EXTENDED LOSS OF AC POWER (ELAP) ANALYSIS OF KUOSHENG BWR/6 USING MELCOR2.1/SNAP

Yu Chiang[1], Yu-Ting Ku[1], Jong-Rong Wang[2], Shao-Wen Chen[1], Wen-Sheng Hsu[3], Sheng-Shun Wang[4], Jing Chang[1], Chunkuan Shih[2]

[1] *Institute of Nuclear Engineering and Science, National Tsing Hua University, Hsinchu, Taiwan*
[2] *Nuclear and New Energy Education and Research Foundation, Hsinchu, Taiwan*
[3] *Nuclear Science and Technology Development Center, National Tsing Hua University, Hsinchu, Taiwan*
[4] *Atomic Energy Council, New Taipei City, Taiwan*
E-mail: s101013702@m101.nthu.edu.tw

After Fukushima event, researchers did lots of safety analysis and procedure improvement of the nuclear power plants (NPPs) in Taiwan. The procedures such as emergency operating procedures (EOPs) cannot cope with the multiple failures like ELAP accident. Some methods for such accidents were developed, such as Ultimate Response Guideline (URG) and FLEX. In this study, the phenomena of ELAP accident in Kuosheng NPP were calculated by MELCOR2.1/SNAP. By this calculations, the phenomena in ELAP accident can be shown and help the development of emergency procedures for multiple failures accidents.

In this research, the latest version MELCOR2.1 was used and combined with Symbolic Nuclear Analysis Package (SNAP). In this combination, MELCOR was used with a graphical user interface (GUI) that users can easily modify any detail of the model. It can also show the detail results and phenomena through an animation model. There were four main steps in this research. First, the MELCOR model of Kuosheng NPP was built. The steady-state results of this model were compared to TRACE and the Kuosheng NPP data. Second, a case of ELAP was calculated by MELCOR2.1/SNAP. In this case, RCIC was set to be failed for a more conservative result. The results before core damage were compared to the thermal-hydraulic code, TRACE. TRACE is a code developed by U.S.NRC and lots of benchmark was already done for thermal-hydraulic calculations before. The thermal-hydraulic calculations for the severe accident codes such as MELCOR were always been questioned. So in this research, the thermal-hydraulic calculations before core damage were compared to TRACE for checking the MELCOR model of Kuosheng was good for use. Third, the MELCOR results after core damage were discussed in detail, such as hydrogen explosion, containment overpressure, debris relocation, radionuclides movement, etc. Finally, some sensitivity studies such as containment spray were done by MELCOR.

In this study, the MELCOR2.1 results were consist with the TRACE results at the important thermal-hydraulic parameters such as water level, Reactor Pressure Vessel (RPV) pressure, cladding temperature. The MELCOR calculations showed that in the ELAP case of Kuosheng NPP, the water level dropped to top of active fuel (TAF) at 28.5 min. The cladding temperature rose to 1088K at 57.5 min. The fuel cladding started candling at 72.8 min. Several hydrogen burns happened inside the containment starting at 75 min.

This study showed the important phenomena during an ELAP accident of Kuosheng NPP. The results can help NPP safety analysis and emergency procedure improvement in a beyond design basis accident.

I. INTRODUCTION

After Fukushima event, researchers did lots of safety analysis and procedure improvement of the nuclear power plants (NPPs) in Taiwan. The procedures such as emergency operating procedures (EOPs) cannot cope with the multiple failures like ELAP accident. Some methods for such accidents were developed, such as Ultimate Response Guideline (URG) and FLEX. In this study, the phenomena of ELAP accident in Kuosheng NPP were calculated by MELCOR2.1/SNAP. By this calculations, the phenomena in ELAP can be shown and help the development of emergency procedures for multiple failures accidents.

MELCOR is a fully integrated, engineering-level computer code that models the progression of severe accidents in light-water reactor nuclear power plants. MELCOR is being developed at Sandia National Laboratories for the U.S. Nuclear Regulatory Commission as a second-generation plant risk assessment tool and the successor to the Source Term Code package. A broad spectrum of severe accident phenomena in both boiling and pressurized water reactors is treated in MELCOR in a unified framework. These include thermal-hydraulic response in the reactor coolant system, reactor cavity, containment, and confinement buildings; core heatup, degradation, and relocation; core-concrete attack; hydrogen production, transport, and combustion; fission product release and transport behavior (Ref. 1).

In this study, MELCOR2.1 combined to a program called Symbolic Nuclear Analysis Package (SNAP). The model modification of SNAP interface will be easier than the old ASCII file. Figure 1 shows a part of the MELCOR 2.1/SNAP user interface of input file.

There were four main steps in this research. First, the MELCOR model of Kuosheng NPP was built. The steady-state results of this model were compared to TRACE and the Kuosheng NPP data. Second, a case of ELAP was calculated by MELCOR2.1/SNAP. In this case, the RCIC was set to be failed for a more conservative result. Although RCIC is the most important water source in the case like ELAP, this study set RCIC to be failed to make the situation more severe. The RCIC sensitivity study will be concern in the future to complete the ELAP calculations. The results before core damage were compared to the thermal-hydraulic code, TRACE. The thermal-hydraulic calculations for the severe accident codes such as MELCOR were always been questioned. So in this research, the thermal-hydraulic calculations before core damage were compared to TRACE for checking the MELCOR model of Kuosheng was good for use. Third, the MELCOR results after core damage were discussed in detail, such as hydrogen explosion, containment overpressure, debris relocation, radionuclides movement, etc. Finally, a sensitivity study of containment spray was done by MELCOR. Figure 2 shows the TRACE model of Kuosheng NPP (Ref. 2).

