A Study on Required Spray Flow Rate to Mitigate Damage of Spent Fuel Pool Resulting in Large Leak Using MAAP5 Code

KYUNGHO NAM[1], KEOHYOUNG LEE[1], JUNGMIN SHIN[2]

[1] *Future & Challenge Technology Co., Ltd.: 32 Fl., 13 Heungdeok 1-ro, Giheung-gu, Yongin-si, Gyeonggi-do, Korea, khlee@fnctech.com*

[2] *Korea Hydro & Nuclear Power Co., Ltd. Central Research Institute, 70 1312-gil, Yuseong-daero, Yuseong-gu, Daejeon, Korea, jmshinkr@khnp.co.kr*

Spraying the Spent Fuel Pool (SFP) is considered an option to mitigate the spent fuel damage when there is a large leak in the bottom of the SFP and the leakage rate exceeds the make-up flow rate. In accordance with NEI 06-12, spraying at least 200 gpm per unit is considered a sufficient rate for SFP cooling. However, a methodology to determine a sufficient spray flow rate to cool recently discharged fuel is not presented in NEI 06-12. Thus, a study to investigate the required spray flow rate to mitigate the damage of SFP was carried out with the Modular Accident Analysis Program (MAAP) version 5. In this study, the local decay power of each spent fuel storage rack as well as the averaged decay power of the spent fuel in the SFP is considered. According to the analysis result, a flow rate of more than 200 gpm is necessary to maintain the integrity of all spent fuel in the SFP.

I. INTRODUCTION

In Nuclear Power Plants (NPPs), spent fuel assemblies unloaded from the reactor core are typically stored in a Spent Fuel Pool (SFP) to ensure their decay power is low enough and prevent spent fuel heat-up. The Fukushima accident, caused by a station blackout after an earthquake, led to concerns regarding the continued cooling capability of the SFP. Thus, the need to enhance means and strategies to maintain the spent fuel cooling capability during abnormal conditions has been highlighted. Injecting into the SFP and spraying the SFP are two major methods utilized to mitigate a spent fuel severe accident. Injection is the preferred method to increase the water level and cool the spent fuel in the SFP. However, if there is a large leak in the bottom of the SFP and the leakage rate exceeds the make-up flow rate, then spraying can be considered an option. Since spraying the SFP can cool the spent fuel from the top down, generally cooling the hotter surfaces first, the integrity of the spent fuel can be maintained without the recovery of the SFP water level.

To implement the SFP spray strategy, it is necessary to determine the SFP spray capability. In accordance with the Nuclear Energy Institute (NEI) document, NEI 06-12 (Ref. 1), spraying at least 200 gpm per unit is considered a sufficient rate for SFP cooling. In addition, NEI 06-12 recommends maximizing the spray flow rate for conditions following a refueling outage where fuel is recently discharged from the reactor. However, a methodology to determine a sufficient spray flow rate to cool the recently discharged fuel is not available in NEI 06-12. Thus, a study to investigate the required spray flow rate to mitigate the damage of the SFP was carried out.

II. ANALYSIS MODEL

II.A. Design Characteristics of Spent Fuel Pool

In this study, a typical SFP for Pressurized Water Reactor (PWR) NPPs was investigated as an example. The spent fuel assemblies are vertically stored in empty spaces in supporting structures called the spent fuel storage rack which are about 5 m in height. The spent fuel storage racks are made up of storage cells containing poison material for high density storage. The spent fuel storage racks are stainless steel structures of rectangular fuel storage cells which poison plates are attached on the outside. The rack modules are free standing on embedment in the SFP floor. As shown in Fig. 1, it is assumed that this example SFP for PWR NPPs has twelve (12) racks.

In case of the SFP for PWR NPPs, the spent fuel storage racks use a two region modular design composed of Region I and Region II as shown in Fig. 1. As shown in Fig. 1, it is assumed that Region I has three (3) racks and Region II has nine (9) racks. Each fuel assembly must be stored within a Region I or Region II rack when placed into the SFP. The partially burnt fuel assemblies are stored only in Region I racks due to recriticality, and the completely burnt fuel assemblies are stored in Region II racks.

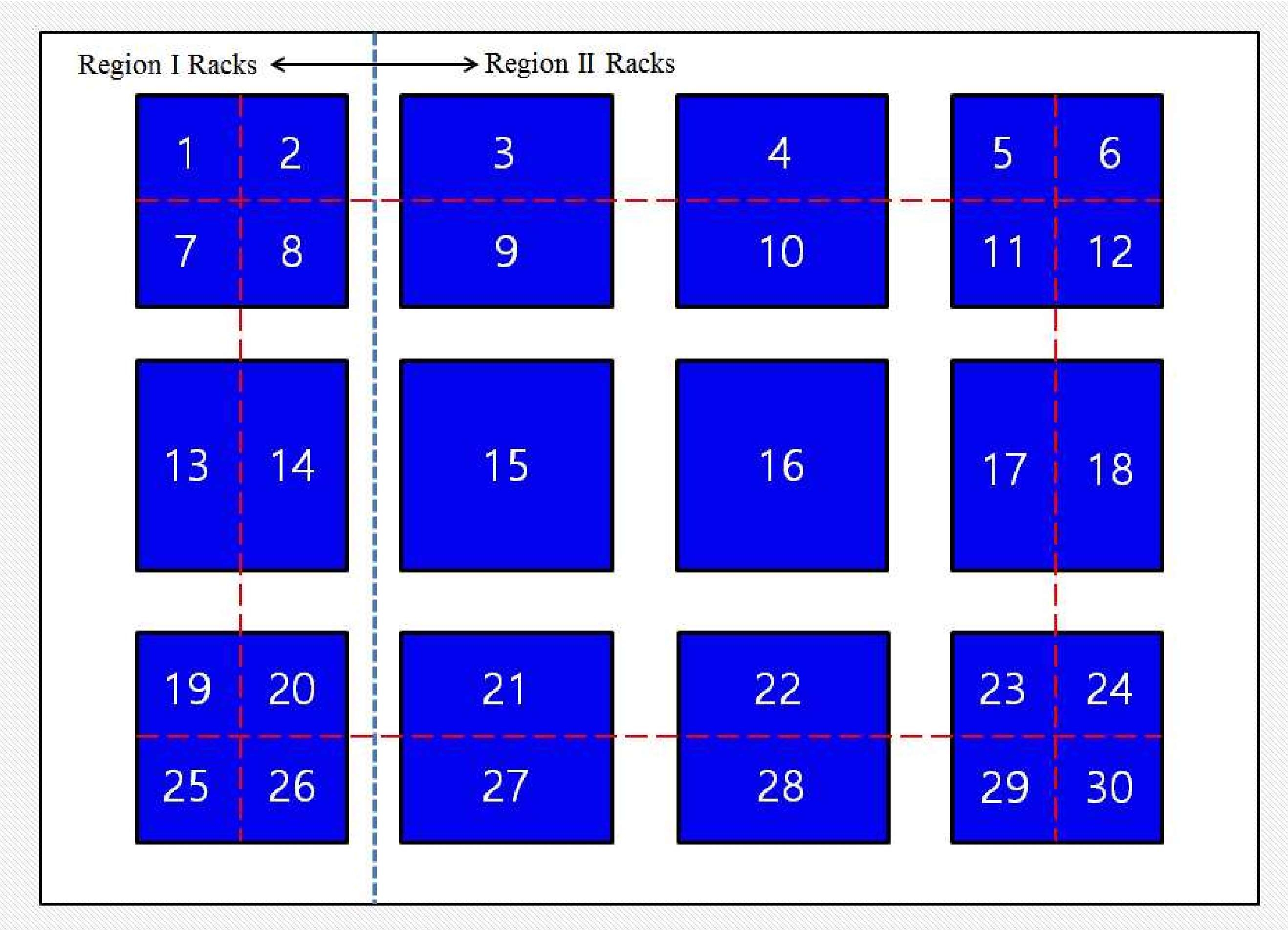

Fig. 1. A Schematic Diagram of Spent Fuel Storage Racks for a typical SFP for PWR NPPs.

II.B. Modeling for Analysis Using MAAP5

Following the accident at Three Mile Island Unit 2, the nuclear power industry has developed Modular Accident Analysis Program (MAAP) 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). Version 5.0.3 of MAAP (Ref. 2), which is the most recent version, includes current state-of-the-art phenomenological models. Also, this version has the capability to simulate accidents in the SFP. Thus, for the evaluation of the SFP spray capability during the accident on the SFP, MAAP5 was used to evaluate the SFP spray capability.

