Spent fuel pool accident analysis and accident management

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1. Introduction

The research of spent fuel pool (SFP) severe accident analysis has been attracted by several nuclear safety research institutes after the Fukushima Daiichi nuclear disaster in 2011. The spent fuel pool in unit 4 of the Fukushima Daiichi NPPs was damaged by an extreme seismic event and subsequent flooding by a tsunami. In order to investigate a progression of spent fuel pool accident scenarios, the well-defined MELCOR 1.8.6 code input deck was prepared and validated by experimental data of the OECD/NEA Sandia Fuel Project [1]. Based on the validated MELCOR code input, three types of spent fuel pool accident scenarios were analyzed. Fig. 1 shows a progression of spent fuel pool accident scenarios.

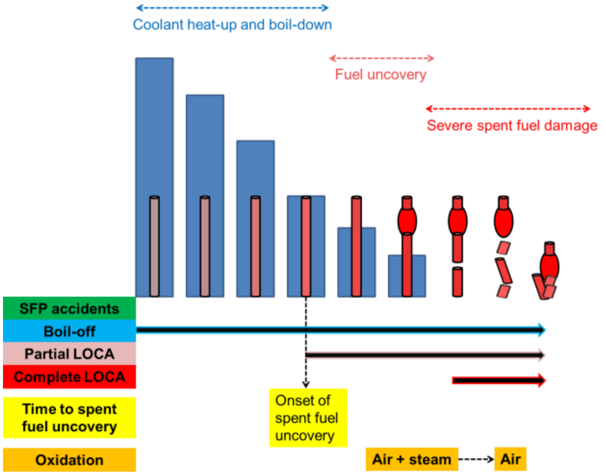

Fig. 1. Progression of SFP accident scenarios

The first accident scenario is a boil-off accident scenario. The second accident scenario is a complete loss of coolant accident and the last is a partial loss of coolant accident. In the boil-off accident scenario, behaviors of boil-off accident in accordance with different burn-up histories of spent fuels and loading configurations in the pool were analyzed. In the complete loss of coolant accident (LOCA) scenarios, sensitivity studies were conducted to identify the modeling boundary conditions to initiate a zirconium fire in the spent fuel assemblies. Lastly, in the partial loss of coolant accident scenarios, the steam cooling effect on the exposed spent fuel assemblies was discussed to cope with an abrupt cladding temperature escalation by the air/steam mixture oxidation. Through this paper, three representative spent fuel pool accident scenarios were carefully analyzed to identify vulnerabilities of spent fuel pool system with numerous MELCOR code calculations with different conditions. Based on the identified vulnerabilities in each spent fuel pool accident scenario, the key operator actions to significantly mitigate the accident progressions were discussed in this paper.

2. MELCOR models of spent fuel pool

MELCOR models of SFP were developed to simulate a single and 1x4 fuel assembly (FA) configurations, respectively. A single FA contained a 17x17 PWR fuel bundle with ca. 4 m of height, and a 1x4 FA included a single center fuel bundles and four peripheral fuel bundles. Each input nodalization is shown in Fig. 2.

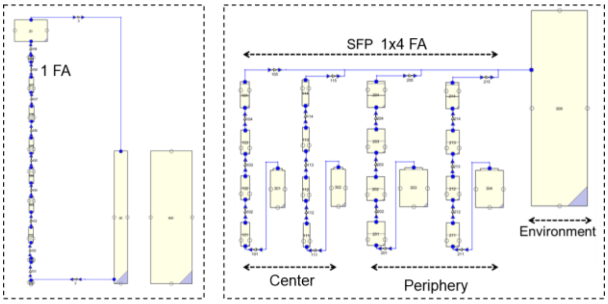

Fig. 2. SFP MELCOR input nodalization

The developed input deck as shown in Fig. 2 was validated by experimental data of the OECD/NEA Sandia Fuel Project Phase-1 and -2, respectively. Tests consist of Phase-1 with one assembly and Phase-2 with 1×4 fuel assemblies to see the propagation of fire [1]. The peak cladding temperature from MELCOR code calculations and the results of experimental data are given in Fig. 3. As shown in Fig. 3, the peak cladding temperature of developed SFP MELCOR model inputs in this paper were comparable with the experimental data. Based on the developed SFP MELCOR model inputs, various calculations were performed to analyze a consequence of SFP accident scenarios. However, it might be limited to represent a full scope of SFP geometry of a real plant with a single or 1x4 FA configurations. This study aims to understand a possible SFP accident sequence progression based on a simple representative spent FAs configurations with the three SFP accident scenarios described in the introduction.

