MELCOR2.2/SNAP Analysis of Oxidation Response during Spent Fuel Pool Quenching

Wei-Yuan Cheng[a], Yu Chiang[a], Jong-Rong Wang[b], Shao-Wen Chen[a], Chunkuan Shih[b]

[a] Institute Of Nuclear Engineering And Science, National Tsing Hua University, Hsinchu, Taiwan
[b] Nuclear And New Energy Education And Research Foundation, Hsinchu

email : terryweiyc@gmail.com

After Fukushima accident, the safety analysis of Spent Fuel Pool (SFP) became one of the safety concerns in Taiwan. Thus, the severe accident code MELCOR2.2 was used in this study for both the case of Station Blackout (SBO) and mitigation strategy. In addition, MELCOR was 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.

There were several steps in this study. First, the model establishment of Maanshan NPP SFP was done by MELCOR2.2. Second, the simulation of losing all water injection was performed. The results showed that the water level dropped to Top of Active Fuel (TAF) at 3.5 days. Third, the mitigation strategy of water injection was simulated by MELCOR2.2. The water injection could cause the fuel temperature rise rapidly due to the oxidation heat generated by the Zirconium-water reaction. Also, the hydrogen issue comes out during the water injection. So, the water injection started when cladding temperature reached 1200K, 1400K, 1500K, 1600K, 1700K and 1800K for simulating the different oxidation response during the mitigation strategy. The results showed that the oxidation heat increased rapidly after 1500K and the water injection of 200GPM cannot stop the oxidation immediately. Finally, the oxidation calculations of MELCOR was discussed in detail and combined with the improvement of SFP mitigation strategy.

Keywords: SFP, Maanshan, MELCOR, Quenching

1. INTRODUCTION

The safety analysis of the nuclear power plant (NPP) is an important work in NPP safety. Especially after Fukushima Daiichi event, the safety analysis of Spent Fuel Pool (SFP) became one of the safety concerns in Taiwan.

In previous works, the SFP safety analyses of Kuosheng and Chinshan Nuclear Power Plant (NPP) were done by TRACE code [1][2]. TRACE is a thermal-hydraulic code developed by U.S.NRC. By the calculation of TRACE, the water level and cladding temperature can be shown in an accident transient of SFP. But for the late stage quenching of the SFP mitigation strategy, water injection may cause extra oxidation heat in the SFP which generated by the Zirconium-water reaction. Therefore, the severe accident code MELCOR2.2 was used in this study to simulate both the case of Station Blackout and mitigation strategy water injection.

MELCOR is a code developed by Sandia National Lab and it can calculate the severe accident phenomena such as core relocation, hydrogen generation, hydrogen deflagration, and detonation, etc. The SFP model was built in the MELCOR code this years for the increasing demand of SFP safety analysis. The latest version MELCOR2.2 was used and combined with Symbolic Nuclear Analysis Package (SNAP). With this combination, MELCOR was used with a graphical user interface (GUI) that users can easily modify any detail of the model.

There were several steps in this study. First, the model establishment of Maanshan NPP SFP was done by MELCOR. The geometric data and thermal power of Maanshan NPP SFP were collected from the training material of Taiwan Power Company [3][4]. Second, an accident of losing all water injection was performed by MELCOR2.2/SNAP. This model was used to calculate a SBO accident and compared to the thermal-hydraulic code TRACE in previous work [5]. Third, the water injection referenced by NEI06-12 could cause the fuel temperature rise rapidly due to the oxidation heat generated by the Zirconium-water reaction. Also, the hydrogen issue comes out during the water injection.

According to some other relative study [6], there is a significant oxidation heat results in locally elevated temperature at higher temperatures. Therefore, the water injection started when cladding temperature reached 1200K, 1400K, 1500K, 1600K, 1700K and 1800K for simulating the different oxidation response during the mitigation strategy.