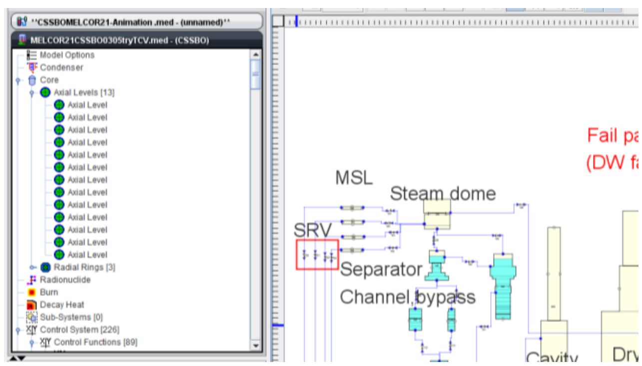

Fig. 1. Interface of MELCOR2.1/SNAP

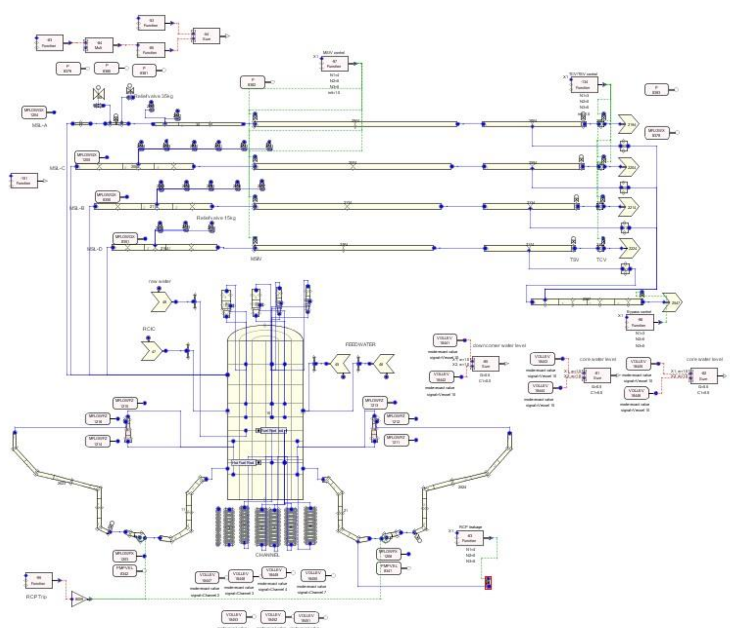

Fig. 2. TRACE model of Kuosheng NPP

II. MODEL DESCRIPTIONS

The code versions used in this research were SNAP2.4.3 and MELCOR2.1. There were several steps for the establishment of Kuosheng NPP MELCOR2.1/SNAP model. Figure 3 is the flow chart of the works in this model. First, the data of the Kuosheng NPP was collected from training materials and FSAR (Ref. 3) (Ref. 4). The geometric values of vessel, containment, etc. were built by MELCOR2.1/SNAP. Second, the control systems and other component were built in, such as Radio-Nuclide (RN), Core (COR), Heat Structure (HS), etc. Third, there was a steady-state test for checking the convergence of this model. Finally, the model was used for the ELAP calculations and the results were compared to the TRACE code.

Figure 4 shows the detail of this MELCR2.1/SNAP model of Kuosheng NPP. The model was separated to several zones: RPV, cavity, drywell, wetwell, upper pool, upper and lower dome for the reactor building. Not like the MK-I containment, the containment type of Kuosheng NPP was MK-III, which was not inert by nitrogen. The hydrogen from the core can burn anywhere in the containment once it reach the ignited concentration. Figure 5 shows the core setting of this model. The operating power of Kuosheng NPP was 2943MWt with 624 fuel assemblies. The core was separated to 4 rings and the 4th ring was for the downcomer region. There were 12 levels in the core for axial separation. The active fuel was located at level 7 to 11 and the power shape was also follow the data in FSAR and training materials (Ref. 3) (Ref. 4).

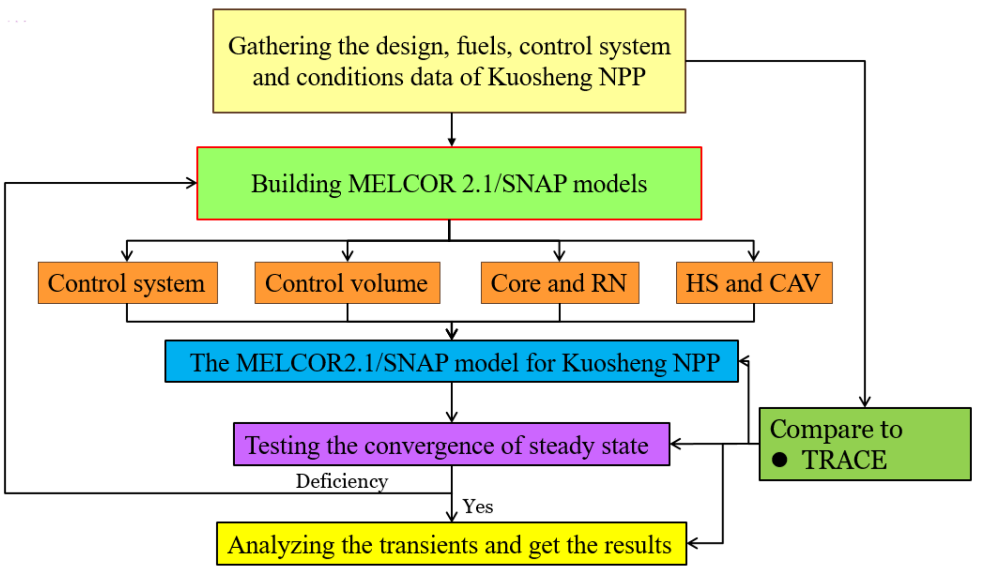

Fig. 3. Flow chart of the model establishment.