The SFP model was developed by using typical design data for the spent fuel and the SFP. Variables for geometry of the spent fuels, the spent fuel storage racks, and the SFP were referred to the typical information, however, some variables such as total number of stored spent fuels, maximum burn-up rate of last cycle, cycle lengths, elapsed time after reactor scram, cycle outage length, etc. were assumed. For a realistic burn-up rate, the accumulated burn-up at the end of cycle is assumed to be 50000 MWD/MTU. Thereby, the decay heat generated in the first cycle was assumed to be 42%, 81% in the second cycle, and 100% in the final cycle. This provides a more realistic power history between the fuel cycles. And, the cycle length, elapsed time after reactor scram, etc. are calculated based on the assumed burn-up and typical plant data (e.g. total uranium mass). It was assumed that fuel assemblies from 10 cycles are accumulated in the SFP. Since the first fuel assembly group consists of three batch types, total 12 fuel assembly groups were defined in the SFP model. The cooling time of first fuel assembly group was determined to be 150 hours. In addition, the cycle outage length during the overhaul period and the cycle lengths were assumed to be 1 month and 15 months, respectively. Information relating to the spent fuel is listed in Table I.

TABLE I. Spent Fuel Information for MAAP5 Model

Variables	Input			Notes
Cycles	Definition	Input		Unit: month
	Cycle length	15		
	Cycle outage length	1		
	The cooling time of spent fuel assemblies	1st group	150	Unit: hour
		2nd group	150	
		3rd group	150	
		4th group	15.2	Unit: month
		5th group	31.2	
		6th group	47.2	
		7th group	63.2	
		8th group	79.2	
		9th group	95.2	
		10th group	111.2	
		11th group	127.2	
		12th group	143.2	
Burn-up (MWD/MTU)	1st cycle for 1st group	21000		Maximum burn-up rate : 50000 MWD/MTU
	2nd cycle for 2nd group	40500		
	3rd cycle for other groups	50000		
Number of spent fuel assemblies	1st group	59		Number of fuel assembly
	2nd group	59		
	3rd group	59		
	4th group	68		
	5th group	68		
	6th group	68		
	7th group	68		
	8th group	68		
	9th group	68		
	10th group	68		
	11th group	68		
	12th group	68		
Enrichment	4.2			Unit: %

The SFP floor and side walls were represented by distributed heat sinks which may be ablated by molten corium. Non-uniform distribution of decay power according to the axial power peaking factor was applied in the axial direction of the spent fuel assembly. 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 as illustrated in Fig. 2.

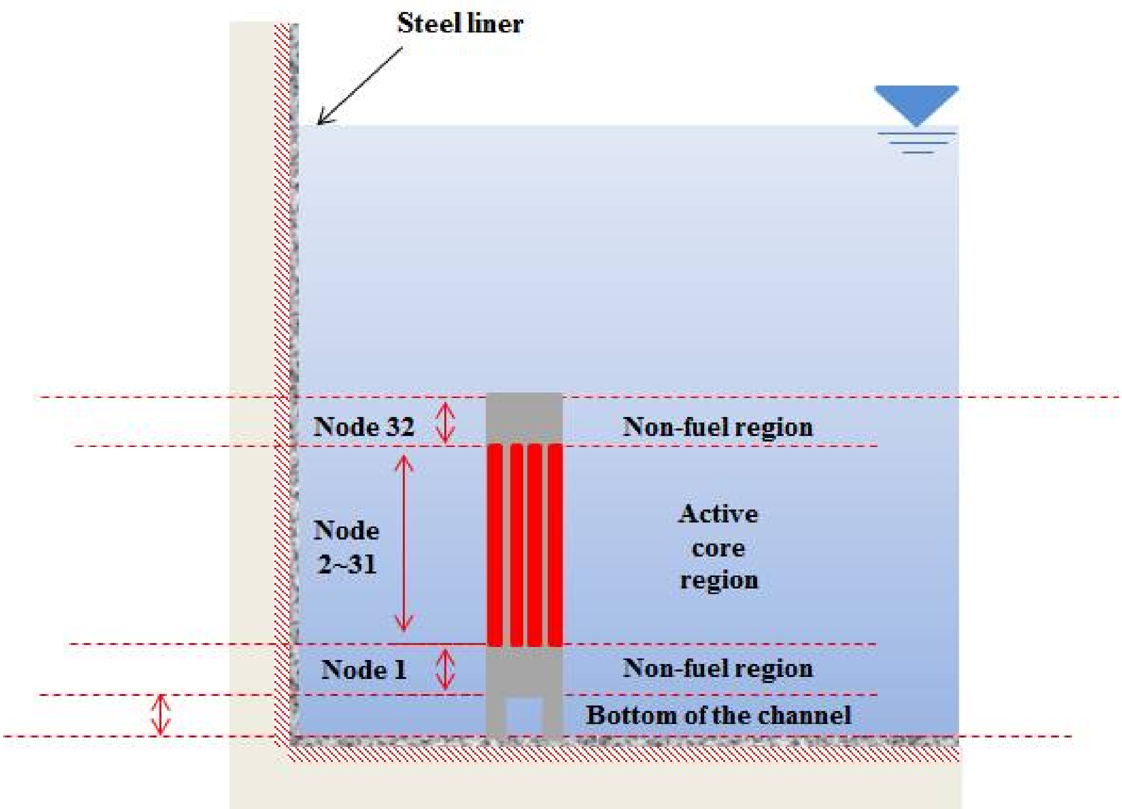

Fig. 2. A Schematic Diagram of Spent Fuel Assembly in the SFP Model.

It is necessary to arrange channels (concept of MAAP5) to compose multiple fuel assembly groups to build SFP models. The channels in the SFP refer to the radial arrangement of the spent fuel pool racks relative to one another and the spent fuel pool structural walls. Once the racks begin to have significant interaction with adjacent racks and the SFP walls, it is necessary to have a detailed radial model in order to account for the temperature gradients developing near the boundary. Temperatures gradients develop due to radiation heat transfer between the adjacent rack regions and the SFP wall. The SFP structural walls are made of thick concrete and maintain a relatively cold temperature when compared to the fuel racks. Therefore, the assemblies on the outer edges of the pool will have significant radiation heat transfer to the SFP walls because of the large temperature difference present in the area. Similarly, racks in the center of the SFP will have temperatures near the adjacent fuel racks which will limit the heat transfer. With the limiting radiation heat transfer the center rack regions will increase in temperature due to the lack of an available heat sink. Therefore, a significant temperature gradient can develop across the radial regions in the SFP In MAAP5, there is a balance between providing a detailed model to account for the radial temperature gradient which can develop and providing a model with too much detail. MAAP5 model run time will increase with the addition of every radial node. Additionally, providing a radial node with only several assemblies can lead to localized hot channels which are not physical and produce skewed results. Thus, the SFP was divided into 30 channels as shown in Fig. 1. The modeled value of 30 provides sufficient detail for the development of the radial temperature gradient while managing run time and relevant results.

On the other hands, Region I and Region II racks have different geometry. In case of Region II racks, there is only one (1) wall to divide each storage cell to insert the spent fuel assembly. And, there is no gap between the cells in Region II racks. However, Region I racks have two (2) walls and a gap between each storage cell. Thus, the multiple fuel rack type option available in MAAP5 was applied to model the spent fuel racks. However, the current MAAP5 does not have the capability to model the gaps between the storage cells. Thus, it was assumed that the gap area between the storage cells is included in the storage cell area in this SFP model.

And, in order to simulate the SFP accident conditions, a junction for a leakage on bottom of the SFP and junctions to connect the fuel handling area and the environment node were modeled as illustrated in Fig. 3. Even though NPPs located in

Korea have not adopted the SFP spraying system until now, NPPs which are abroad have this system and the SFP spray is considered a strategy for the SFP. Normally, standpipes are located at diverse locations at the fuel handling area and each standpipe has a hard piped connection to a fixed spray nozzle. The SFP spray is simulated by using the constant flow spray model in MAAP5. This model is applicable for any containment or auxiliary building compartment. The inputs for the constant flow spray model are the spray droplet diameter, the spray fall height, the spray water temperature, and the spray water flow rate.