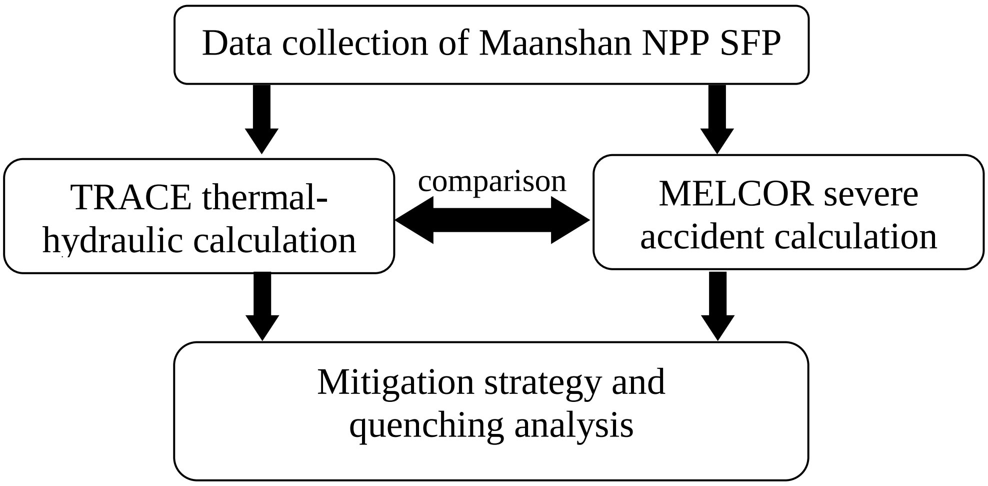


Fig. 1. Flow chart of the SFP analysis

2. MODEL DISCRIPTION

The code versions used in this research were SNAP 2.5.1 and MELCOR2.2. The fuel assemblies were separated into several rings for simulating the different location and decay heat by "COR" package inside the SFP. The size of Maanshan NPP SFP was 16.56 m * 8.73 m and water level was 13.77 m initially. The initial condition of water temperature was 311K and the pressure was $1.013*10^5$ Pa. The total power of the fuels was roughly 10.5411 MWt initially.

Figure 2 shows the MELCOR model of Maanshan NPP SFP in this study. It shows the fuel of SFP which separated into three regions (A, B and C). The three regions was indicated the three rings in the COR package of MELCOR. The SFP was assume to be "Full-core off-load" situation which means all the latest operating fuels were put into the SFP to simulate the most conservative situation. It was totally 1409 fuel bundles in Maanshan NPP SFP. In region A, the thermal power of the 157 fuel bundles which were unloaded from latest-core was 8.5356 MWt. The other 1252 fuel bundles were put into region B and region C. The power distribution of each part was shown in Figure 3.

Figure 4 and Figure 5 show the decay heat and power shape settings of MELCOR model [7][8]. With this settings, this MELCOR model could calculate the SFP transient in the case of SBO and mitigation strategy.