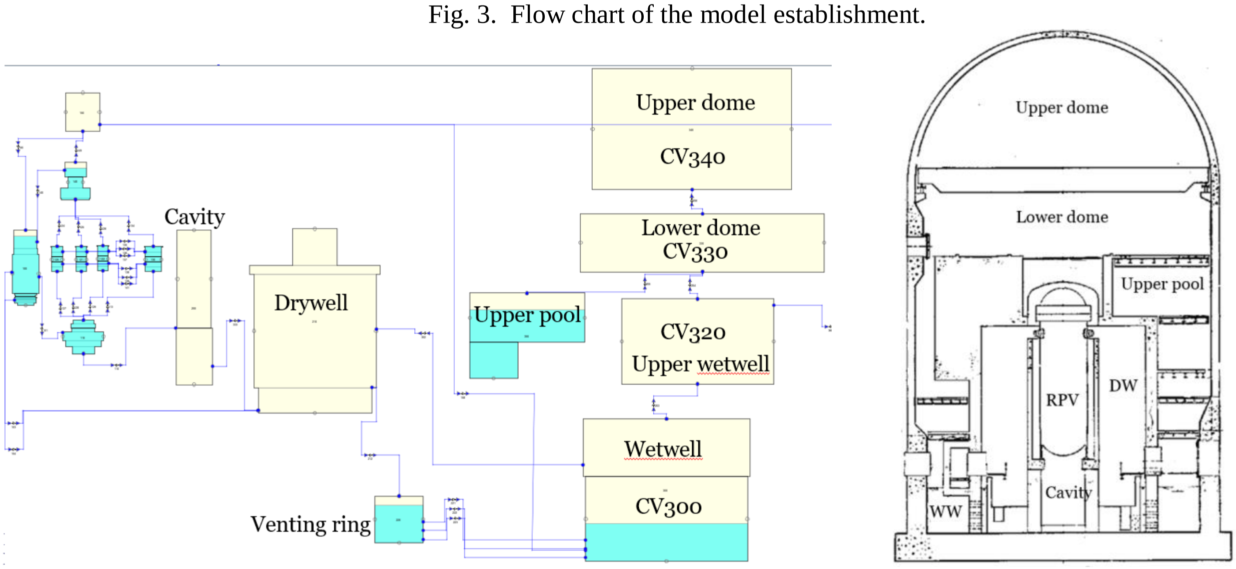

Fig. 4. MELCOR2.1/SNAP model of Kuosheng NPP.

Core cell level		HS
12	Top nozzle	13012
11	Fuel	13011
10	Fuel	13010
9	Fuel	13009
8	Fuel	13008
7	Fuel	13007
6	Core support plate	11006
5	Support materials	11005
4	Bottom of baffle plate	11004
3	Lower plenum	11003
2	Lower plenum	11002
1	Lower plenum	11001

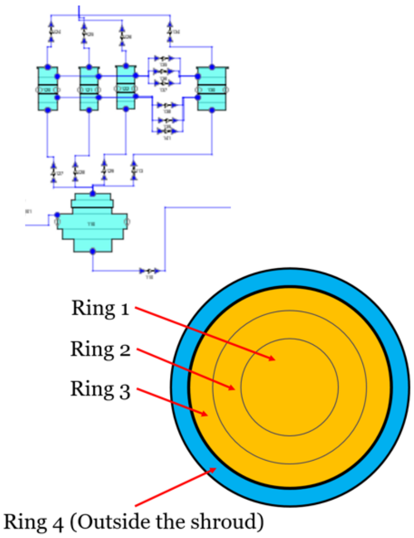

Fig. 5. Detail of the core separation in the MELCOR model.

III. RESULTS

III.A. Steady-state test

The model was set to start the calculations at -300 sec and start the ELAP event at 0 sec. So the time between -300 sec and 0 sec was the steady-state calculation. The results of steady-state calculations are shown in Figure 6 and 7. These two figures show the system pressure and core flow rate control by water level, turbine valve, feed water, etc. Figure 6 shows the system pressure converges to 7170600Pa and the operating system pressure from Kuosheng NPP data was 7170548Pa. The core flow in Figure 7 also converged before 0 sec and the value is 10646kg/s. The data of Kuosheng NPP core flow was 10647kg/s. Both results show that the MELCOR model converged to steady-state before the transient calculation started. The other results such as fuel temperature were also converged before 0 secs, the results were not shown in this paper because there was no operation data for comparison.

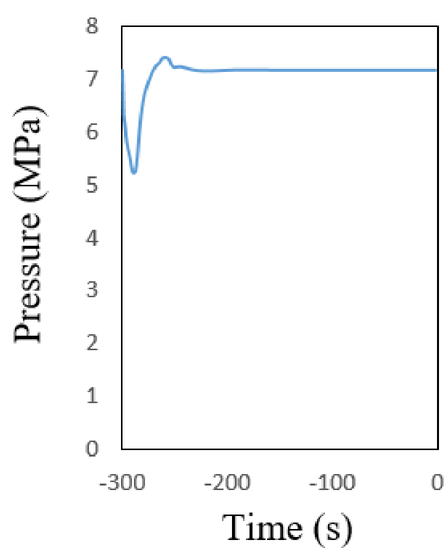

Fig. 6. System pressure of MELCOR model.