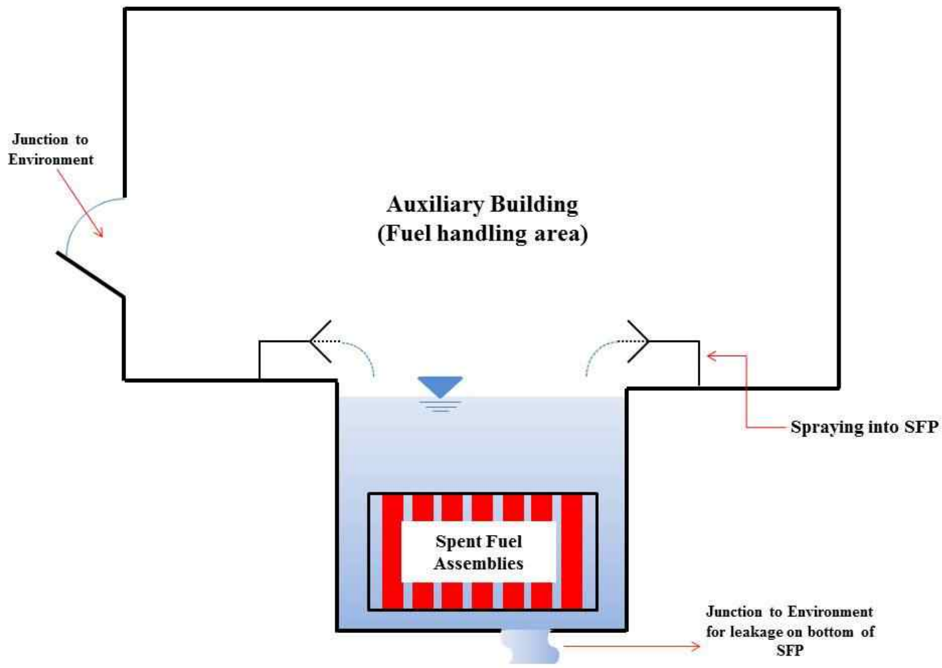

Fig. 3. A Schematic Diagram of Fuel Handling Area in the SFP Model.

III. RESULTS AND DISCUSSION

The loss of SFP water accident can be resulted from a leak in the SFP as presented in Fig. 3. If the leak area is large, then the leakage rate can exceed the injection flow rate. In this situation, the SFP spray can be considered to mitigate the accident in the SFP. To determine the minimum SFP spray flow rate for this situation, not only the total averaged decay power of the spent fuel in the SFP but also the local decay power of each spent fuel storage rack must also be considered. The crucial facets for this evaluation are the grouping of the spent fuel assemblies and the arrangement of the fuel assembly groups. As described in Section II.B, the partially burnt fuel assemblies are stored only in Region I racks due to recriticality, and the completely burnt fuel assemblies are stored in Region II racks. The dominant factors to divide the fuel assembly groups are cooling time and accumulated burn-up. Namely, the fuel assembly groups which are partially burnt and have the shortest cooling time are installed in Region I, and the others are installed in Region II. Because of this spent fuel arrangement, the decay power released in Region I racks is much higher than that of Region II racks. Therefore, when considering that the spray is uniformly distributed to each rack, the required SFP spray flow rate should be determined based on the decay power of the spent fuel in Region I conservatively.

Considering the design of the SFP described above, seven (7) sensitivity cases were selected to determine the required spray flow rate by using MAAP5. The sensitivity conditions include the spray flow rate and the arrangement of the fuel assembly groups as listed in Table II. In addition, the existence of the gap between the storage cells in Region I racks were considered a sensitivity condition. As described in Section II.B, it was assumed that the gap area between the storage cells is included in the storage cell area due to the modeling limitation of the current MAAP5 version. However, it should be considered conservatively that the heat removal rate by the water to spray into the gap is less than that of the water to spray into the storage cells. Thus, the cases not considering the heat removal by water to spray into the gap were selected as sensitivity cases. In these sensitivity analyses, the start time of spray was set when the SFP water level reaches the bottom of the SFP.

Table II. Summary of Test Cases for the Sensitivity Study

<table>
<tr><th rowspan="2">Case</th><th colspan="3">Description</th></tr>
<tr><th>Spray flow rate [gpm]</th><th>Arrangement</th><th>Existence of gap between the cells in Region I racks</th></tr>
<tr><td>Case 1</td><td rowspan="2">200</td><td>Uniformly distributed in all racks (channels)</td><td rowspan="4">Plant-specific gap distance in Region I racks</td></tr>
<tr><td>Case 2</td><td rowspan="6">* 1st and 2nd group spent fuel assemblies
: Uniformly distributed in Region I racks
(Channel No. 1,2,7,8,13,14,19,20,25, and 26)
* From 3rd to 12th group spent fuel assemblies
: Uniformly distributed in Region 2 racks
(Other channels)</td></tr>
<tr><td>Case 3</td><td>210</td></tr>
<tr><td>Case 4</td><td>220</td></tr>
<tr><td>Case 5</td><td>250</td><td rowspan="3">No gap in Region I racks</td></tr>
<tr><td>Case 6</td><td>300</td></tr>
<tr><td>Case 7</td><td>350</td></tr>
</table>

III.A. Arrangement of Spent Fuel Assemblies Stored in the SFP

In MAAP5, the types and number of fuel assemblies for each channel can be specified. For a given channel, there can be filled or empty cells as illustrated in Fig. 4 (Ref. 3). And, average fuel assembly properties are used to represent filled cells. In the analysis for Case 1, it was assumed that all fuel assemblies stored in the SFP are uniformly distributed in all racks (channels) as illustrated in Fig. 5. And the flow rate through the spray nozzle is set to 200 gpm, as suggested in NEI 06-12 (Ref. 1). According to the analysis result, the SFP water level rapidly decreases in the beginning of the accident due to the crack in the bottom of the SFP as shown in Fig. 6. Even though the water level in the SFP decreases below the top of the spent fuel assemblies, the maximum fuel temperature does not increase by spraying on the SFP with 200 gpm as shown in Fig. 7. It is because spraying the SFP cools the spent fuel from the top down and the spray flow rate is enough to remove the decay power of all spent fuel. According to the analysis for Case 1, if the spent fuel assemblies are uniformly distributed in all racks, then a rate of spray water for SFP cooling can be set to 200 gpm per unit.

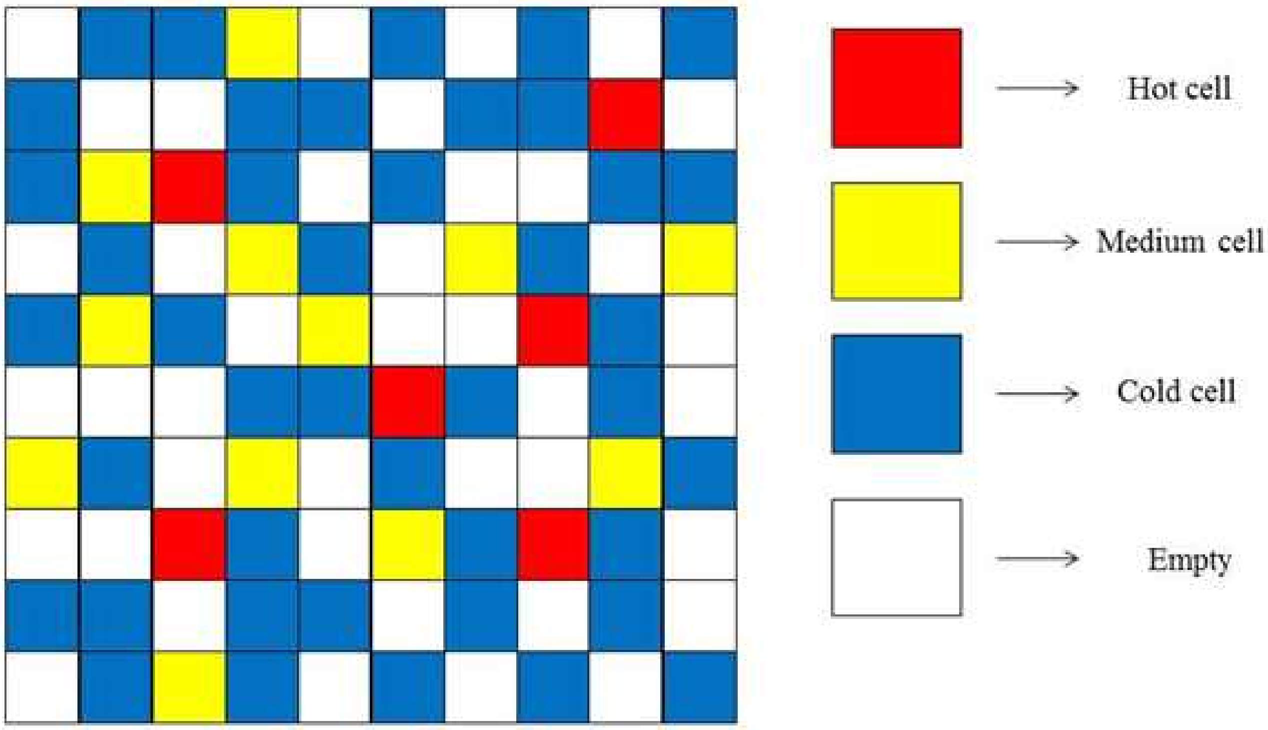

Fig. 4. An Example of Spent Fuel Assemblies in a Spent Fuel Channel.