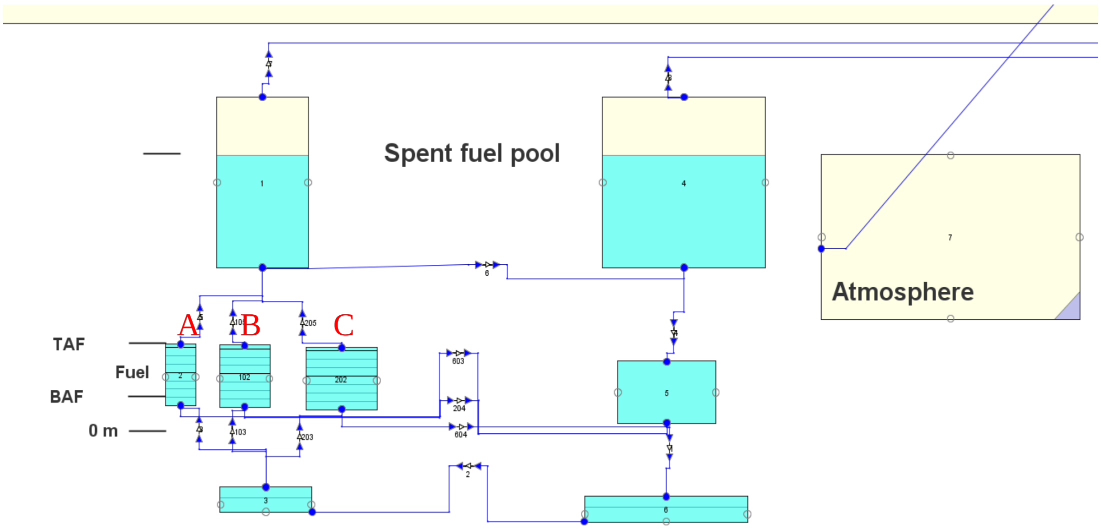
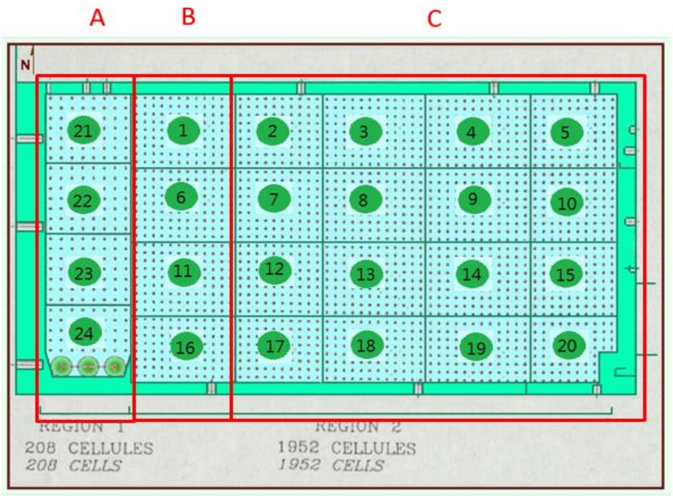


Fig 2. MELCOR2.2/SNAP model of Maanshan SFP



MELCOR area	Power fraction (%)	Thermal power (MWt)
A	80.9	8.5356
B	3.82	0.4011
C	15.28	1.6044