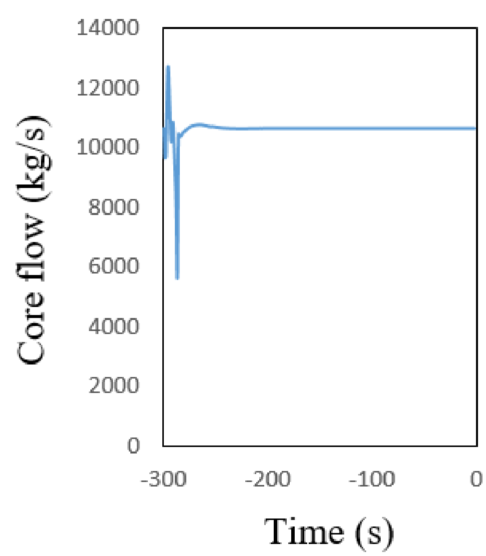

Fig. 7. Core flow rate of MELCOR model.

III.B. ELAP case simulation

The loss of AC power transient started at 0 sec. All the water injection systems including RCIC were set to be failed. The water level went down because of the decay heat and water evaporation. Figure 8 shows the water level results of MELCOR and TRACE. The results of two codes were very close. MELCOR calculated the time to Top of Active Fuel (TAF) was 28.5 minutes. The water level kept going down with SRV cycling. RPV remain at high pressure due to the steam generation (Shown in Figure 9). Figure 10 is the cladding temperature of MELCOR and TRACE. The trend of cladding temperature calculated by MELCOR and TRACE was very close at the heat up time. After the temperature reach 1088K. MELCOR calculated the cladding temperature rose rapidly due to zirconium-water reaction. The TRACE oxidation heat and break away oxidation model were different from MELCOR and gave a result of slower temperature rising. MELCOR calculated that cladding temperature reach 1088K at 57.5 minutes and started generated hydrogen in the core. Hydrogen flowed to wetwell through SRVs and started a burn at wetwell. There were totally 7 burns in wetwell from 75 minutes to 103 minutes. The water level went to Bottom of Active Fuel (BAF) at 79 minutes and the RPV failed at 400 minutes due to the debris in lower plenum. The hydrogen in the core leaked to drywell and cost another burn in wetwell at this time. Figure 11 shows the containment pressure. The drywell and wetwell pressure were very close because of vacuum breaker between them. There are two peaks in Figure 11. The first peak is the pressure rising caused by RPV failure. The second peak is the hydrogen burn in upper dome at 1391 minutes before the calculation ended. Figure 12 and Figure 13 show the gas concentrations in drywell and wetwell. Figure 12 is drywell and the hydrogen concentration went down at 400 minutes because of the steam from the failed RPV. But after the steam flowed to wetwell, the concentration of hydrogen rose back and cause a burn in drywell before 600 min. Figure 13 is wetwell, the 7 burns in wetwell were shown in Figure 13 clearly between 75 minutes to 100 minutes. The steam from RPV caused a concentration change was also shown in Figure 13. After these burns, the hydrogen concentration kept rising due to Molten Core Concrete Interaction (MCCI). The hydrogen flowed to the upper dome and caused another burn at 1391 minutes. Figure 14 is the hydrogen burn rate. The burns were already discussed previously. Figure 15 is the mass of hydrogen generation. There was totally 1000kg hydrogen generation in this ELAP accident. Table I is the summary of the MELCOR calculation and some important event time.

For further discussion, the containment was not inert in the case of MK-III. The gas composition was just like the environment and had a risk of hydrogen burn. So the leakage paths from dome to environment were not assumed in this study to get a more conservative results. It was because the setting like this can reduce the hydrogen leakage to the environment and always get a higher hydrogen concentration.

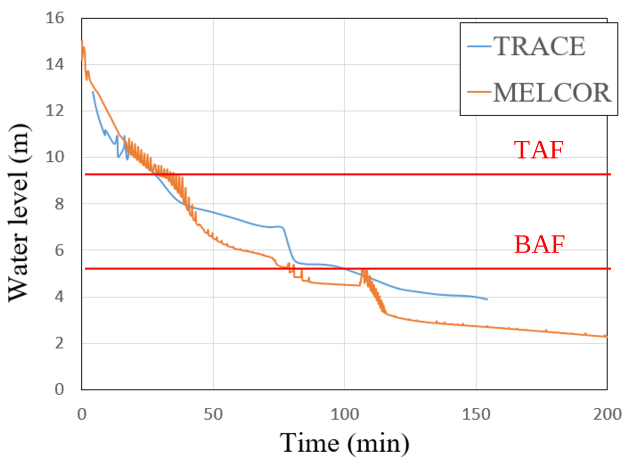

Fig. 8. Water level of MELCOR and TRACE calculations.