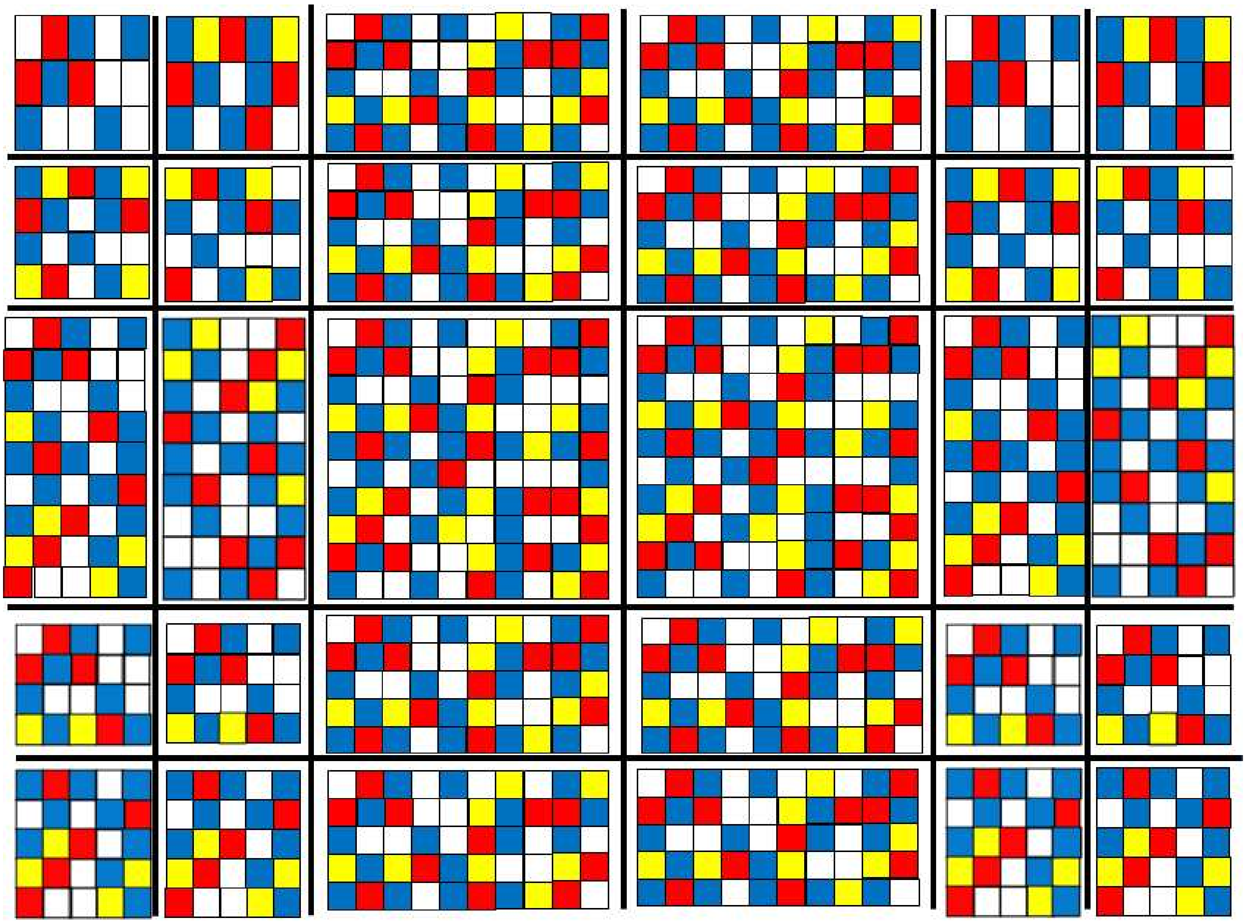

Fig. 5. An Arrangement of Spent Fuel Assemblies for Case 1 in the SFP with 30 Channels.

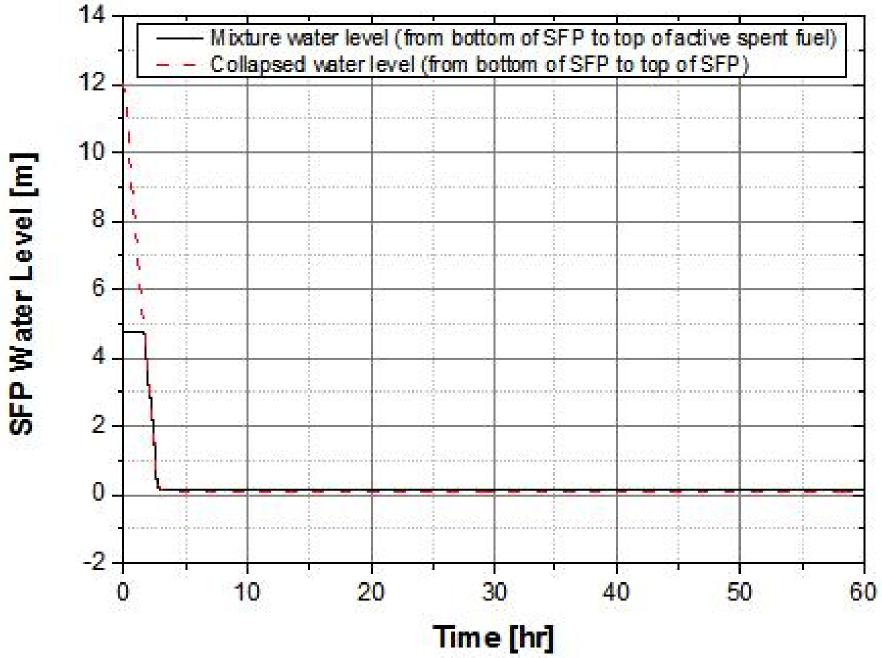

Fig. 6. SFP Water Level for Case 1.

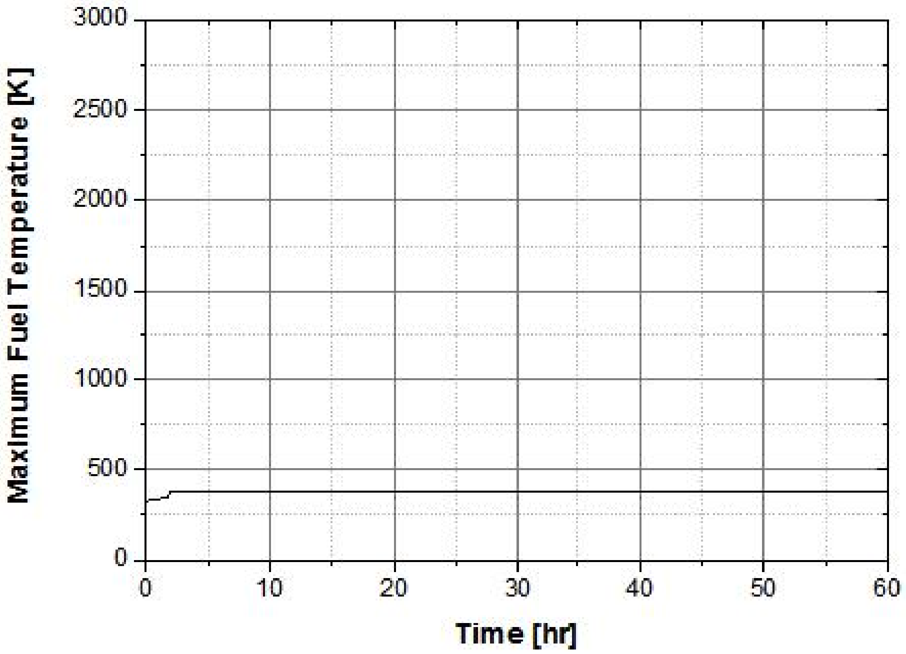

Fig. 7. Maximum Temperature of Spent Fuel for Case 1.

However, the partially burnt fuel assemblies which have short cooling time and high decay power are stored only in Region I racks during refueling outage as described in Section II.B. Therefore, a realistic arrangement of the spent fuel assemblies should be considered for the realistic evaluation. Expected distribution of the spent fuel assemblies during refueling outage is presented in Fig. 8. And, in the analysis for Case 2, the arrangement illustrated in Fig. 8 was applied. According to the analysis result, the maximum fuel temperature rapidly increased and exceeded 2500 K in spite of spraying the SFP as shown in Fig. 9. For the detailed evaluation, the fuel temperature behavior on each channels were identified and presented in Fig. 10 through Fig. 13.

The temperature of the spent fuel in channel no.16 did not increase as shown in Fig. 12. It is because channel no. 16 is included in Region II racks which have relatively low decay power. However, the temperature of channel no. 13 and 19 which are included in Region I racks increased and exceeded 2500 K as presented in Fig. 11 and Fig. 13. If the spent fuel assemblies are not uniformly distributed during the refueling outage, then 200 gpm is not sufficient spray flow rate to cool the recently discharged spent fuel. Therefore, it is necessary that the required SFP spray flow rate is determined based on the decay power of the spent fuel in Region I conservatively.

