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Development of MAAP5.0.3 Spent Fuel Pool Model for Severe Accident Analysis

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1. Introduction

After the Fukushima accident, the severe accident phenomena in the Spent Fuel Pool (SFP) have been the great issues in the nuclear industry. Generally, during full power operation status, the decay heat of the spent fuel in the SFP is not high enough to cause the severe accident that is the say, the melting of fuel and fuel rack. In addition to this, the SFP of the PWR is not isolated within the containment like the SFP of the old BWR plant, there are so many possible measures to prevent and mitigate severe accidents in the SFP. On the other hand, in the low power shutdown status (fuel refueling), all the core is transferred into the SFP during the refueling period. At this period, if some accidents happen such as the loss of SFP cooling and the failure of SFP integrity then the accidents may be developed into severe accident because the decay heat is high enough. So, the analysis of severe accidents in the SFP during low power shutdown state is greatly affected to the establishment of the major strategies in the severe accident management guideline (SAMG). However, the status of the domestic technical background for those analyses is very weak.

Until now, the fact that there is no proper tool for the severe accident analysis in the SFP is the one of the reason for weak technical background. In Korea, the MAAP (Modular Accident Analysis Program) code developed by EPRI has been widely used in the severe accident analysis for PSA and SAMG development. The SFP model of MAAP code was firstly introduced in the MAAP version 5.0.2 officially released in December, 2013 and the newest version is MAAP 5.0.3 (Build 5030000) officially released in August, 2014.

In this study, the SFP model of MAAP code developed for low power shutdown mode SAMG is introduced and some possible severe accident phenomena were analyzed. Also, the sensitivity studies for some model parameters were performed.

2. Methods and Results

2.1 The characteristics of SFP model in the MAAP code

The SFP model parameters are described in the Spent Fuel Pool section of the parameter file and this model can calculate the phenomena in the SFP as below;

1) Time to boil
2) Time to uncover fuel assemblies
3) Heatup of fuel assemblies
4) Zr-water and Zr-O2 oxidation (Zircaloy Fire)
5) Fission product release
6) Melt progression of fuel assemblies

When the SFP model in MAAP is activated, the SFP specific modules will be called and MAAP5 will run at the special "containment benchmark mode". For this mode, only the modules related to the containment will be called. This means if users are simulating the SFP, they won't be able to simulate the core and RCS at the same time since the SFP model use the core model

The major characteristics of SFP model in the MAAP are described as below;

1) Fuel assemblies homogenized into fuel group. It means that the fuel assemblies with the same burnup, cooling time, operation history, enrichment are averaged.

2) Spent fuel racks are divided into channels. Each channel can contain filled or empty cells with any type and number of assemblies modeled in the fuel group.

3) 100 Axial and 100 Radial nodes are allowed. However, the total number of nodes (Axial×Radial) cannot exceed 4,000.

4) Each channel and fuel group is homogenized. Therefore, each channel calculates a single temperature for water and gas.

5) Current model does not calculate water natural circulation within fuel racks.

6) MAAP calculates natural circulation of gas once the water level decrease below the bottom of the fuel rack or fuel rack has melted away.

7) The storage pool wall is represented by distributed heat sink model and nodalized internally by the code.

8) Radiation heat transfer between the adjacent channels and the spent fuel pool wall is calculated. This is the important heat transfer mechanism in SFP.

9) Fission product information is input on a total pool basis, and then homogenized across all fuel groups.

2.2 SFP Parameter Development

In order to analyze the severe accident phenomena in SFP, the SFP parameters for OPR1000 type NPP was developed.

For this study, it is assumed that the refueling interval is approximately 18 months and that the one-third of the fuel assemblies in the entire core is replaced at each refueling, which is the typical refueling process for OPR1000 type NPPs in Korea.

Also, it is assumed that 10 cycles fuel assembly are accumulated in the SFP. And, first fuel assembly group consists with three type of batch. It is assumed that the one cycle outage length is 1 month (30 days).

Generally, there are 12 racks in the SFP of OPR1000 type NPP. We divide the 12 racks into 30 channels as shown in the Fig. 1, since the radiation heat transfer between the rack and the SFP wall is important in the SFP.

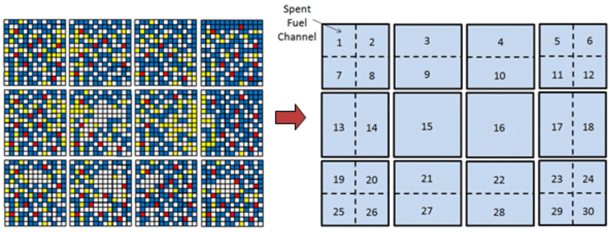

Fig. 1. SFP Channel Model

Each spent fuel assemblies in the SFP had the different enrichment, cycles, and burnup history, so we classified the entire spent fuel assemblies into 12 groups. And, since the each fuel groups use the homogeneous material properties, we applied the same burnup, cooling time, operation history, enrichment value in each group. In these 12 groups, there are 3 groups of fuel assemblies transferred into SFP for refueling and the cooling time for these 3 groups is assumed to be 150 hours.

