Evaluating the Effectiveness of Mitigation Strategies during Severe Accidents in the Spent Fuel Pool for the APR1400 Using the MAAP5 Code

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1. Introduction

After the Fukushima accident, the risk of the Spent Fuel Pool (SFP) accident during severe accident has been issued. Therefore, the generic Severe Accident Management Guidance (SAMG) of the Advanced Power Reactor 1400 (APR1400) which is under developing includes SFP severe accident mitigation actions [1]. The major actions are the injection into the SFP and the ventilation of the fuel handling area. The water injection to recover the cooling capability of the SFP can be achieved by using the direct injection line and the spray nozzle. The ventilation of the fuel handling area to reduce hydrogen concentration can be done by using the ventilation system and opening the doors. In this paper, the effectiveness of these mitigation actions are investigated by using the Modular Accident Analysis Program, Version 5 (MAAP5) code [2].

2. Severe Accident Management Strategies Regarding SFP

Most important factor related to SFP severe accident is the time interval until the top of the fuel assemblies is uncovered. If the water level above the fuel assemblies reaches a height of approximately 10 ft above the top of the fuel assemblies, either due to leakage or boil-off, the habitability of fuel handling area may become an issue. Further, if the water level decreases below the top of the fuel assemblies, significant fission product releases could occur along with a large production of hydrogen that could become explosive and compromise the integrity of the fuel handling area. Therefore, it is important to monitor the water level in the SFP during severe accidents. For these reasons, the following strategies are reflected in the generic SAMG of the APR1400: injecting water into SFP and venting the fuel handling area.

2.1 Injection into the SFP

The purpose of injecting water into the SFP is to recover SFP water level. This would recover fuel cooling and radiation shielding. There would be two methods can be used to inject the water into SFP. Firstly, the water can be injected into SFP directly by using the SFP cleanup pumps, etc. The direct injection into SFP is an effective method to refill the pool in a short time. Secondly, the water can be injected by spraying into the upper area of SFP. This would quench and cool the overheated spent fuel by cooling from the top down, generally cooling the hotter surfaces first. In addition, sprayed droplets would remove aerosols, including fission products, from the steam and non-condensable gases exiting the SFP. Also the spray water can compensate the loss of water due to leakage.

2.2 Ventilation of the Fuel Handling Area

Primarily, venting the fuel handling area would reduce the hydrogen concentrations and prevent the hydrogen explosion. Firstly, the fuel handling area ventilation system can be used. It is preferred method to vent to others because it has a charcoal filter; thus, it can minimize the fission product releases. If the ventilation system is not running, alternative means of ventilation should be attempted because starting the electrical equipment of ventilation system could trigger a hydrogen explosion. The alternative means of ventilation could include the opening of doors at a high and low elevation to establish flow through the fuel handling area.

3. Modeling for Analysis using the MAAP5

Following the accident at Three Mile Island Unit 2, the nuclear power industry has developed the MAAP (Modular Accident Analysis Program) computer code as part of the Industry Degraded Core Rulemaking (IDCOR) program. Its objective was to provide a useful tool for analyzing the consequences of a wide range of postulated plant transients and severe accidents for current plant designs and Advanced Light Water Reactors (ALWRs). MAAP 5.0.3 is the latest version in the suite of MAAP computer codes (i.e., MAAP3B, MAAP4) designed specifically to perform severe accident analyses for numerous nuclear plant designs.

The objective of modeling the SFP is to analyze phenomena of a severe accident in SFP for the chosen accident scenarios including time to boil, time to uncover fuel assemblies, heat-up of fuel assemblies, Zr-water and Zr-O_2 reaction, fission product release, molten progression of fuel assemblies, and Molten Core-Concrete Interaction (MCCI), etc.