On the other hands, even though channel no. 1 is included in Region I racks, the temperature of the spent fuel did not increase as shown in Fig. 10. It is because there are two types of racks in Region I. First rack type is for channel no. 1, 2, 7, and 8, and second rack type is for channel no. 13, 14, 19, 20, 25, and 26. The cell size and the gap distance in the first rack type (e.g. channel no. 1) are larger than those in the second rack type (e.g. channel no. 13) as illustrated in Fig. 14. Thus, the temperature in channel no. 1 could be maintained with low. This result showed that the rack geometry such as the cell size and the gap distance contributes to the spray cooling effect. Therefore, the sensitivity study regarding the existence of the gap between the storage cells was performed and the evaluation results were presented in Section III. C.

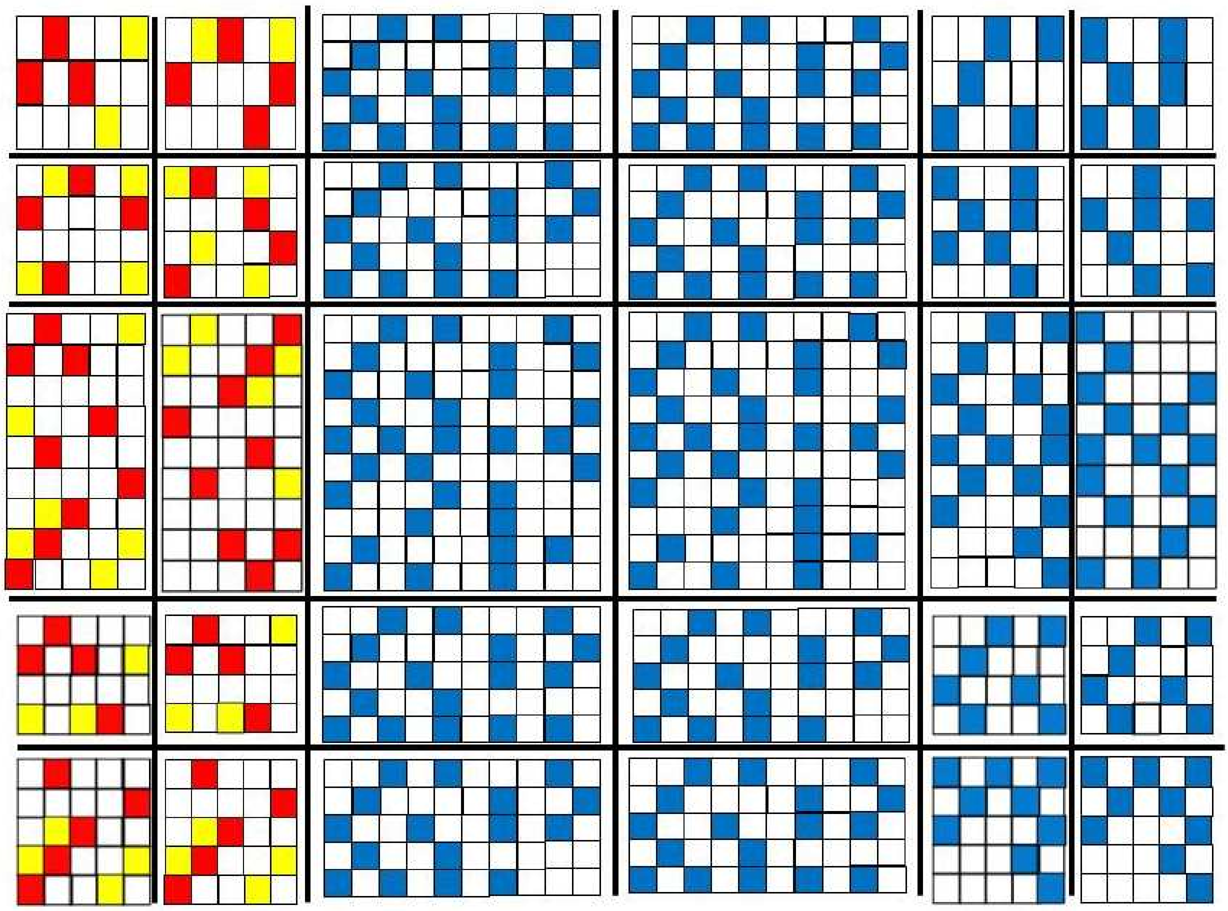

Fig. 8. An Arrangement of Spent Fuel Assemblies for Case 2 ~ 8 in the SFP with 30 Channels.

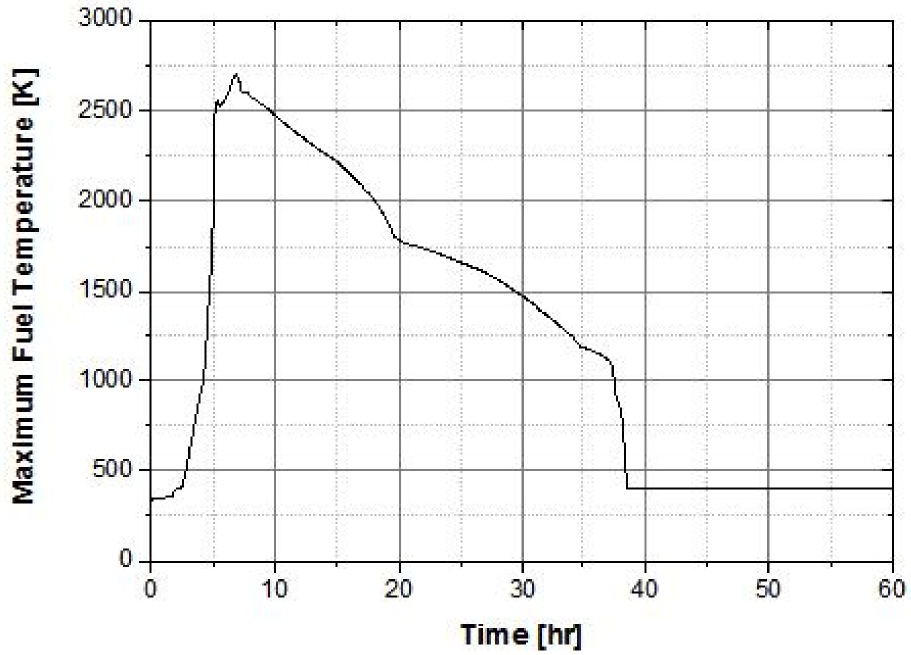

Fig. 9. Maximum Temperature of Spent Fuel for Case 2.

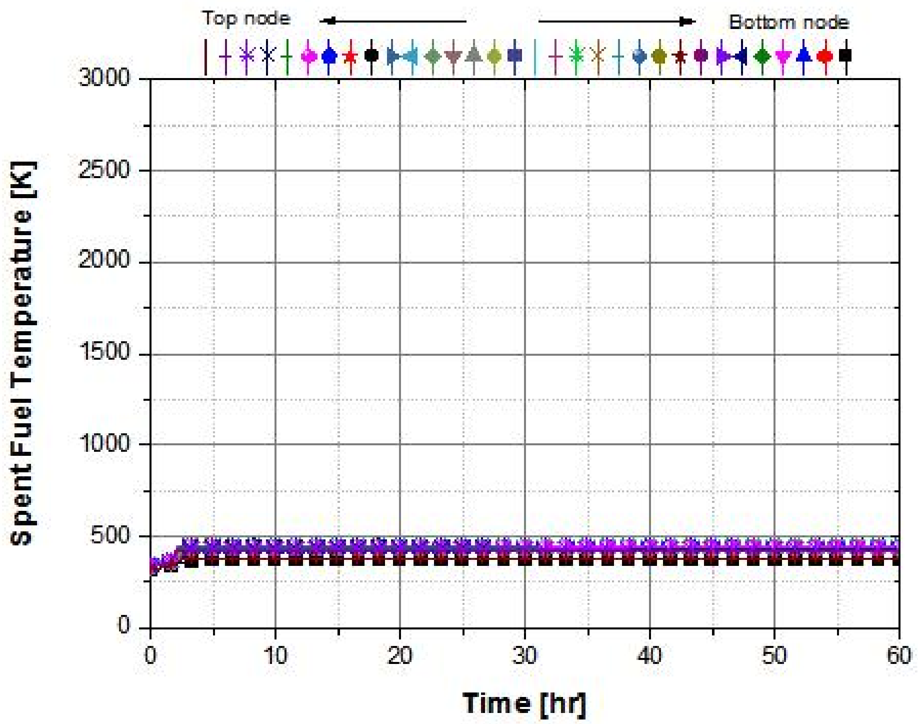

Fig. 10. Spent Fuel Temperature of Channel No. 1 for Case 2.

