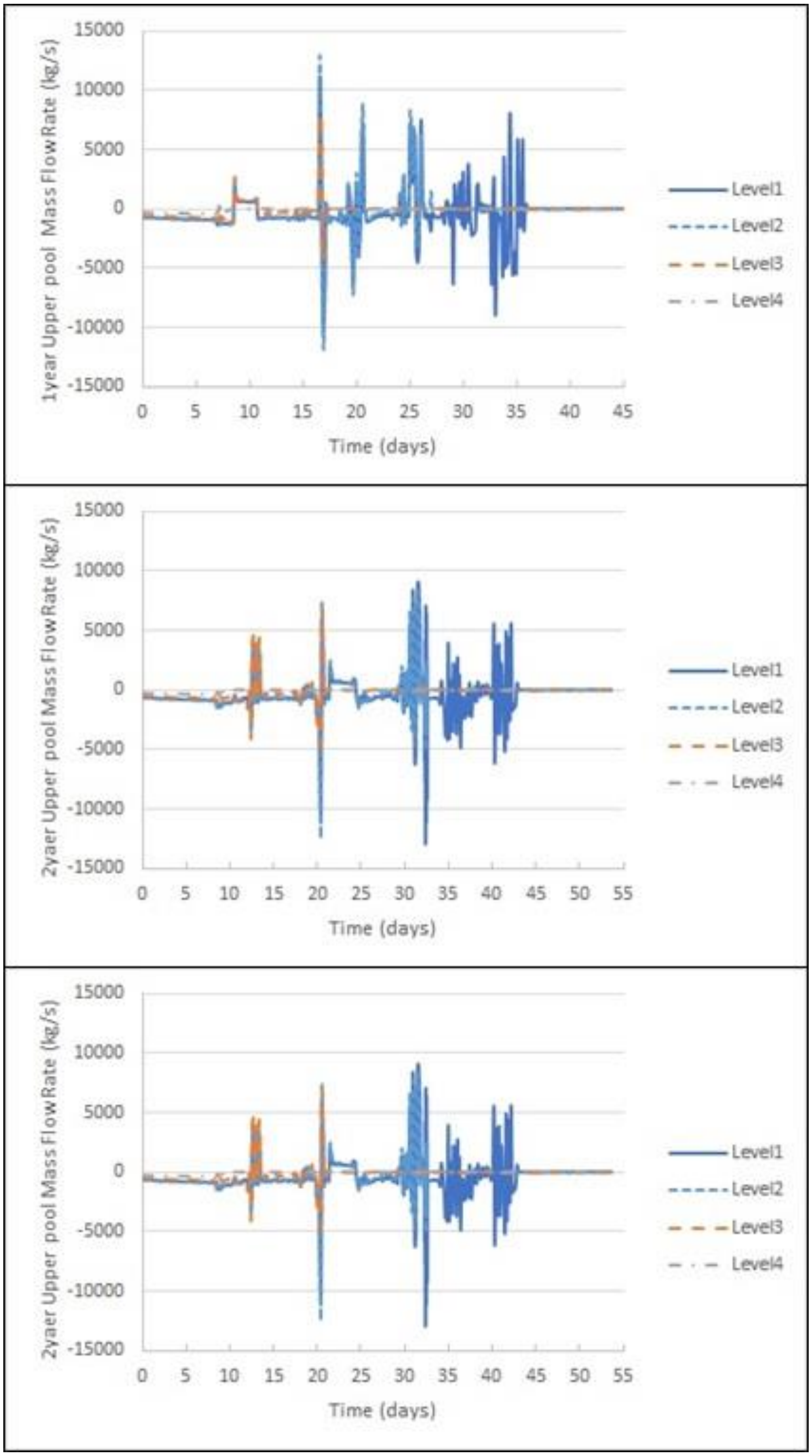


Figure 4-7 Upper Pool Vertical Mass Flow

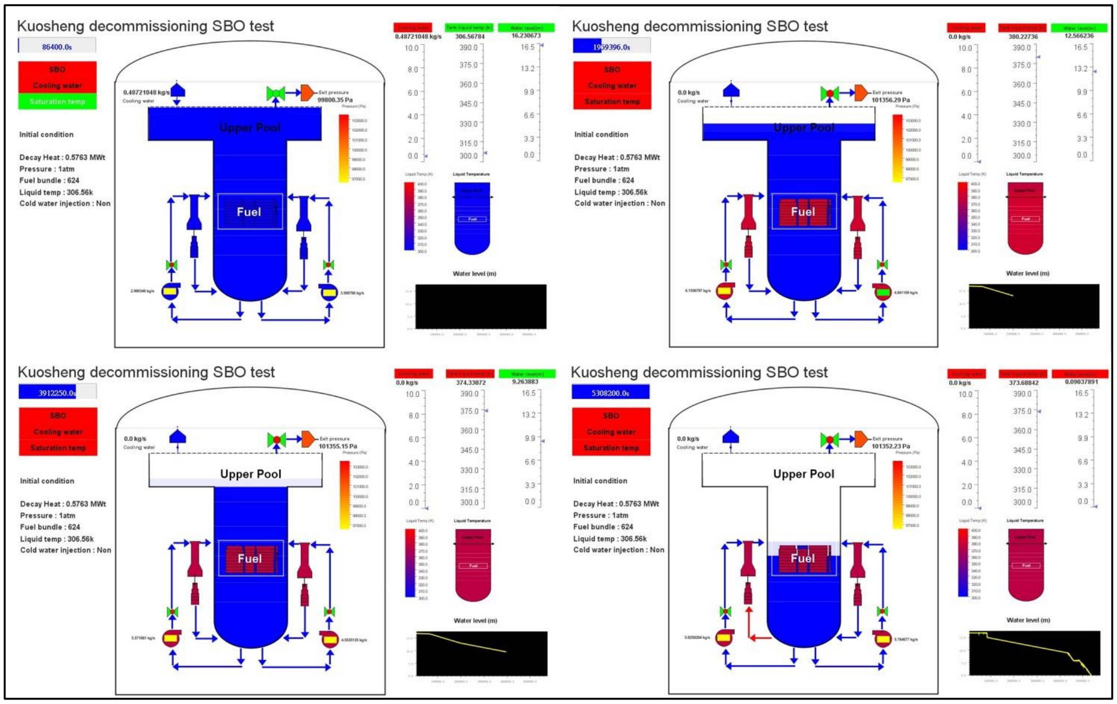


Figure 4-8 SNAP/RELAP5 Kuosheng Decommissioning SBO Animation

5 CONCLUSION

This study successfully established the RELAP5/MOD3.3 coupled graphical interface program SNAP for the Kuosheng NPP decommissioning mode. It incorporated decay heat input parameters from the decommissioning plan report and verified the ability of this model to simulate the basic actions of uncovering SBO by comparing heat flux formulas with relevant cases from previous TRACE versions.

Cutting the upper pool structure longitudinally is beneficial for thermal flow circulation, allowing for a more uniform transfer of heat energy, whether during upper pool boiling or TAF arrival time, this study also attempted to add more layers for upper pool, but it did not significantly affect the results.

Using the corresponding RG3.54 version decay heat simulation calculation based on the current shutdown days of the Kuosheng NPP, from the perspective of water level changes, in the event of an SBO one year after shutdown, it is observed that approximately 164.88 hours (approximately 6.87 days) are required for the overall water temperature to reach saturation temperature. Additionally, approximately 867.6 hours (approximately 36.15 days) are needed for the upper pool's overall pool water to evaporate, and the time to reach the TAF position is approximately 1,075 hours (approximately 44.83 days).

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10. SUPPLEMENTARY NOTES

K. Tien, NRC Project Manager

11. ABSTRACT (200 words or less)

The Taiwan Power Company and the Nuclear Safety Commission (formerly the Atomic Energy Commission) of our country have, since 2004, engaged in research projects under the Taiwan-U.S. Civil Nuclear Regulatory Cooperation Agreement, signed with the U.S. Nuclear Regulatory Commission (U.S. NRC) through the representative