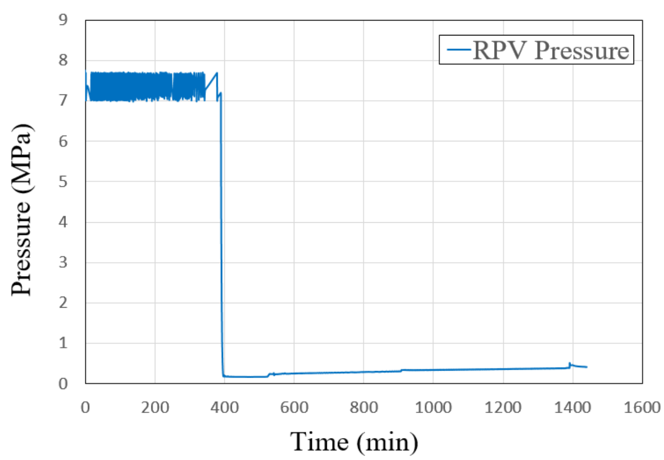

Fig. 9. RPV pressure of MELCOR calculation.

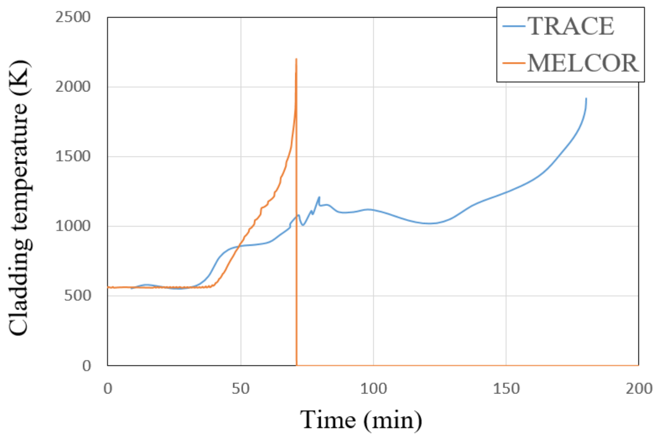

Fig. 10. Peak cladding temperature of MELCOR and TRACE.

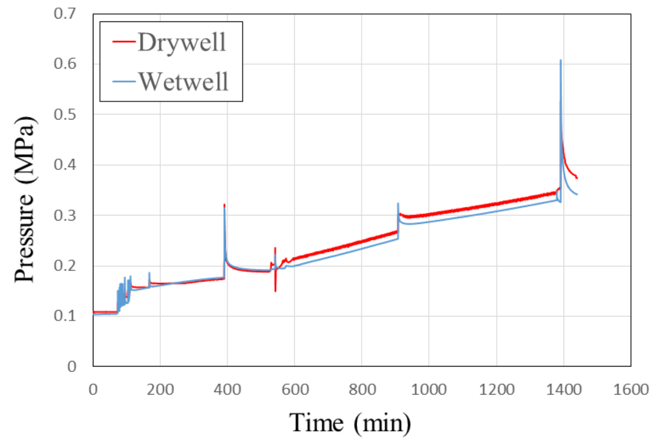

Fig. 11. Containment pressure of MELCOR.

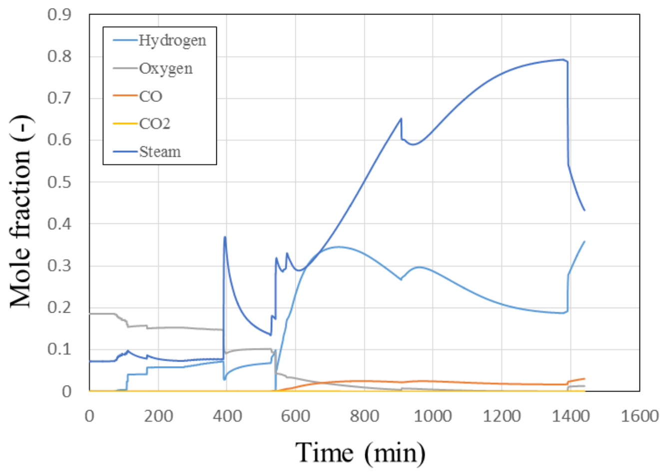

Fig. 12. Gas concentration of drywell.

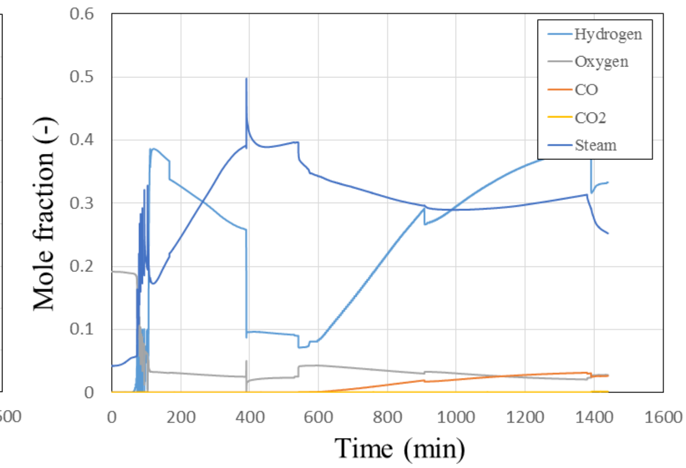

Fig. 13. Gas concentration of wetwell.

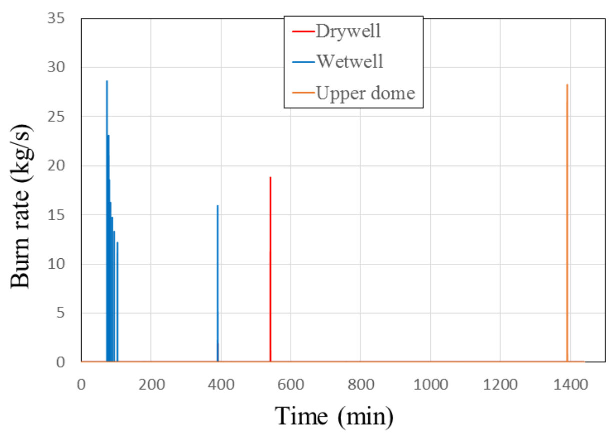

Fig. 14. Burn rate of hydrogen.