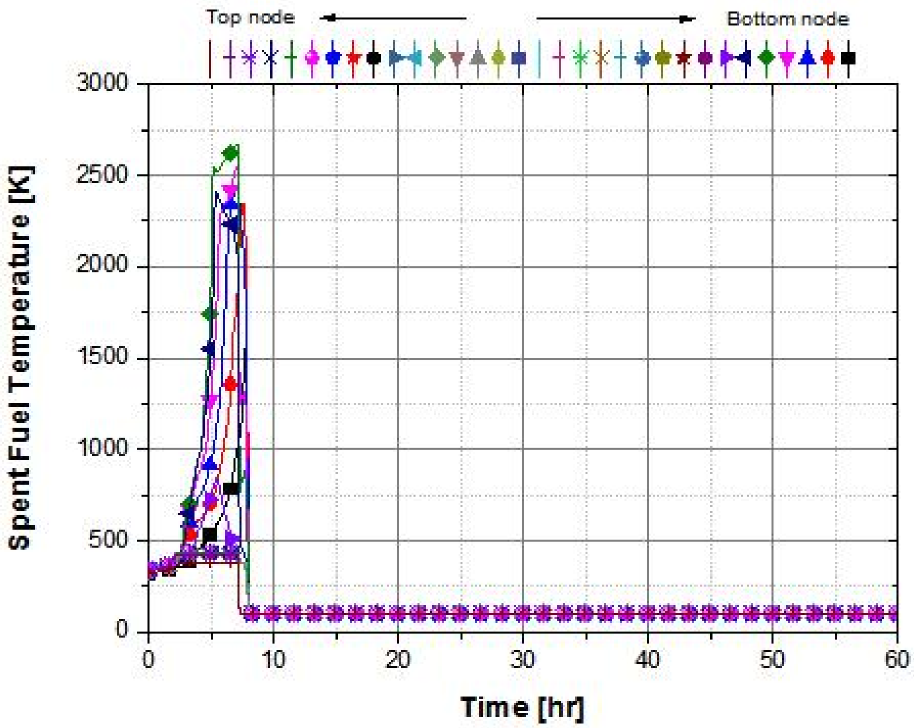

Fig. 11. Spent Fuel Temperature of Channel No. 13 for Case 2.

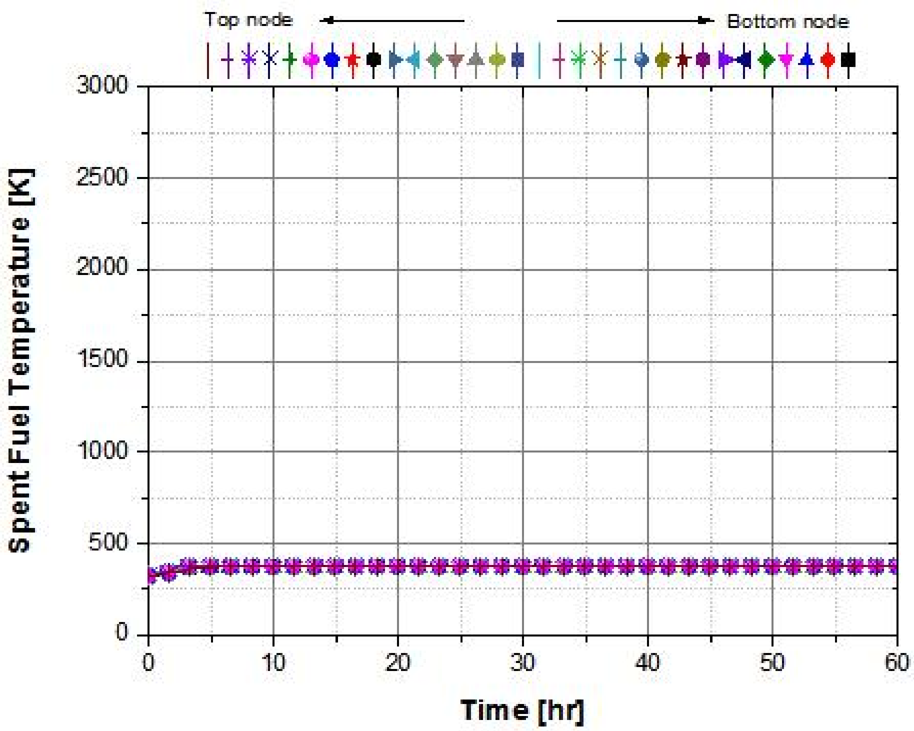

Fig. 12. Spent Fuel Temperature of Channel No. 16 for Case 2.

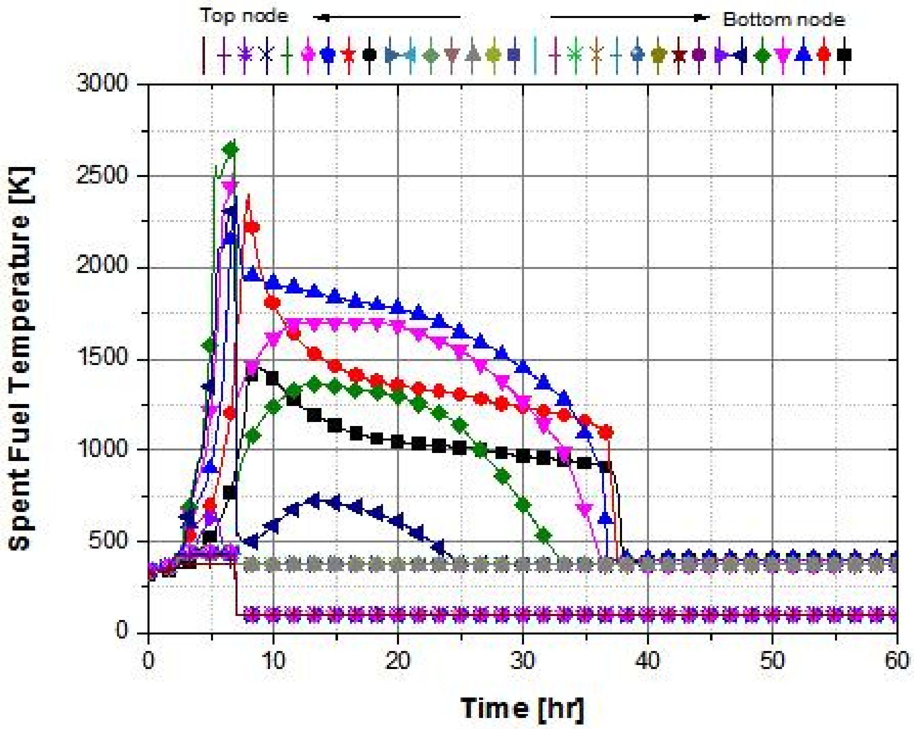

Fig. 13. Spent Fuel Temperature of Channel No. 19 for Case 2.

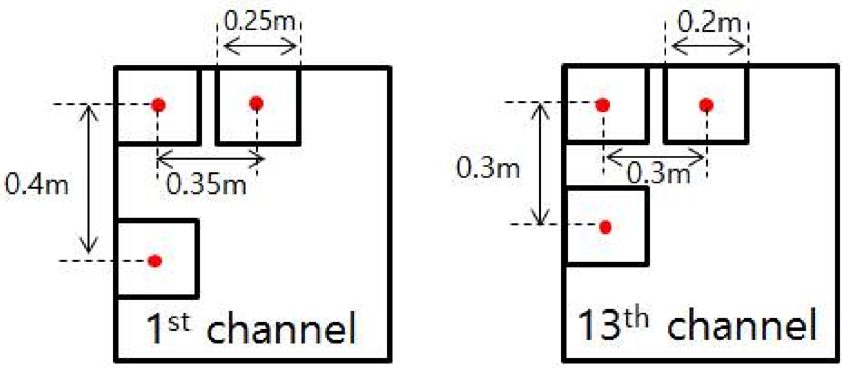

Fig. 14. Schematic Diagrams of the Cell Size and the Center-to-center Distance between the Adjacent Cells.

III.B. Sensitivity Study on Spray Flow Rate

According to the result of section III A, the temperature in channel no. 13 and 19 exceeded 2500 K in spite of the SFP spraying at 200 gpm. Thus, in this section, the sensitivity study regarding the spray flow rate was carried out. The spray flow rate increased by 10 gpm step-by-step for sensitivity cases as listed in Table II.