The enrichment of the entire spent fuel group is assumed to be 0.042 that is the average value for entire spent fuel assemblies described in the Nuclear Design Report (NDR). Actually, the enrichment of each fuel rod is different and the specific enrichment value for each group can be assigned. The range of ^{235}U enrichment for the new fuel is from 2.42w/o to 3.42w/o. The range of ^{235}U enrichment for spent fuel is from 4.0w/o to 4.5w/o. However, since the spent fuel assemblies are stored evenly distributed locations in the entire fuel racks, it is meaningless that the specific value is assigned for each fuel group.

The decay power in a spent fuel assembly is set to be calculated by the code. The 2 standard are applied in the SFP model depending on the cooling time.

1) Cooling Time < 1year

- ANSI/ANS-5.1-1979, 1994, 2005 is used.
- It calculates the energy due to ^{235}U, ^{239}Pu, ^{241}Pu, and ^{238}U and includes the two short-lived actinides, ^{239}U and ^{239}Np.

2) 1year < Cooling Time < 110 years

- NRC Regulatory Guide 3.54, Rev. 1 is used.
- It calculates the energy by the interpolation of decay heat data for BWR and PWR designs
- Standard limited by maximum accumulated burnup of 45MWd/kgU for BWRs and 50 MWd/kgU for PWRs

The material properties such as the mass of Zr and number of fuel rod for spent fuels are calculated as the same method used in the core parameter calculations. Also, the axial power peaking factor for all assemblies in a spent fuel pool is assumed to be the same values in fuel node.

The number of nodes in the axial direction in a spent fuel pool is determined as 32 nodes as shown in Fig 2.

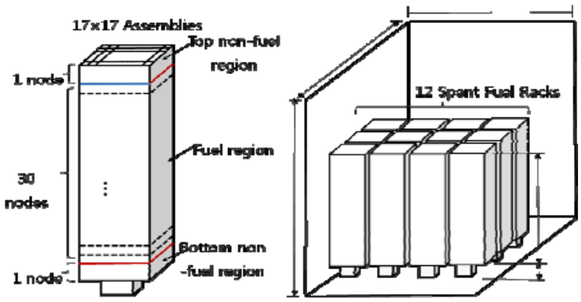

Fig. 2. Axial Nodalization of Fuel Assemblies

The total mass of fission products elemental group in the entire spent fuel pool at time zero, the fraction of decay power in each MAAP fission product group, and the fraction of decay power in each MAAP fission product group are determined by the results of OrigenArp 5.1.01 code calculation.

2.3 Accident Scenario

(1) Base case

In general, since the decay heat in the SFP during normal operation is low and there is much amount of water in the SFP, it has been known that the accident progression is very slow for loss of spent fuel pool cooling only. During the refueling stage, the whole core is transferred in the SFP for refueling, and the decay heat of the core is added to that of SFP. If the accident like the loss of SFP cooling happens in this period, the accident progression is faster than that during the normal operation. So, we select the loss of spent fuel pool cooling accident without any recovery actions during refueling as the base case. The analyses are performed for 500 hours (20.8 days) as a MAAP time step.

(2) Case for loss of SFP cooling and integrity

The accident progression for simple loss of SFP cooling event is very slow enough to perform the mitigation action after doing emergency recovery or mitigation action for core firstly. However, if the SFP has been damaged or cracked by the earthquake, even though this probability is extremely low, the situation is expected to be some more severe. It is expected that the overall accident progression is somewhat faster. So, in addition to the base case, we evaluate the accident sequence that the loss of SFP cooling and the loss of SFP integrity occur simultaneously.

2.4 Sensitivity Study

As described above, since the MAAP SFP model assumed the homogeneous material properties for each fuel groups, it is necessarily assessed that the differences in material properties can affect the analysis results. First of all, the enrichment of ^{235}U is assumed to be 4.2w/o for the entire spent fuel group. Since the enrichment can affect the decay heat, it is selected as the sensitivity factor that can affect the accident progression. The enrichment is changed from 0.042 to 0.04 and 0.045 in this sensitivity study

In Table 1, we classified the accident conditions for this study.

Table 1. Case Classification

Case	Initiator	Enrichment
Base	Loss of SFP cooling	0.042
S-Base	Loss of SFP cooling	0.040
L-Base	Loss of SFP cooling	0.045
Base-C	Loss of SFP cooling and Integrity	0.042

2.5 Analysis Results

The representative major event occurrence time for each case are summarized in Table 2.