The SFP model has been developed using the design data for the spent fuel and the SFP of the APR1400. Variables for geometry of the spent fuels, the spent fuel storage racks and the SFP are referred to the design data, however, some variables such as total number of stored spent fuel assemblies, maximum burn-up of last cycle, cycle lengths, elapsed time after reactor scram, cycle outage length, and enrichment, etc. were assumed. The assumed information regarding the spent fuel and the SFP model is listed in Table I.

Table I: Assumed spent fuel and SFP model information

Variables	Definition	Input
Spent Fuel	Cycle length	15.5 months
	Outage length	1 month
	Burn-up	50000 MWD/MTU
	Number of fuel assembly	1000
	Enrichment	4.2 %
Spent Fuel Pool	Number of Channels	42
	Axial nodes	32
	Total nodes	1344
	Initial water level	12.5 m

The SFP floor and side walls are represented by distributed heat sinks which may be ablated by molten corium (refer to Fig. 1). Non-uniform distribution of decay power according to the axial power peaking factor was applied in the axial direction of the spent fuel assembly. As shown in Fig. 1, the spent fuel assembly was divided into 32 nodes in the axial direction, with the bottom axial node 1 simulating the lower non-fuel region, the top axial node 32 representing the upper non-fuel region, and nodes 2 to 31 denoting the active fuel region.

The channels in the SFP represent physical rack boundaries. Those are subdivided for better model resolution. Each channel has a single temperature for water and gas. In addition, the radiation heat transfer between the adjacent channels and the spent fuel wall is calculated. As shown in Fig. 2, the SFP was divided into 42 channels.

In order to simulate the mitigation strategies for the SFP, junctions connecting the SFP and environment are added to model the leakage paths and probable venting gates (refer to Fig. 3). The SFP spray is simulated by using the spray model in MAAP code.

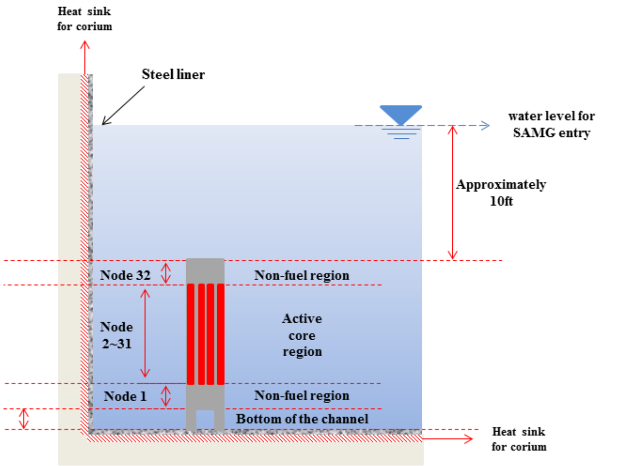

Fig 1. The schematic diagram of the spent fuel assemblies.

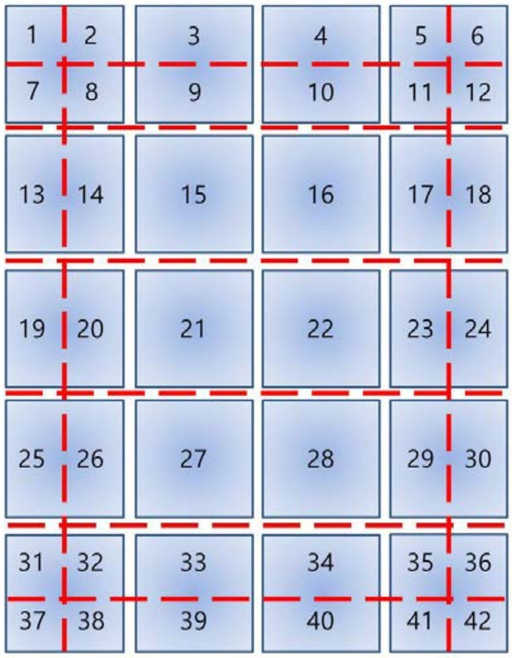

Fig 2. The channel nodalization for the SFP model.