Fig. 3. Power distribution of Maanshan NPP SFP

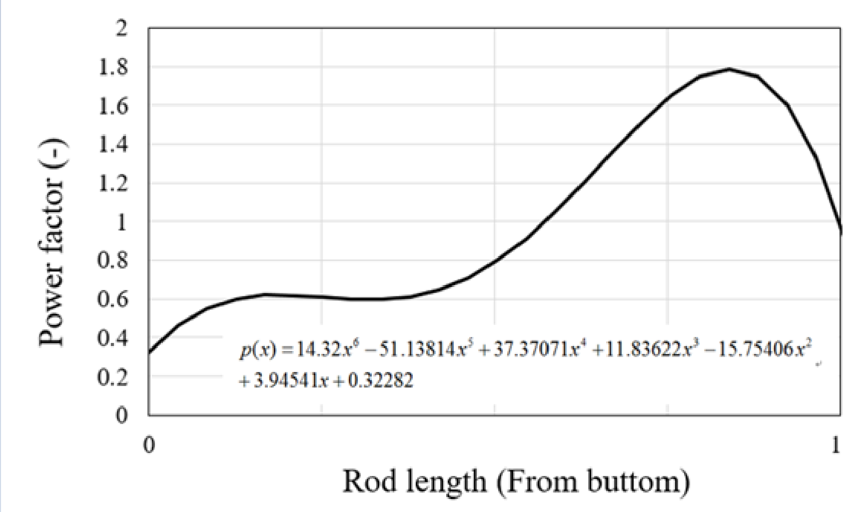
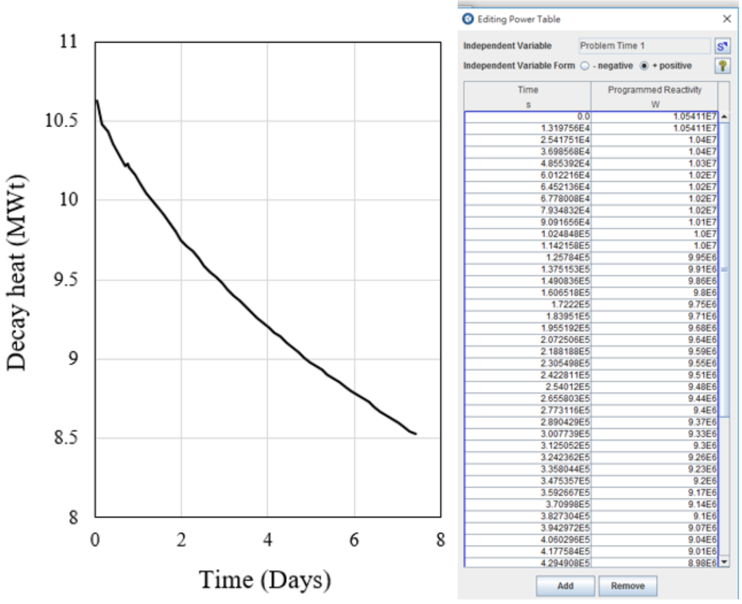


Fig. 4. Power shape used in MELCOR



Independent Variable: Problem Time 1

Independent Variable Form ○ - negative ● + positive

Time s	Programmed Reactivity W
0.0	1.05411E7
1.319756E4	1.05411E7
2.541751E4	1.04E7
3.698568E4	1.04E7
4.855392E4	1.03E7
6.012216E4	1.02E7
6.452136E4	1.02E7
6.778008E4	1.02E7
7.934832E4	1.02E7
9.091656E4	1.01E7
1.024848E5	1.0E7
1.142158E5	1.0E7
1.25784E5	9.95E6
1.375153E5	9.91E6
1.490836E5	9.86E6
1.606518E5	9.8E6
1.7222E5	9.75E6
1.83951E5	9.71E6
1.955192E5	9.68E6
2.072506E5	9.64E6
2.188188E5	9.59E6
2.305498E5	9.55E6
2.422811E5	9.51E6
2.54012E5	9.48E6
2.655803E5	9.44E6
2.773116E5	9.4E6
2.890429E5	9.37E6
3.007739E5	9.33E6
3.125052E5	9.3E6
3.242362E5	9.26E6
3.358044E5	9.23E6
3.475357E5	9.2E6
3.592667E5	9.17E6
3.70998E5	9.14E6
3.827304E5	9.1E6
3.942972E5	9.07E6
4.060296E5	9.04E6
4.177584E5	9.01E6
4.294908E5	8.98E6

Fig. 5. Decay heat used in MELCOR

3. RESULTS

3.1. Fukushima-like condition (SBO)

In this case, all water injection of Maanshan NPP SFP was set to be failed. The pool water level kept going down due to the evaporation caused by the decay heat. The cladding temperature rose over 1088.7K and may cause the release of radiation nuclides inside the fuel cladding when the water level drops below Top of Active fuel (TAF), 5.815m.

Figure 6 and Figure 7 show the results of MELCOR2.2 and TRACE. The simulation started at 0 sec with initial water level 13.77m,. Figure 6 is the result of the water level. MELCOR2.2 and TRACE show almost the same result before the water level reached TAF. The water level dropped to TAF at about 3.5 days and the cladding temperature went up because of fuel uncover. However, the water level went down more rapidly in MELCOR than TRACE after fuel uncovered since water-zirconium reaction occurred. The oxidation heat of this chemical reaction was ten times more than the decay heat of the spent fuel. These result show the thermal-hydraulic calculation of MELCOR in the early accident time, which fit the thermal-hydraulic code well.