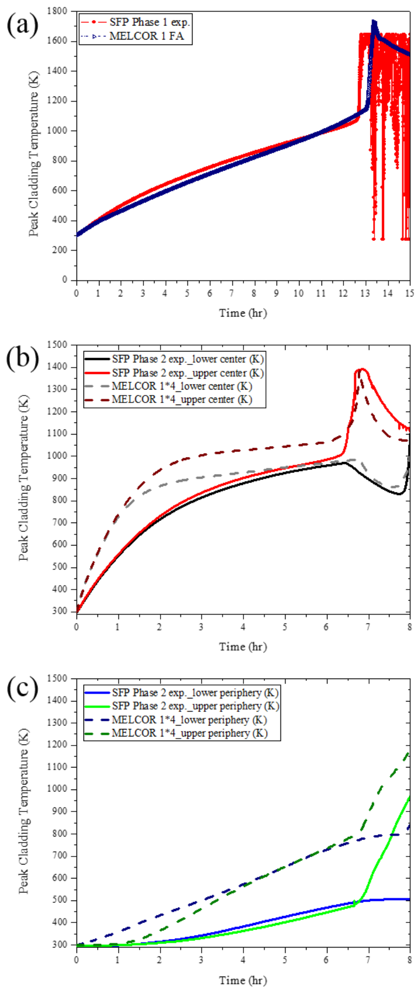

Fig. 3. SFP MELCOR model inputs validation by Sandia Fuel Project experimental data: (a) Phase-1 (1 FA), (b) Phase-2 (1x4 FAs center) and (c) Phase-2 (1x4 FAs periphery)

3. Spent fuel pool accident analysis

As previously described in the introduction, three representative SFP accident scenarios were investigated by MELCOR code calculations.

3.1 Complete Loss of Coolant Accident

Zirconium fire phenomenon was observed in both Sandia Fuel Project Phase-1 and -2 experiments. This phenomenon led to an abrupt escalation of cladding temperature. In order to find an initial condition that leads the zirconium fire phenomenon, 1FA-SFP MELCOR model was calculated by varying an initial decay heat of spent fuel from 0.3 kW to 20 kW.

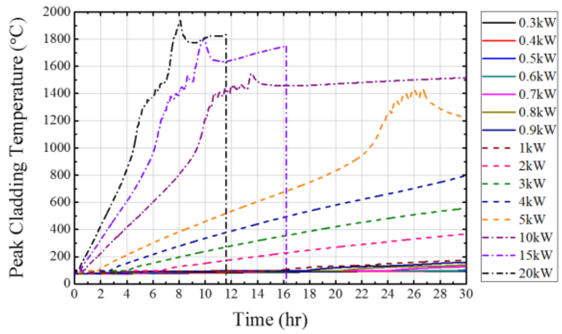

Fig. 4. Peak cladding temperature of spent fuel

As shown in Fig. 4, an abrupt escalation of cladding temperature was shown from the case of initial decay heat of 5 kW. In case of 20 kW of initial decay heat calculation, an abrupt escalation of cladding temperature initiated at ca. 4.5 hr from the beginning of SFP complete LOCA. In addition, ca. 6.2 hr for 15 kW, ca. 9.5 hr for 10 kW and ca. 22.5 hr for 5 kW were given as an initiation point of the abrupt escalation of cladding temperature. In the Sandia Fuel Project experiments, fire was observed on the surface of cladding at this initiation point (see Fig. 3). It is expected that the cladding might be severely degraded after this zirconium fire phenomenon and the radioactive fission product could be released substantially after this severe cladding degradation. In order to find a consequence of the zirconium fire on a fission product release, CsI release was calculated in this postulated SFP complete LOCA of the initial decay heat from 5 kW to 20 kW.

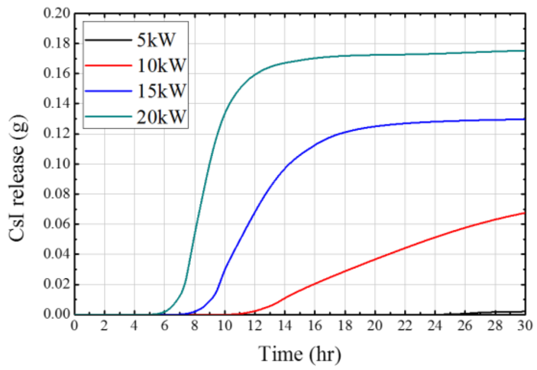

Fig. 5. CsI release in the postulated SFP complete LOCA

As shown in Fig. 5, CsI release was dramatically increased at ca. 5 hr for 20 kW, ca. 7 hr for 15 kW, ca. 10.5 hr for 10 kW and 24.5 hr for 5 kW case. It seems that the CsI release could be significantly enhanced a bit after the initiation of zirconium fire (e.g ca. 0.5 hr for 20 kW, ca. 0.8 hr for 15 kW, ca. 1.0 hr for 10 kW and ca.