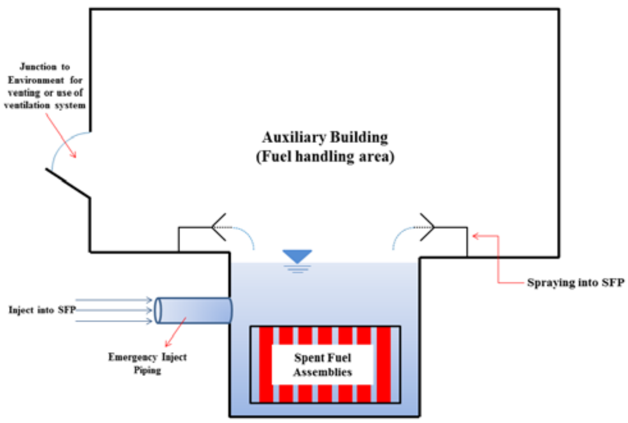

Fig 3. The schematic diagram of the mitigation means of the SFP model.

4. Results of Analysis

4.1 Base Case without Mitigation Measures

In order to demonstrate the SFP behavior in severe accidents and risk related to SFP, the severe accident without implementing the mitigation strategies are investigated. Two sequences are considered as base cases: Loss of SFP cooling (LOSC) and SFP cooling system line break (SCLB). It is assumed that the LOSC sequence was caused by a station blackout (SBO) during which all electric power is lost and thus the SFP cooling system and the SFP make-up water system fail to work. The SCLB sequence can be resulted from the piping line break connected in the SFP. The summary of key events for two base cases is presented in Table II.

Table II: Summary of key events for the base case.

	LOSC	SCLB
Events	Time (hr)	
Loss of Cooling	0	0
Initiation of boiling	3.0	2.1
SAMG entry	42.7	5.0
Spent Fuel Assemblies Uncover	73.0	35.2
Maximum fuel temperature exceeds 1800 °F	83.8	45.2
SFP dry out	101.0	61.4
Corium-Concrete Interaction (CCI)	194.3	133.8

As shown in Fig. 4, there is an increase in the temperature of SFP water from 323 K up to a boiling point (about 373 K), at 3.0 hours and 2.1 hours in the LOSC and SCLB sequences respectively. The collapsed water level in SFP is presented in Fig. 5. Water level increases at the beginning of the LOSC sequence due to the expansion of pool water with increasing temperature. On the other hand, the water level rapidly decreases in case of SCLB due to the break of the piping line connected to the SFP. Figure 6 presents the maximum temperature of spent fuel assembly. After 73.0 hr and 35.2 hr in the LOSC and SCLB sequences respectively, the temperatures increase quickly because the spent fuel assemblies are uncovered. Without external cooling measures, a collapse of the spent fuel assemblies occurs. Figure 7 shows accumulated mass of hydrogen generated in the SFP. The temperatures of uncovered spent fuel claddings increase rapidly in the steam-enriched atmosphere and the hydrogen is generated mainly by Metal Water Reaction (MWR). Total amount of hydrogen generated from oxidation is about 4500 kg in the SCLB case which is 100 kg more than that in the LOSC case. Hydrogen is generated by the MCCI as well as the MWR. As shown in Fig. 7 and Fig. 8, the MCCI occurs during the both cases, and the erosion depth in LOSC and SCLB sequences are almost same as 0.65 m. Even though massive hydrogen is generated, it is expected that the hydrogen explosion does not occur because the volume fraction of steam exceeded 53 vol. % as illustrated in Fig. 9 and it is inert to hydrogen combustion or detonation. However, after 104 hr and 64 hr in the LOSC and SCLB sequences respectively, the volume fraction of steam is lower than that of hydrogen. At this period the SFP fully dry out and the steam cannot be more generated from the water. Thereby steam concentration is decreased and there is a possibility of the hydrogen explosion. In addition, at 220 hr and 154 hr in the LOSC and SCLB sequences respectively, the volume fractions of hydrogen exceed 15 vol. % because of the MCCI. At this period there would be a possibility of the hydrogen explosion in the fuel handling area. Therefore, it is necessary to mitigate the severe accident in the SFP in accordance with the SAMG.