Figure 7 is the comparison of the peak cladding temperature between MELCOR and TRACE. The result of TRACE shows that the temperature reached 1088.7K at 4.3 days and MELCOR is around 4 days. Because of the oxidation heat, the cladding temperature of MELCOR rose more rapidly. And the irregularity of the curve in MELCOR means the zirconium fire happened when the temperature kept rising.

The result shows that the fuel uncover happened at 3.5 days with both MELCOR and TRACE calculations, which means there may be 3.5 days for preparing the extra water source in a SFP accident.

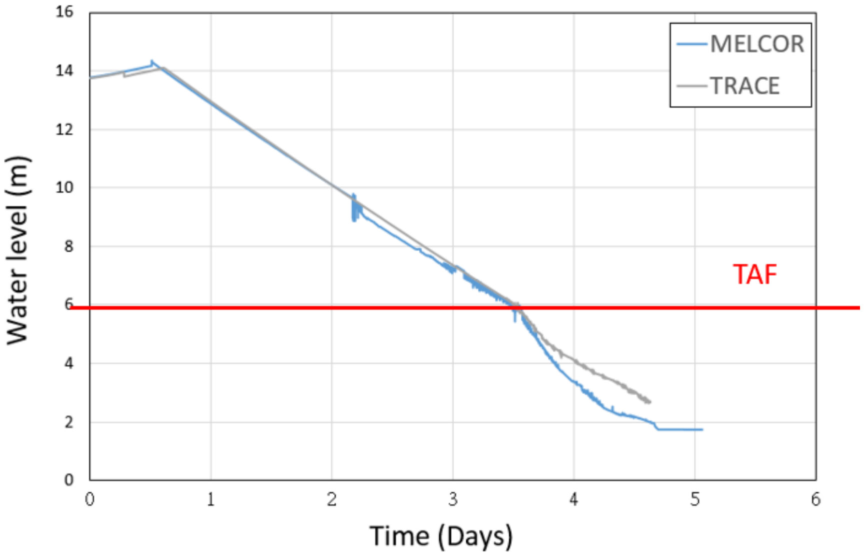


Fig. 6. Water level results of MELCOR and TRACE

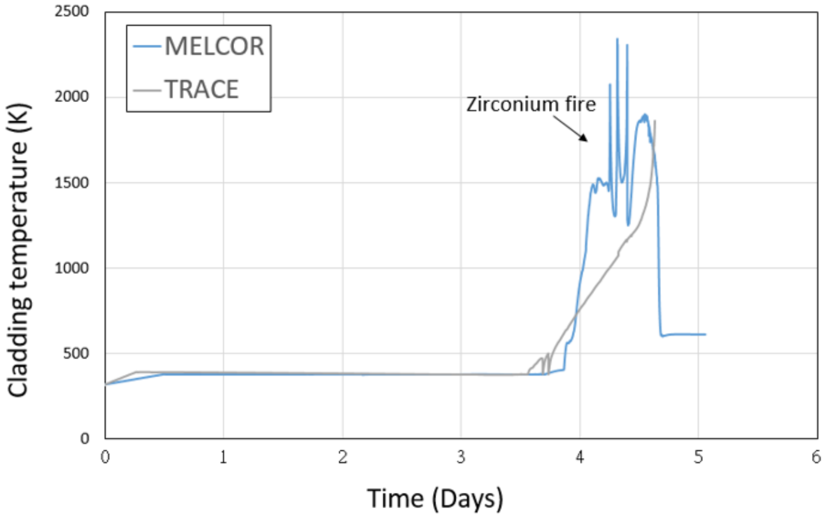


Fig. 7. Peak cladding temperature results of MELCOR and TRACE

3.2. Mitigation Strategy

After the simulation of SBO, the results give that a mitigation strategy which started before 3.5days can keep SFP in a safe situation. The following research tried to find out the phenomenon may happen after 3.5days. In this study, the water injection was assumed to be 200GPM (12.61 kg/s) with homogeneous water injection. It was the lowest water flow rate of the NEI06-12 suggestion for a SFP accident. There were six cases in this study. The water injection started when the cladding temperature rose to 1200K, 1400K, 1500K, 1600K, 1700K, and 1800K.