In Case 3, the temperature of the spent fuel in channel no. 13 increased and exceeded 2500 K as shown in Fig. 15. It means that 210 gpm is not sufficient spray flow rate to cool all spent fuel in the SFP. However, if the spray flow rate is larger than 220 gpm in Case 4, then the temperature could be maintained with low and the peak temperature is about 600 K as presented in Fig. 16. From these results, it can be concluded that the required SFP spray flow rate based on the decay power of the spent fuel in Region 1 is 220 gpm.

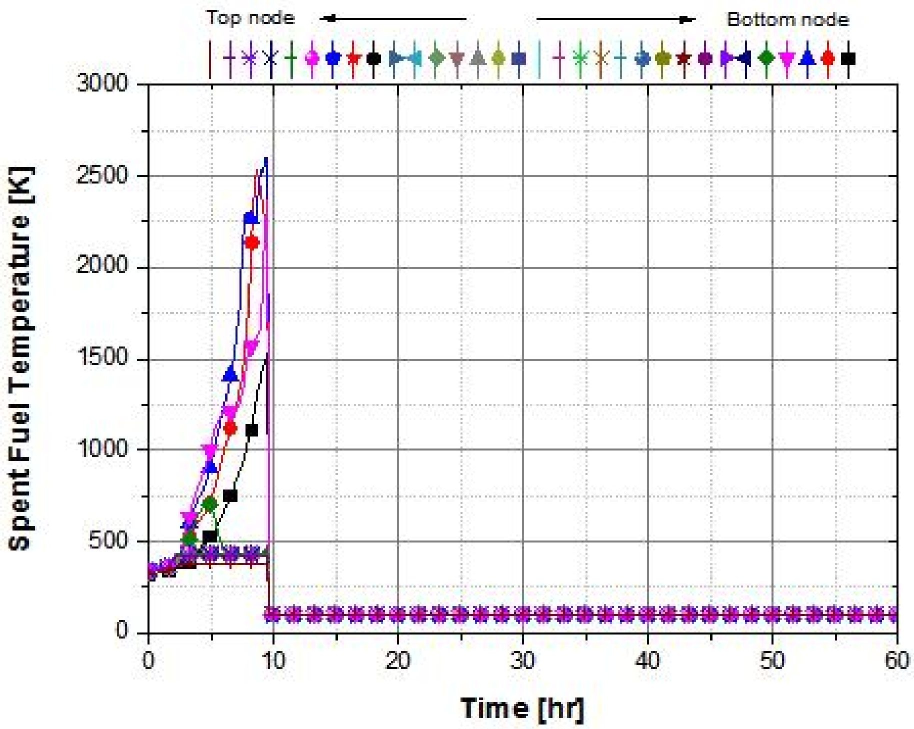

Fig. 15. Spent Fuel Temperature of Channel No. 13 for Case 3.

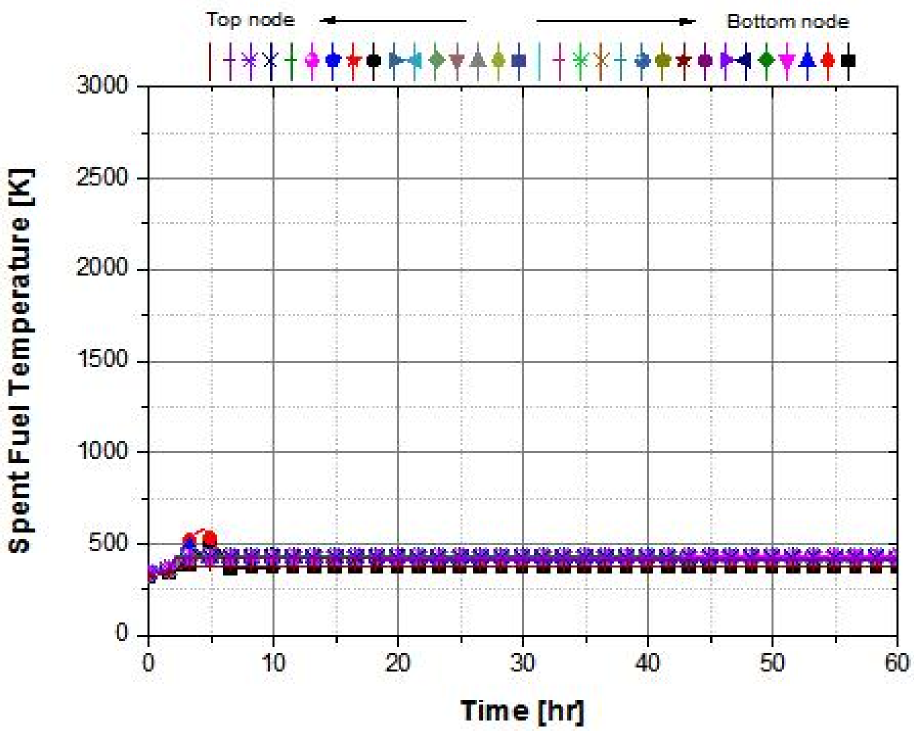

Fig. 16. Spent Fuel Temperature of Channel No. 13 for Case 4.

III.C. Influence of Existence of the Gap between the Storage Cells

According to the result of section III A, the temperature behavior in channel no. 13 is different from channel no. 1. It is because the cell size and the gap distance of channel no. 1 are larger than those of channel no. 13 as illustrated in Fig. 14. When considering that the gap area is included in the storage cell area due to the modeling limitation of the current MAAP5 version, the difference in the temperature behavior was caused by the over-estimated storage cell area of each channel. Since the heat removal rate by the water sprayed into the gap is less than that by the water sprayed into the storage cells, it is necessary to evaluate the influence of the existence of the gap between the storage cells. Thus, in this section, the sensitivity study regarding the existence of the gap was carried out.

For these sensitivity analyses, the center-to-center distance between the adjacent cells in Region I rack was reduced as illustrated in Fig. 18. Thus, Region I racks were modeled without gap between the storage cells for the sensitivity cases. And, the spray flow rate increased by 50 gpm step-by-step as listed in Table II.

In Case 5, when the spray flow rate was 250 gpm, the temperature of the spent fuel in channel no. 13 increased and exceeded 2500 K as shown in Fig. 19. When the spray flow rate was 300 gpm, the peak temperature was about 2300 K as illustrated in Fig. 20. It means that 300 gpm is also not sufficient spray flow rate to cool all spent fuel in the SFP. However, if the spray flow rate is set at 350 gpm, then the temperature could be maintained at a relatively with low value and the peak temperature is about 600 K as presented in Fig. 21. From these results, it can be concluded that the required SFP spray flow rate based on the most conservative methodology (to consider the local decay power of the spent fuel storage racks and not to consider the heat removal by the water to spray into the gap) is about 350 gpm per unit. And this value is considerably larger than 200 gpm suggested in NEI 06-12 (Ref. 1).

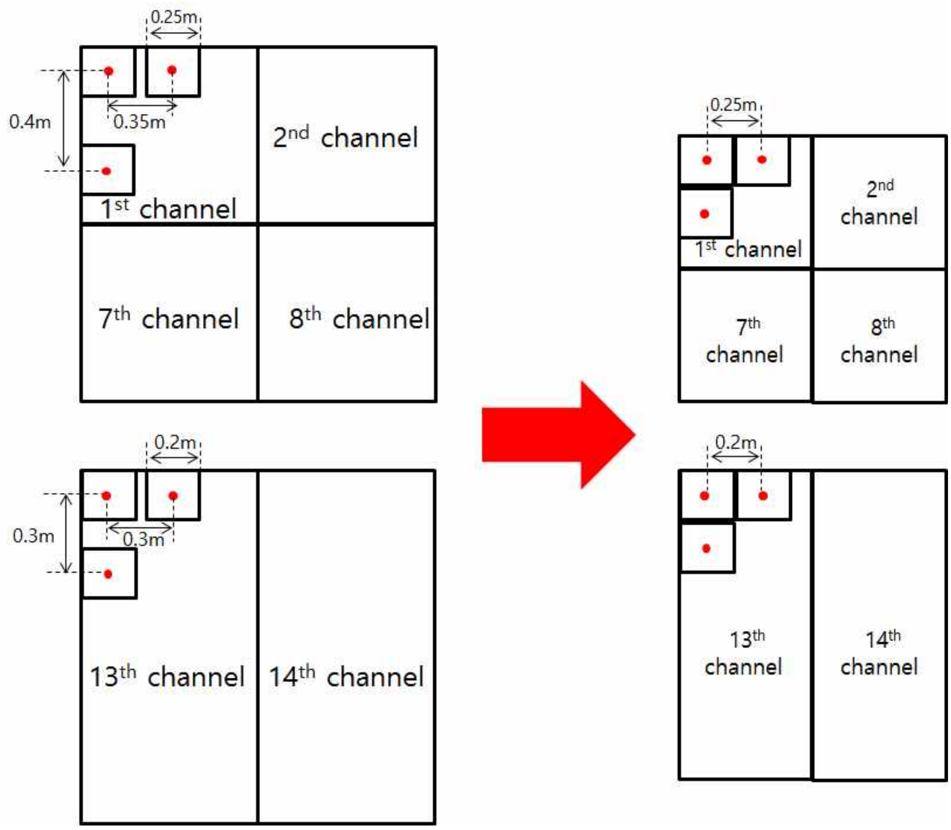

Fig. 18. Schematic Diagrams of the Changed Center-to-center Distance between the Adjacent Cells.