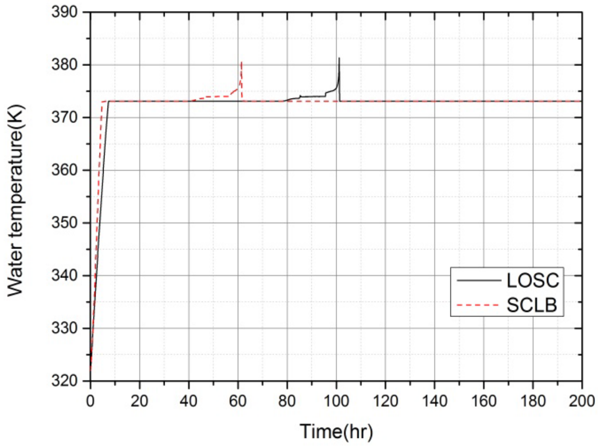

Fig 4. The water temperature in the SFP (LOSC and SCLB sequences).

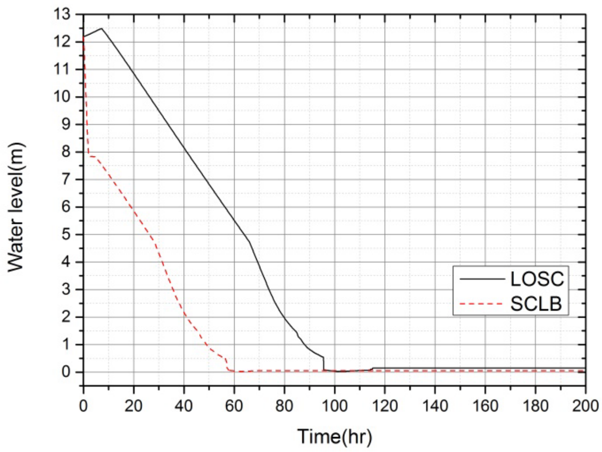

Fig 5. The water level in the SFP (LOSC and SCLB sequences).

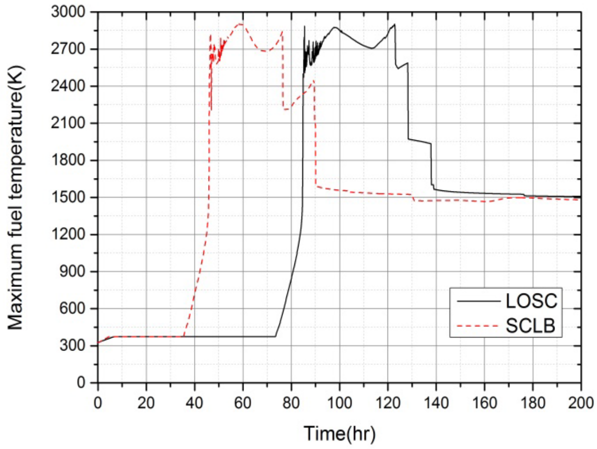

Fig 6. The maximum fuel temperature (LOSC and SCLB sequences).

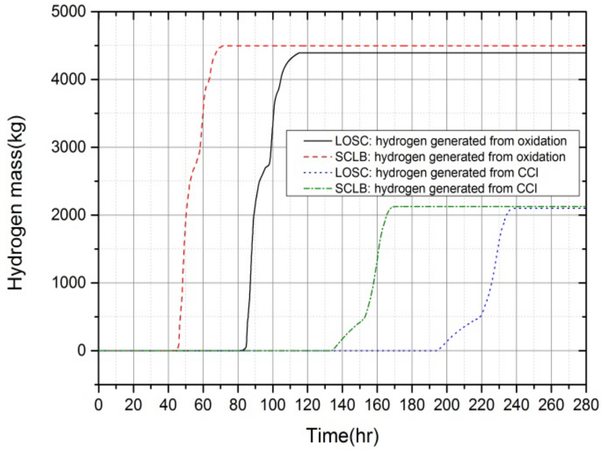

Fig 7. The accumulated mass of the generated hydrogen (LOSC and SCLB sequences).