Figure 8 is the water level results of this sensitivity study. After temperature was higher than 1600K, the water injection started at almost the same time because of the rapidly temperature rising. Figure 6 also shows that a 200GPM water injection could make the water level back to TAF even the temperature reached 1800K.

Figure 9 shows the cladding temperature and Figure 10 shows oxidation heat generated during the quenching. The water injection in a higher fuel temperature could cause more oxidation heat because of the Zirconium-water reaction. First peak of each curve was cause by oxidation heat because of water injection. The results of the water injection started at 1200K, 1400K and 1500K were simple that the temperature rose to the setting point and be cooled down shortly. However, in the cases that water injection started at over 1600K, there were more than one peak which was higher than the first one. The reason of this phenomenon was that the water caused the zirconium reaction more severe and generated more oxidation heat when the water injected into the pool. The zirconium-water calculation of MELCOR2.2 was shown in equation (1) and (2). It was called "Breakaway oxidation" [9] that the oxidation rate may speed up and make the zirconium fire happen when temperature was higher than 1853K. The unstable concussion curves that the temperature is higher than 1600K in Figure 9 and Figure 10 show that the zirconium fire occurred. Therefore, the water caused extra oxidation heat in this case that water injection started when the temperature reached 1600K. This sensitivity study made a conclusion that water injection should start before the cladding temperature was over 1500K which was around 4.3days to prevent the severe accident from making more hydrogen generation and more oxidation heat.