office in the United States. The collaboration involves the Code Application and Maintenance Program (CAMP), focusing on the application and maintenance of thermal-hydraulic codes (RELAP5 and TRACE) for nuclear power plants. The technical research outcomes are published in the NUREG/IA series reports. The CAMP internati-nal collaboration initiative was initiated by the U.S. Nuclear Regulatory Commission to ensure the safe operation of nuclear power plants promote international information exchange, cooperation, and experience feedback in the nuclear field. In addition to ongoing experiments and simulation program development related to safety, active efforts are made to seek international experiences and feedback. Therefore, it is essential for our country to continue participating in the CAMP cooperation agreement, contributing research analysis and assessment results through international collaborative projects, and publishing NUREG reports for information and experience exchange with international organizations. Aligned with the national national energy policy, this project will be responsible for analyzing the decommissioning planning and operational safety of Taiwan Power Company's nuclear power plants. Over the four-year project period, analysis will be conducted using the SNAP/RELAP5 program. The current project aims to establish a model for the decommissioning transitional phase of Kuosheng Nuclear Power Plant using SNAP/RELAP5, supplemented by heat formula calculations and TRACE analysis for validation and comparison [1]. This effort will assist Taiwan Power Company in conducting assessments related to the decommissioning transitional phase of Kuosheng NPP and other associated tasks.

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BWR, Boiling Water Reactor, SBO, station blackout, TAF, Top Active Fuel, NPP Decommission, Reactor Cavity, Spent Fuel Pool, Loss Cooling Water

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