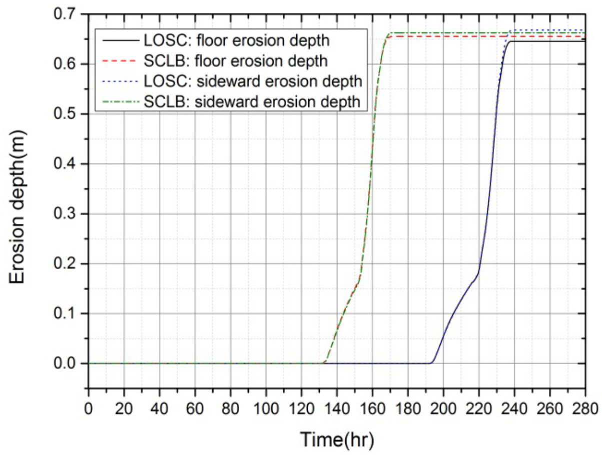

Fig 8. The floor and sideward erosion depth (LOSC and SCLB sequences).

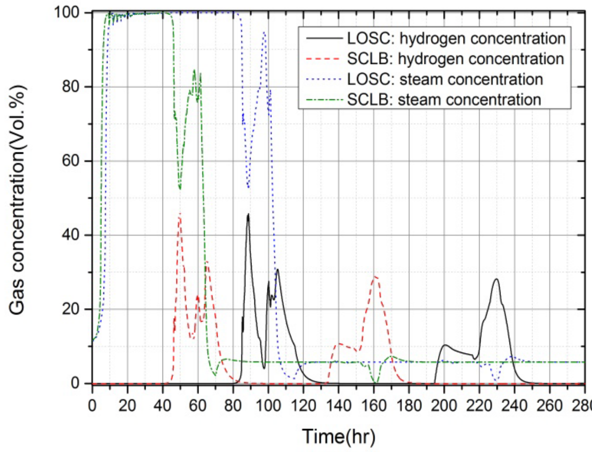

Fig 9. The hydrogen and steam concentration (LOSC and SCLB sequences).

4.2 Injection into the SFP

For the injection into the SFP, it is considered that the make-up water of 323 K flowed through the pipe at 500 gpm. For the sensitivity study, two sequences were analyzed. The start time of the injection is determined when the spent fuel assemblies is uncovered at the 1/3 and 1/4 of that respectively in Case 1 and Case 2. And the injection time interval between two cases is around 6 hr.

As shown in Fig. 10, the water level decreases gradually until the injection into the SFP is started. Figure 11 shows the maximum fuel temperatures in Case 1 and Case 2. After the water injection, the fuel temperature decreases rapidly. However, the peak temperatures of the fuel for both cases are significantly different due to the timings of the water injection initiation. Additionally, Case 2 shows that the hydrogen concentration in the fuel handling area is greater than 20 vol. %, while the hydrogen concentration in Case 2 is very low as shown in Fig. 12. Thus, the early injection into the SFP via the recovery of the means and the quick operation actions is important in the view point of the mitigation strategy for the SFP.