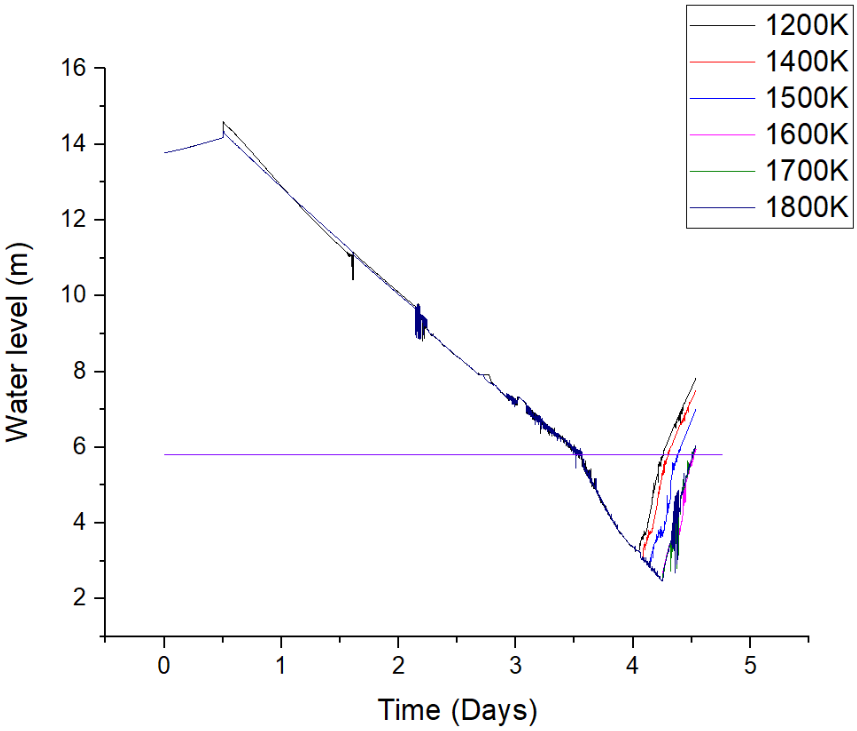


Fig. 8. Water level results of sensitivity study

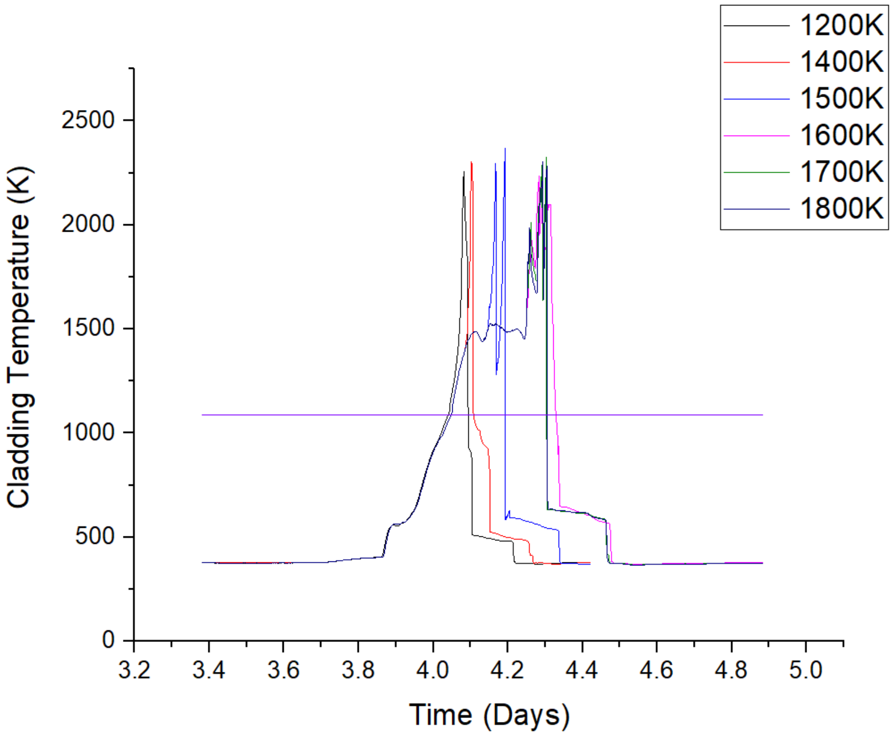


Fig. 7. Peak cladding temperature results of sensitivity study

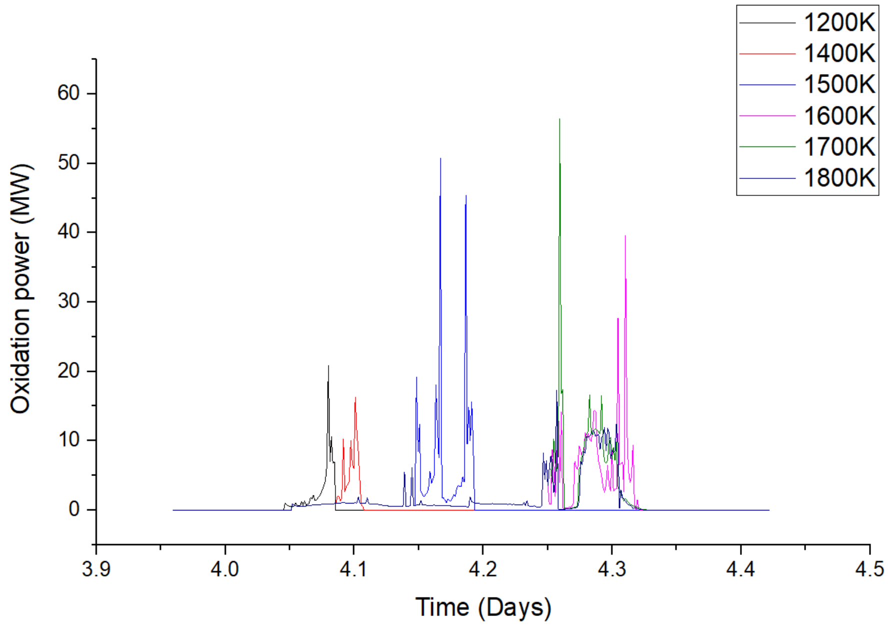


Fig. 8. Oxidation heat results of sensitivity study

$$\mathbf{K(T) = 29.6\, exp\left(\frac{-16820.0}{\mathit{T}}\right) for\ T < 1853.0\ K} \qquad (1)$$

$$\mathbf{K(T) = 87.9\, exp\left(\frac{-16610.0}{\mathit{T}}\right) for\ T \geq 1853.0\ K} \qquad (2)$$

4. CONCLUSION

By the calculation of MELCOR2.2/SNAP, this study makes some conclusion. First, this study successfully established the MELCOR2.2/SNAP model of Maanshan NPP SFP. Second, the analysis of MELCOR and TRACE were similar in the case of SBO It indicated that there was a respectable accuracy in MELCOR2.2/SNAP model. Third, the water level dropped to TAF in 3.5days and the cladding temperature reach 1088.7K at 4days in the case of SBO. So, it gave at least a four days safety margin for preparing extra water source in a SFP accident. Forth, the mitigation strategy analysis shows that a 200GPM water injection can bring back the water level of SFP no matter when the water injection started. But, the result of cladding temperature shows that if the water injection started after the temperature was higher than 1500K, the situation could be more severe because of oxidation heat and zirconium fire. It is the best way to start the water injection before 3.5days. However, if the extra water cannot be prepared before 3.5 days, the water injection must start before 4.3days to prevent he severe accident from making more hydrogen generation and more oxidation heat.