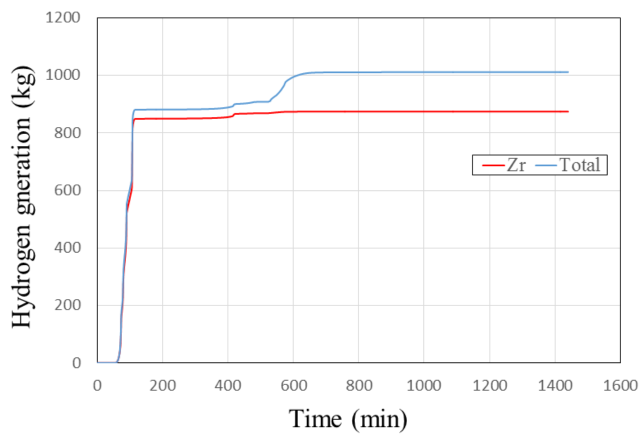

Fig. 15. Hydrogen generation.

TABLE I. Important event of ELAP calculation

Time (min.)	**Event**	83.6	4th wetwell hydrogen burn
-300 sec	Calculation start	88.6	5th wetwell hydrogen burn
0 sec	SBO (ELAP)	94.3	6th wetwell hydrogen burn
28.5	TAF	103.7	7th wetwell hydrogen burn
40	Cladding temperature rising up	106	Fuel drop to lower plenum
57.5	Cladding temperature reach1088K	389.9	RPV small leakage
72.8	Relocation start	390.5	8th wetwell hydrogen burn
75	1st wetwell hydrogen burn	390.62	1st drywell hydrogen burn
78.5	2nd wetwell hydrogen burn	400	RPV failed
79	BAF	541.6	2nd drywell hydrogen burn
80.4	3rd wetwell hydrogen burn	1391	1st upper dome hydrogen burn

Figure 16 is the animation model generated through SNAP. The animation model can show the detail of calculations down by MELCOR. Figure 17 is also an animation model and it can show the hydrogen deflagration in a moving tri-figure. The three values of the tri-figure were the concentration of hydrogen plus carbon monoxide (Burn gas), steam plus carbon dioxide (Inert gas) and air. The ignition area was also shown in the animation but it cannot be seen in Figure 17 because it was time dependent. The users can get the deflagrations data easily through this animation.

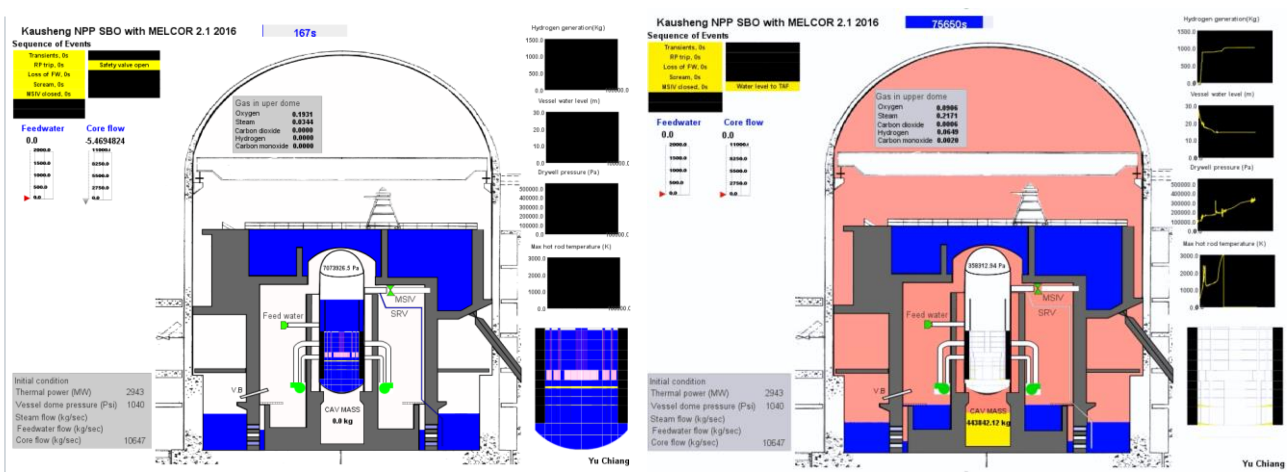

Fig. 16. Animation model of Kuosheng NPP.