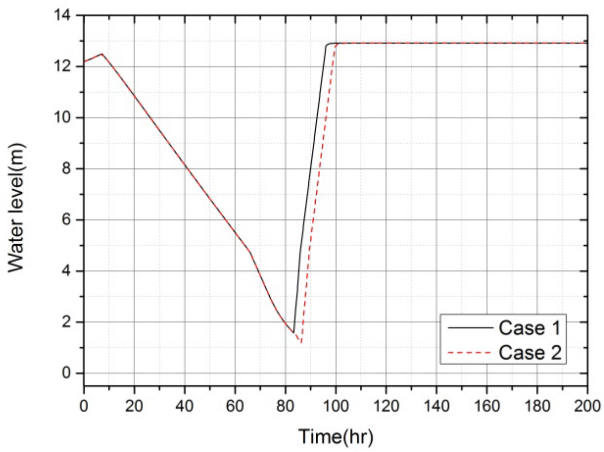

Fig 10. The water level in the SFP (implementation of the strategy to inject into the SFP).

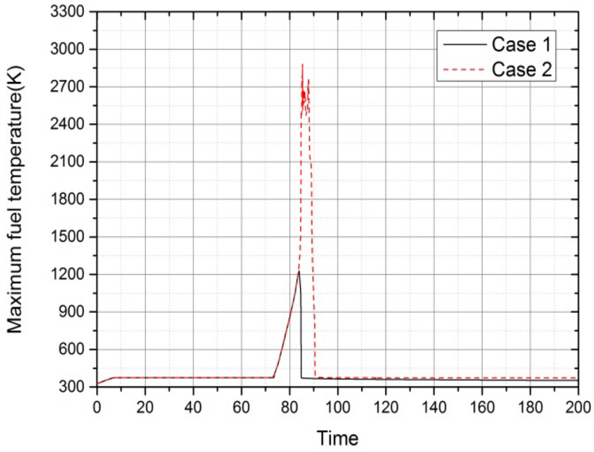

Fig 11. Maximum fuel temperature (implementation of the strategy to inject into the SFP).

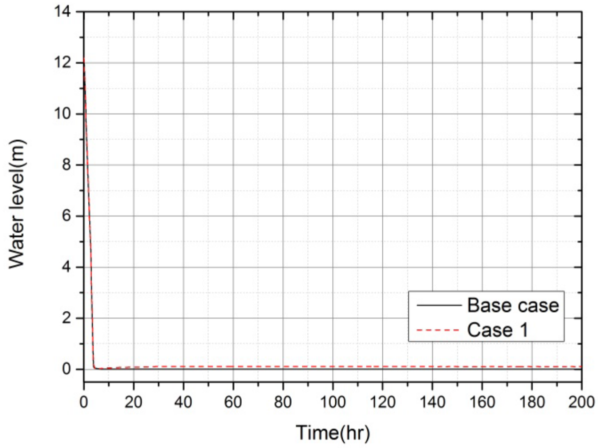

Fig 13. Water level in the SFP (implementation of the strategy to spray the spent fuel).

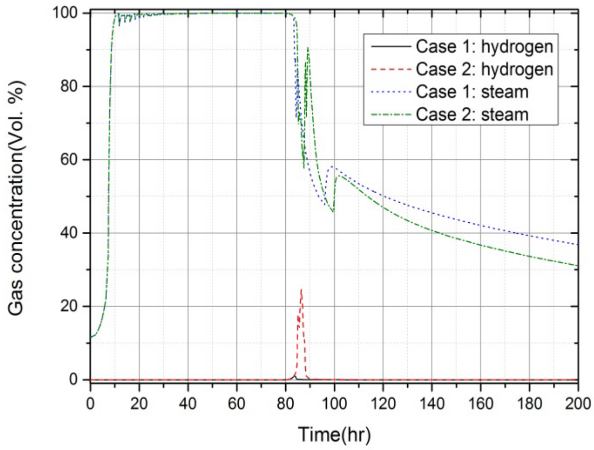

Fig 12. Hydrogen and steam concentration (implementation of the strategy to inject into the SFP).