References

[1] J. R. Wang, H. T. Lin, Y. S. Tseng, W. Y. Li, H. C. Chen, S. W. Chen, C. Shih, June, "*The Model Establishment and Analysis of TRACE/FRAPTRAN for Chinshan Nuclear Power Plant Spent Fuel Pool*", ICNRER 2016, June 6-7, 2016.

[2] W. S. Hsu, Y. Chiang, Y. S. Tseng, J. R. Wang, C. Shih, S. W. Chen, "*The Model Establishment and Analysis of TRACE/MELCOR for Kuosheng Nuclear Power Plant Spent Fuel Pool*" International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering Vol:10, No:10, 2016.

[3] "*Teaching material of Maanshan PWR Training*", Taiwan Power Company.

[4] "*Final Safety Analysis Report of Maanshan NPP*", Taiwan Power Company.

[5] Y. Chiang*, W. Y. Li, J. H. Yang, S. W. Chen, R. J. Sheu, J. R. Wang, C. Shih, "*The Mitigation Strategy Analysis of Maanshan Nuclear Power Plant Spent Fuel Pool Using TRACE/FRAPTRAN/SNAP*", SDEWES2017,Oct,4-8/in Dubronik Croatia

[6] Jon Birchley and Yehong Liao, "*Development and Assessment Program for the MELCOR Code*" ENSI Erfahrungs-und Forschungsberrichy, pp. 117-123, 2009.

[7] "*Thermal-Hydraulic Design Procedure Manual*" Westinghouse, 2009

[8] "*Residual Decay Energy for Light-Water Reactors for Long-Term Cooling*", (NUREG-0800), Rev.2,Section 9.2.5, Branch Technical Position ASB 9-2, July 1981。

[9] Robert Beaton Alexander Velazquez-Lozada, Abdelghani Zigh, "*Experiment on Ignition of Zirconium-Alloy in Prototypical Pressurized Water Reactor Fuel Assemblies in a Spent Fuel Pool with Complete Loss of Coolant*", Sandia National Lab report.