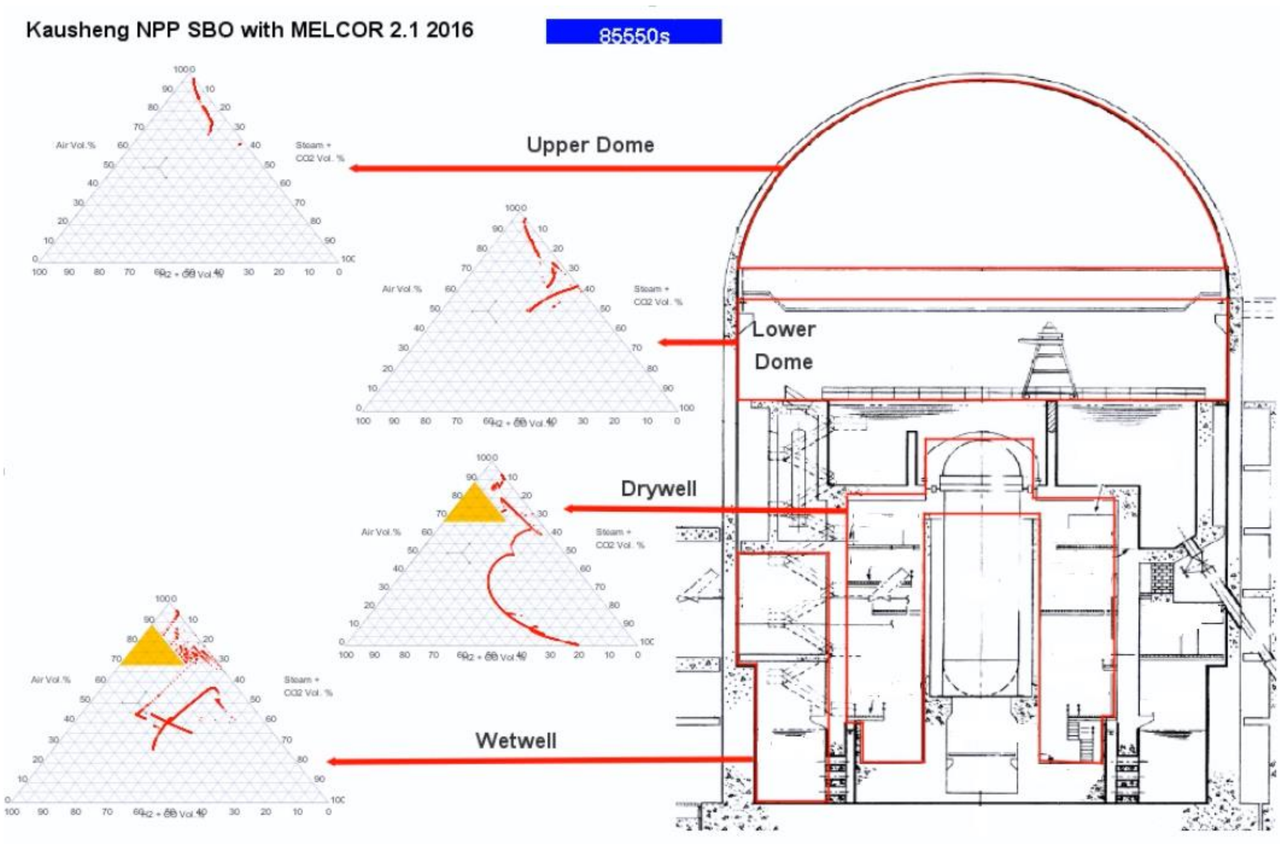

Fig. 17. Animation model of Kuosheng NPP (Deflagrations animation).

III.C. Sensitivity study of containment spray

In Kuosheng NPP, containment spray is a system from RHR. The water injected from upper dome to decrease the temperature and pressure inside the containment. In a situation of ELAP, any water injection could cost some differences to the hydrogen concentration or the debris cooling. The containment spray water will fall into suppression pool directly without touching the debris in the cavity of MK-III containment. Figure 18 shows the hydrogen burn rate of upper dome. In the case with containment spray, the upper dome was full by steam and the steam decreased the concentration of hydrogen. So there was no any burn in upper dome for the case with containment spray. But other area such as wetwell and drywell still had deflagration. The containment spray in the case of ELAP did not cause much different in the hydrogen behaviors in the MELCOR calculations. Figure 19 is the animation of the case with containment spray. The routes of the tri-figure were different and the upper dome did not have deflagration in this case.

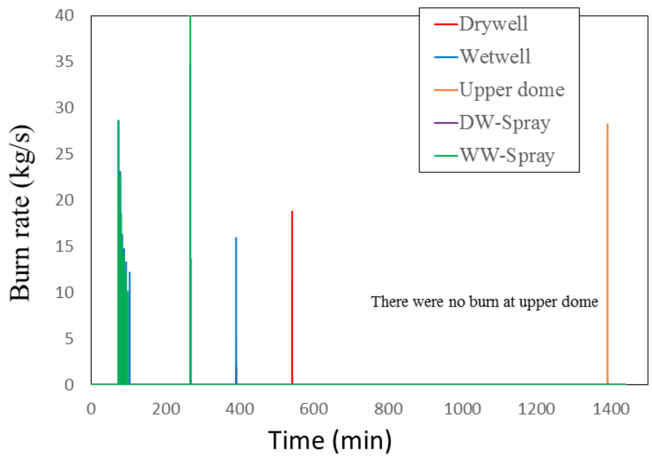

Fig. 18. Burn rate of hydrogen in the case of containment spray.