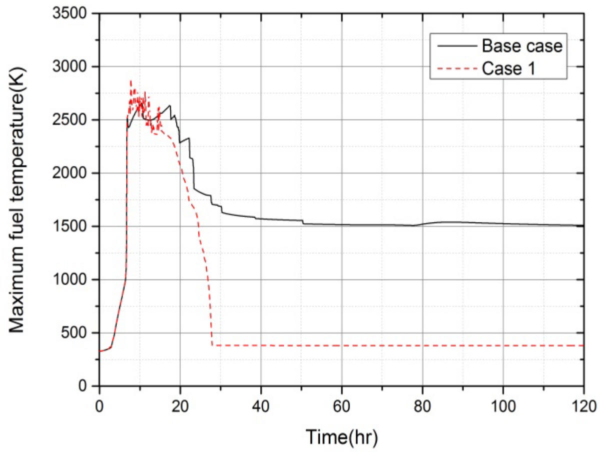

Fig 14. Maximum fuel temperature (implementation of the strategy to spray the spent fuel).

4.3 Spent Fuel Pool Spray

The SFP spray is also important strategy to mitigate the severe accident in the SFP. It is considered that the flow rate through the spray nozzle is 200 gpm for the analyses. For the sensitivity study, two cases were analyzed. In the base case, it is assumed that a leak in the bottom of the SFP occurs and there are no mitigation actions. In Case 1, the operation of the SFP spray started at 4 hr after spent fuel assemblies uncovered.

As shown in Fig. 13, the water levels rapidly decreased at the beginning of the accident. And the water level in the SFP does not increase in Case 1 as well as the base case due to the leak in the bottom. Even though the water level in the SFP does not increase, the fuel temperature decreases gradually in Case 1 as shown in Fig. 14. It is because quench and cool the overheated spent fuel by cooling from the top down.

4.4 Operation of the Ventilation System

The ventilation system including fans can help to decrease the hydrogen concentration in the fuel handling area. For the sensitivity study, two cases were compared. The base case is same with the LOSC sequence without any mitigation action. In Case 1, the operation of the ventilation system in the fuel handling area is considered. There are two types of the ventilation systems in the fuel handling area of the APR1400. One is the normal ventilation system, and the other is the emergency ventilation system. The flow rate of the normal ventilation system is around 5 times larger than the flow rate of the emergency ventilation system. In this analysis, it is assumed that the only operable ventilation system is the emergency ventilation system conservatively.

As shown in Fig. 15, the hydrogen concentration in the fuel handling area is less than 24 vol. % in Case 1, while the hydrogen concentration increases until 45 vol. % in the base case. It means that the hydrogen challenge in the fuel handling area can be reduced by the operation the ventilation system. And, if the normal ventilation system is available, then the capability to decrease the hydrogen concentration in the fuel handling area would be enhanced.

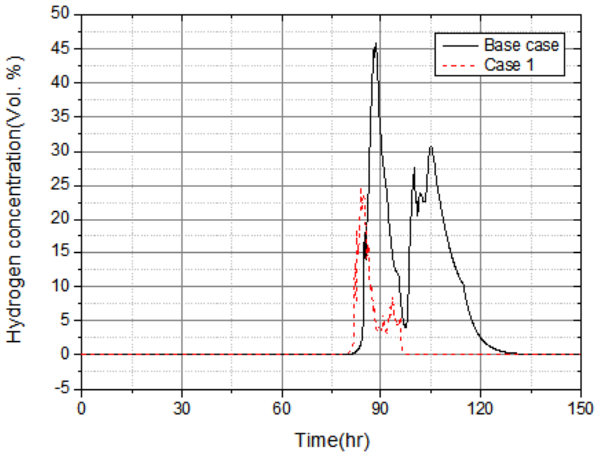

Fig 15. Hydrogen concentration (implementation of the strategy to vent the fuel handing area with the ventilation system).

4.5 Ventilation of the Fuel Handling Area by Opening the Door.

The door open is an alternative means to vent the fuel handling area for decreasing the hydrogen concentration. The major point of this method is to make the gas natural circulation in the fuel handling area. This method would be most effective if openings at both the spent fuel pool operating deck elevation and a higher elevation of the building could be created.