2.0 hr for 5 kW). The initial condition that leads to the zirconium fire in case of SFP complete LOCA was calculated to 5 kW in the present study. In case of 17x17 UO_x PWR spent fuel assembly of 35,000 MWd/MtU burn-up history, it was reported that 600 days of pool storage would be required after a discharge from the reactor to reduce its decay heat to 5 kW [2]. In addition, 1100 days would be required for the 50,000 MWd/MtU burn-up history [2]. In this respect, a cooling time in SFP seems critical to avoid the zirconium fire phenomenon not to release a considerable amount of a radioactive fission product (e.g. CsI). Fig. 6 shows a peak cladding temperature as a function of initial decay at 35,000 MWd/MtU and 50,000 MWd/MtU, respectively.

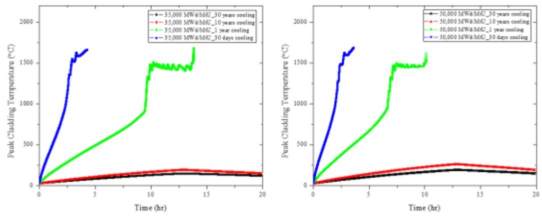

Fig. 6. PCT as a function of cooling time

For both burn-up cases, 1 month- and 1 year-cooled spent fuel showed the zirconium fire phenomenon.

3.2 Partial Loss of Coolant Accident

The coolant of spent fuel pool might be drained due to a leakage in the pool and a part of spent fuel assembly could be uncovered. In this assumed partial loss of coolant accident, an uncovered part of spent fuel assembly might be exposed by air and steam mixture.

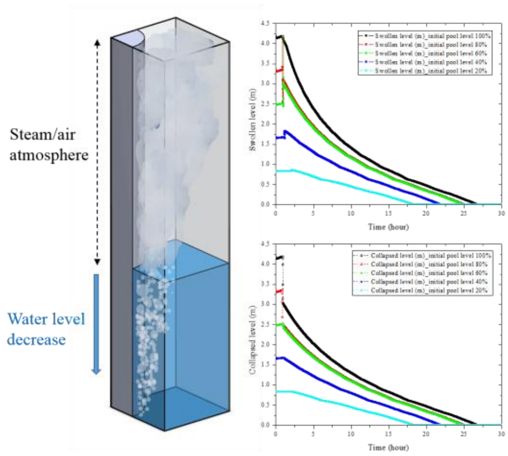

Fig. 7. Water level decrease in SFP partial LOCA

Due to a rapid steam production by a heat-up of spent fuel assembly, a produced steam could cool-down the upper uncovered part of spent fuel. This steam cooling effect on a partially uncovered spent fuel was studied in [3]. The present paper calculated a behavior of water level decrease in the partial LOCA to find an effective regime of steam cooling on overheated uncovered upper part of spent fuel. An initial water level was set from 100% of spent fuel assembly height to 0%. As shown in Fig. 7, both swollen and collapsed water level decrease was highly comparable in the 60 and 80% of initial water level cases. It seems that the steam cooling was effective to cool-down an overheated spent fuel until around one-third of uncovery of spent fuel height.

3.3 Boil-off accident

In case of loss of cooling in the SFP, the coolant in the pool might be evaporated and boiled-down and the spent fuel would be uncovered. In order to investigate an effect of initial decay heat on the water level decrease, the water level was set to 100% of spent fuel assembly height.

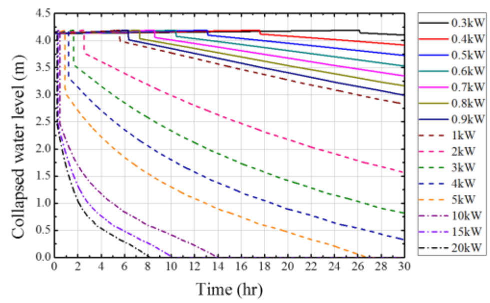

Fig. 8. Water level decrease as a function of decay heat

As shown in Fig. 8, a low decay heat group (0.3 to 1.0 kW) showed a relatively slow decrease of water level, but a high decay heat group (10 to 20 kW) showed a relatively fast decrease of water level. In every case of boil-off accident from the 100% of spent fuel assembly height, a release of radioactive fission product is not be inevitable, and the water level was decreased within a day or a few days. For this reason, a role of upper pool above the top of spent fuel assembly might be critical as a heat sink to retard the water level decrease and a fission product release by removing a heat from spent fuel.