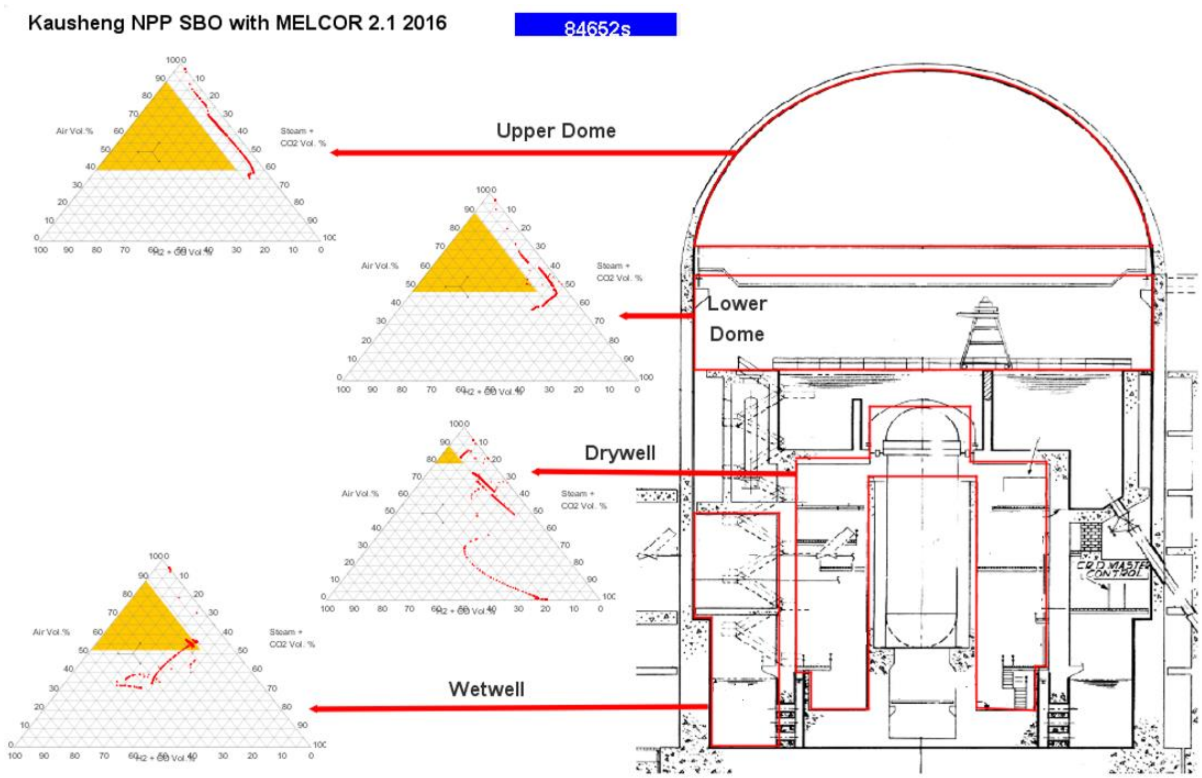

Fig. 19. Animation model of Kuosheng NPP (Deflagrations animation).

IV. CONCLUSION

By the calculation of MELCOR2.1/SNAP, this study gives several conclusions:

1. This study successfully established the MELCOR2.1/SNAP model of Kuosheng NPP.
2. In the case of ELAP, the analysis results of MELCOR, TRACE were similar in thermal-hydraulic results.
3. In a conservative situation that no any water injection was available, RPV failed at 400 minutes in MELCOR calculation.
4. The hydrogen burn happened in containment due to no hydrogen control system.
5. By MELCOR calculations, the containment spray system in the case of ELAP did not cause much different for the hydrogen behaviors.

REFERENCES

1. “MELCOR website,” http://melcor.sandia.gov/
2. Jong-Rong Wang, Hsiung-Chih Chen, Fei-Hao Huang, Hao-Tzu Lin,Shao-Wen Chen, Chunkuan Shih, “Containment Simulation and Analysis ofTRACE in Kuosheng (BWR/6) Nuclear Power Plant, ” ICONE23,ICONE23-1219, May 17-21, 2015, Chiba, Japan . (2015)
3. Taiwan power company, “Teaching material of Chinshan BWR/4 Training,” (2007).
4. Taiwan power company, “Final Safety Analysis Report.”
5. Randall Gauntt, Donald Kalinich, Jeff Cardoni, Jesse Phillips, Andrew Goldmann, Susan Pickering, Matthew Francis, Kevin Robb, Larry Ott, Dean Wang, Curtis Smith, Shawn St.Germain, David Schwieder, Cherie Phelan, “Fukushima Daiichi Accident Study (Status as of April 2012),” SAND2012-6173 (2012).
6. Jong-Rong Wang, Hao-Tzu Lin, Hsiung-Chih Chen, Chunkuan Shih, “The Establishment and Assessment of Chinshan (BWR/4) Nuclear Power Plant TRACE/SNAP Model,” NUREG/IA-0445, (2014).
7. Hsin Cheng, “Building MELCOR Input Deck of Chinshan Nuclear Power Station and Analyses of Station Blackout Sequence,” Institute of Nuclear Engineering and Science, (2014).
8. Yu Chiang, Jong-Rong Wang, Ting-Yi Wang, Hao-Tzu Lin, Te-Chuan Wang, Wen-Sheng Hsu, Jyh-Tong Teng, Shao-Wen Chen and Chunkuan Shih, “The Ultimate Response Guideline Simulation and Analysis by Using MELCOR2.1/SNAP for Chinshan BWR/4 Nuclear Power Plant,” ICAPP-2016, Sanfrancisco (2016).
6. Yu Chiang, Jong-Rong Wang, Hao-Tzu Lin, Shao-Wen Chen and Chunkuan Shih, “Methodology Using MELCOR2.1/SNAP to Establish an SBO Model of Chinshan BWR/4 Nuclear Power Plant,” NURETH-16, Chicago (2015).

ACRONYMS

ELAP - Extended Loss of AC Power
EOP - Emergency Operating Procedure
URG - Ultimate Response Guideline
SNAP - Symbolic Nuclear Analysis Package
NPP - Nuclear Power Plant
SBO - Station Blackout
RPV - Reactor Pressure Vessel
RCIC - Reactor Core Isolation Cooling system
SRVs - Safety Relief Valves
TAF - Top of Active Fuel
BAF- Bottom of Active Fuel