For the sensitivity study, two cases were compared. The base case is same with the LOSC sequence without any mitigation action. In the base case, two opening (doors) are modeled. The elevation of one opening is the spent fuel pool operating deck. And, the elevation of the other opening is 0.5 m above the spent fuel pool operating deck. On the other hand, in Case 1, the elevation difference between two openings is modeled as 15 m to evaluate the effectiveness of the ventilation according to the location of the openings.

Figure 16 shows the hydrogen generation rate. The Case 1 shows higher hydrogen generation rate than the base case. However, the hydrogen concentration in Case 1 is lower than that in the base case as shown in Fig. 17. It means that the hydrogen challenge in the fuel handling area can be reduced by openings at the different elevation. However, the strategy to open the doors shows less effective than the strategy to use the ventilation system including fans. Therefore, the strategy to open the doors should be considered as an alternative means.

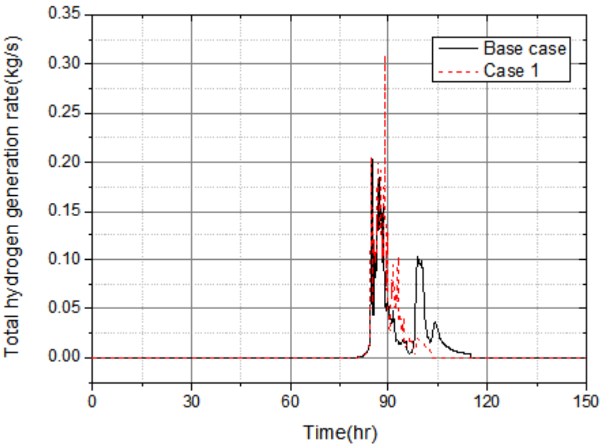

Fig 16. The hydrogen generation rate (implementation of the strategy to vent the fuel handing area by opening the doors).

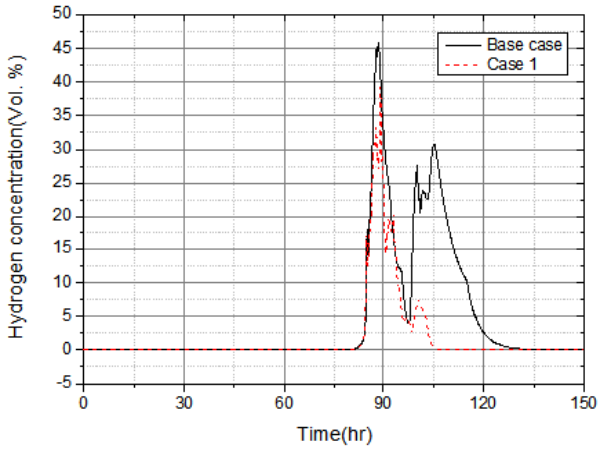

Fig 17. Hydrogen concentration (implementation of the strategy to vent the fuel handing area by opening the doors).

5. Summary and Conclusions

Various sequences regarding the severe accident in the SFP were analyzed by using the MAAP5 code. According to the analysis results, the early injection into the SFP can minimize the negative impacts such as the hydrogen generation by the MWR. Also the SFP can maintain the cooling capability by using the SFP spray even if there is a leak in the bottom of the SFP that is preventing level increase. The operation of the ventilation system is effective to reduce the concentration of the hydrogen. In addition, the opening of doors at a high and low elevation to establish flow through the fuel handling area can be an alternate method to reduce the hydrogen concentration in this area.

REFERENCES

[1] "Generic Severe Accident Management Guidance for the Advanced Power Reactor 1400 MW," Korea Hydro & Nuclear Power Company, Ltd., 2012.

[2] "Modular Accident Analysis Program (MAAP 5) Version 5.0.3 - Windows," Electric Power Research Institute, August 2014.