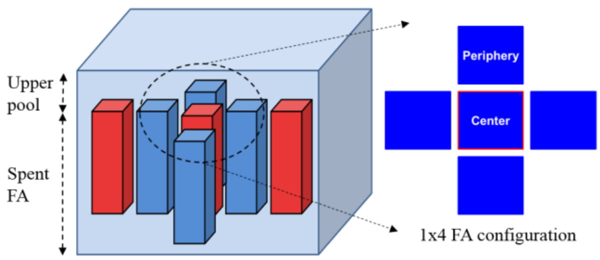

Fig. 9. 1x4 Spent fuel assemblies configuration

Considering a certain loading configuration of spent fuel assemblies according to the cooling time and burn-up history as shown in Fig. 9, the cooling time was assumed one year and the burn-up of the central fuel assembly was 50,000 MWd/MtU and the peripheral part

was 35,000 MWd/MtU in the boil-off accident calculation.
The height of spent fuel was around 4 m and the height of upper pool level was varied from 0.5 to 5.5 m.

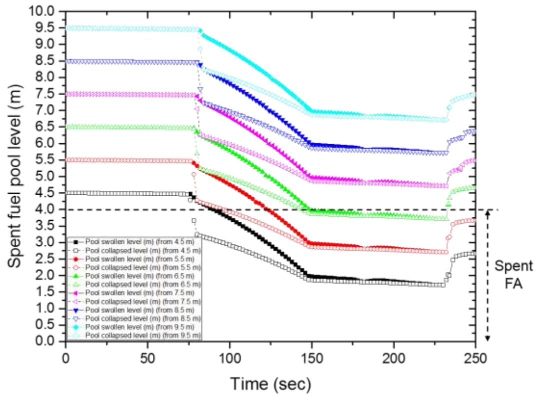

Fig. 10. Spent fuel pool level decrease as a function of upper pool level

As shown in Fig. 10, cases of upper pool level of 0.5 to 2.5 m showed rapid spent fuel uncovery less than 100 sec. However cases of upper pool level of 3.5 to 9.5 m showed an initial water level drop, but it was restored and the spent fuel was flooded by the upper pool. In this respect, at least more than 3 m of upper pool level might be required to avoid a rapid water level drop to the top of spent fuel assembly.

4. Spent fuel pool accident management

Based on findings from the calculations in the section 3, a possible accident management to cope with a consequence of each SFP accident scenario.

4.1 Accident management for the SFP complete LOCA

In the SFP complete LOCA, the zirconium fire phenomenon led to an abrupt heat-up and a substantial fission product release. Therefore, the operator should reflood the SFP before an initiation of the zirconium fire phenomenon. It was found that the zirconium fire could be occurred above the 5 kW of the decay heat of spent fuel. It is recommended that the spent fuel would be cooled-down in a robust pool against an extra hazard (e.g. severe seismic event) until an inactive regime of zirconium fire (i.e. decay heat of below 5 kW).

4.2 Accident management for the SFP partial LOCA

In the SFP partial LOCA, a produced steam from an overheated pool could cool-down an uncovered spent fuel until a certain uncovery of spent fuel. MELCOR code calculations showed that the steam cooling could be effective until around the one-third of spent fuel uncovery. It is highly recommended that the operators should reflood the SFP at the latest the point of one-third uncovery of spent fuel. However it is highly better to reflood before the spent fuel uncovery, since a radioactive fission product might be released after the onset of spent fuel uncovery.

4.3 Accident management for the SFP boil-off

From the MELCOR calculations by varying the level of upper pool above the top of spent fuel assembly, at least more than 3.5 m would be required to avoid rapid water level drop to the top of spent fuel. In case of operation of spent fuel pool of APR1400 [4], at least 3.05 m of upper pool is required to assure the safety of spent fuel pool. In the spent fuel pool of APR1400, the upper pool level should be sufficient high to reduce a radiation at a surface of the upper pool to 0.025 mSv/hr and to keep temperature of the spent fuel pool below 60℃. For this reason, one of the critical accident management to terminate a severe consequence of SFP accidents, the upper pool level should be maintained above a certain level (e.g. 3.5 m).

5. Conclusions

A series of MELCOR code calculations were performed to investigate a consequence of each SFP accident scenario. Based on findings from the calculations, the recommended operator actions were proposed to manage the SFP accident progressions. However MELCOR codes cannot simulate a role of nitrogen in the spent fuel cladding oxidation. An improved model has been developed by authors and will be implemented to codes to give a better understanding of the consequences of SFP accident scenarios.

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