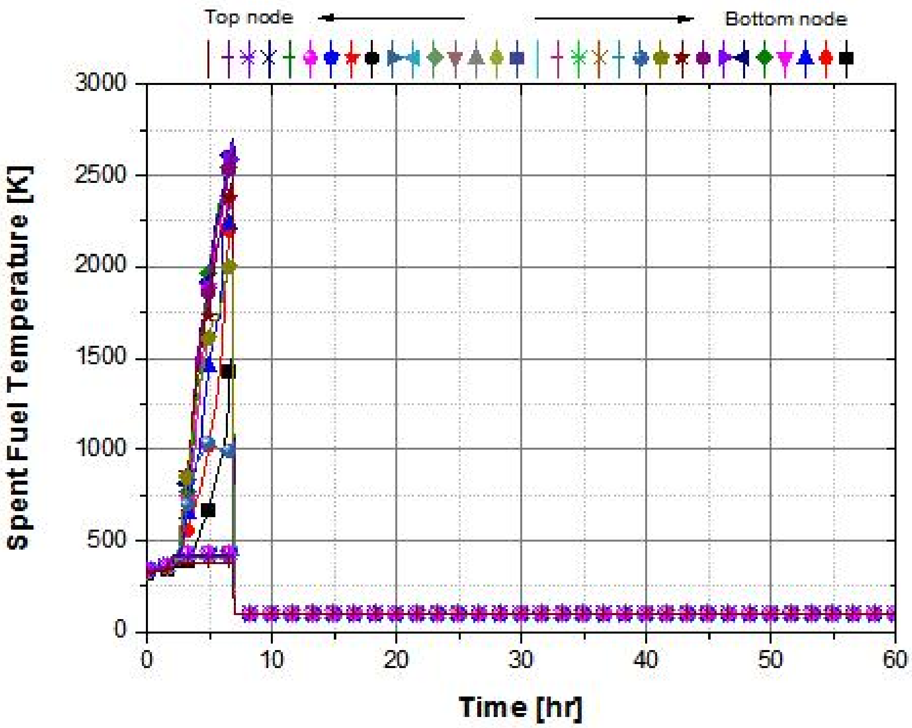

Fig. 19. Spent Fuel Temperature of Channel No. 13 for Case 5.

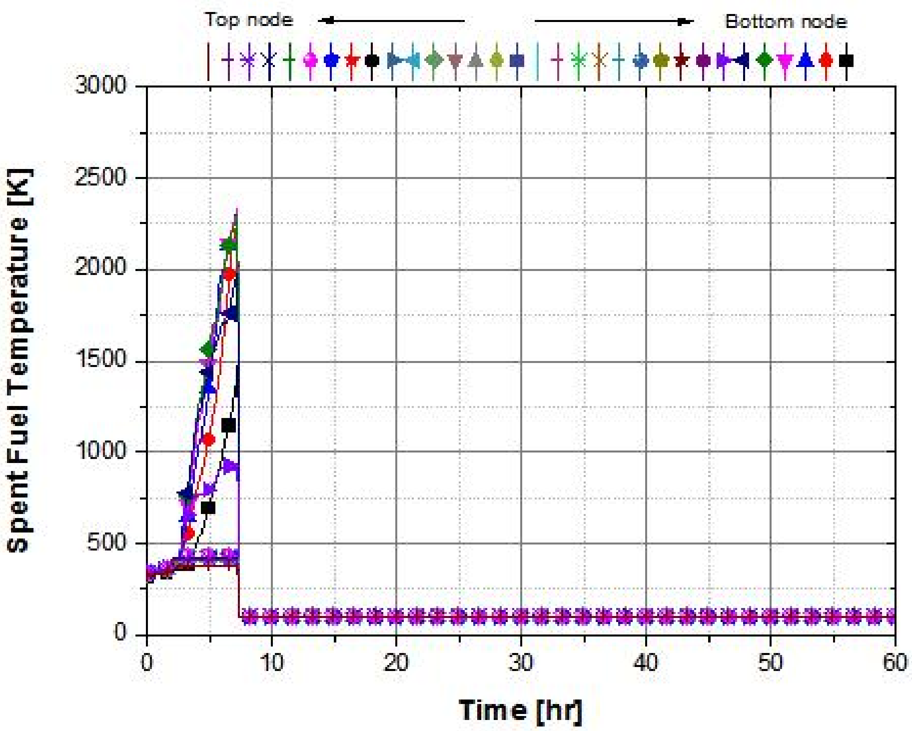

Fig. 20. Spent Fuel Temperature of Channel No. 13 for Case 6.

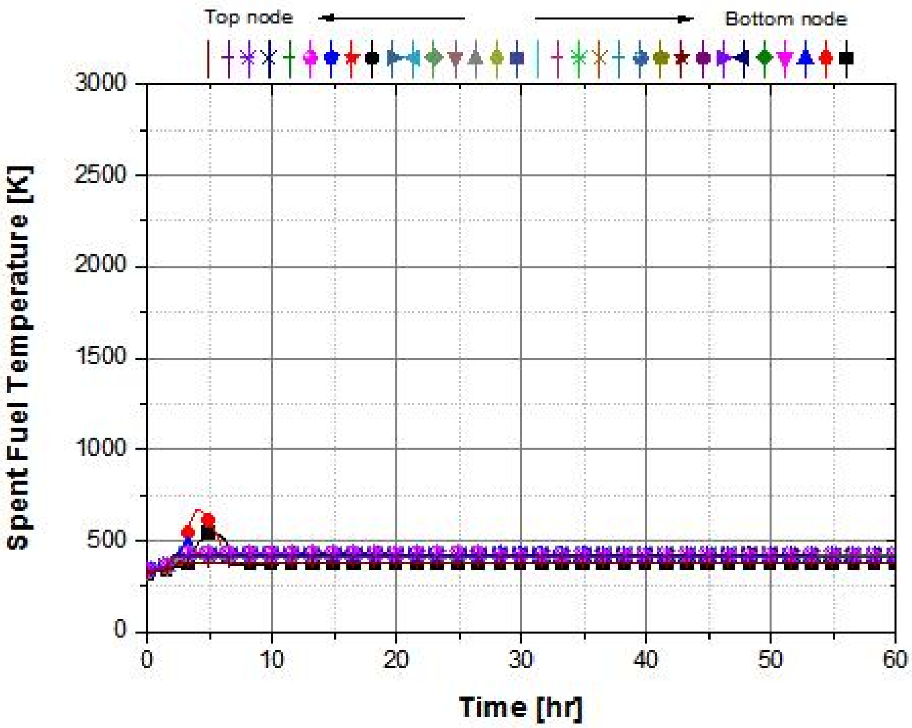

Fig. 21. Spent Fuel Temperature of Channel No. 13 for Case 7.

II. SUMMARY AND CONCLUSIONS

Sensitivity analyses were performed by using MAAP5 to determine the required spray flow rate. The sensitivity conditions include the spray flow rate, the arrangement of the fuel assembly groups, and the existence of the gap between the storage cells in Region I. Different arrangements of the spent fuel assemblies were taken into account. If all spent fuel assemblies are distributed uniformly irrespective of recriticality, the recommended spray rate in accordance with NEI 06-12 (Ref. 1) is sufficient, even considering the conditions during a refueling outage. However, when the partially burnt fuel assemblies are stored in Region I, the temperature of almost spent fuel assemblies in Region I rack increased rapidly. Eventually, the spent fuel assemblies in Region I could be damaged and severe accident phenomenon such as the hydrogen generation could occur. Even though the required spray flow rate depended on the sensitivity cases, the analyses showed that the flow rate of more than 200 gpm was necessary to maintain the integrity of all spent fuel in the SFP during the refueling outage. And, when determining the sufficient SFP spray flow rate to maintain the integrity of the spent fuel, the most conservative methodology, which was suggested in this paper by considering the local decay power of the spent fuel storage racks and not considering the heat removal by the water to spray into the gap, are recommended for nuclear safety.

ACKNOWLEDGMENTS

This work was supported by Korea Hydro & Nuclear Power Company, Ltd. (KHNP). The authors would like to thank the staff in the Central Research Institute of KHNP for many helpful technical discussions.

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