Table 2. Major Accident Progression

Case	Fuel Assembly Uncover (S)	SFP Dryout (S)	BMT (S)
Base	228630 (64h)	290618 (81h)	598000 (166h)
S-Base	228275 (63h)	293965 (82h)	598000 (166h)
L-Base	228805 (64h)	224920 (62h)	541000 (150h)
Base-C	640 (0.2h)	13597 (3.8h)	15318 (4.3h)

Figure 3 shows the change for the total mass of spent fuel remaining in the SFP Rack.

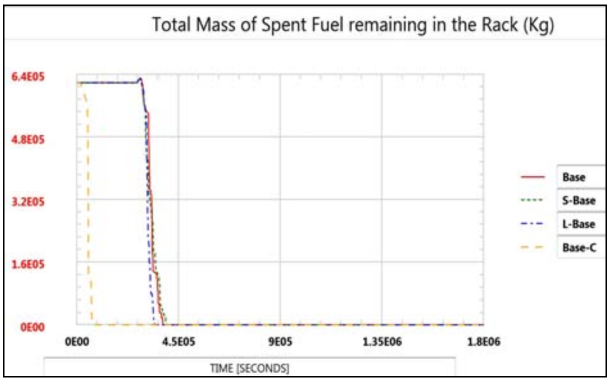

Fig. 3. Total Mass of Spent Fuel remaining in the Rack

If the water in the SFP is decrease, the fuel is uncovered and heated by the decay heat because the heat transfer mechanism is changed to radiation heat transfer. When the water is almost dried out, the mass of fuel increased slightly due to Zr oxidation. Then, the mass of fuel is started to decrease since the fuel begin to melt and drop to SFP floor. The difference in enrichment of ^{235}U cannot make the meaningful effect. In the Base-C case, since the water decrease rate is faster than that of other cases, the melting and dropping down progression of spent fuel is so fast as to end within 17.8 hours

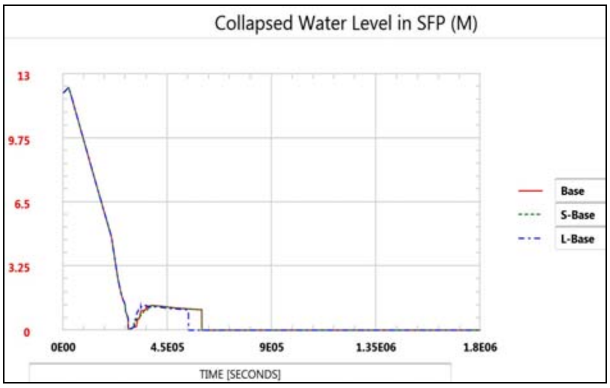

Fig. 4. Collapsed Water Level in SFP

Figure 4 shows the change of Water level (collapsed level) in the SFP. The water level is continuously decreased to bottom level around 80 hours without any difference due to enrichment, and then, the water level is slightly increased. Actually, this level is the corium level, and when the SFP basement melt through (BMT) happens, the level is sharply dropped down to 0 level. The case for high enrichment, the BMT happens somewhat earlier. However, from the viewpoint of entire accident progression, it is judged that this difference is not meaningful.

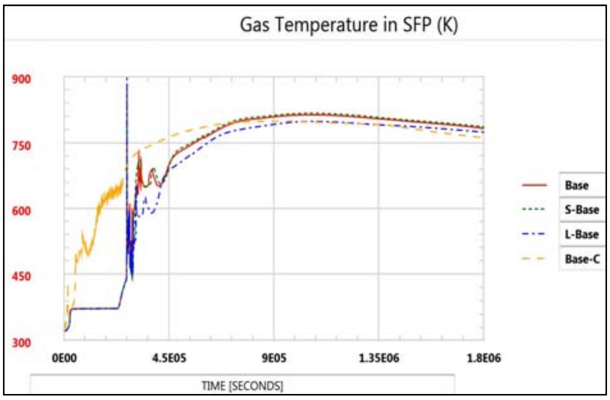

Fig. 5. Gas Temperature in SFP

Figure 5 shows the change of Gas Temperature in the SFP. The Base case, the S-Base case, and the L-Base case show the similar behaviors. However, the Base-C case shows that the temperature is rapidly increase in early phase because of the rapid accident progression.

Figure 6 and Figure 7 shows the amount of H_2 generation change in the spent fuel by the metal water reaction (Oxidation) and in the SFP floor by the molten core concrete interaction (MCCI) each. The Base case, the S-Base case, and the L-Base case show the similar behaviors. As the enrichment is higher, the more hydrogen is produced by MCCI because the fuel melting is slightly fast.

Since the accident progression is fast in the Base-C case, the hydrogen generation in fuel is limited and the amount of hydrogen generation from MCCI is much larger.

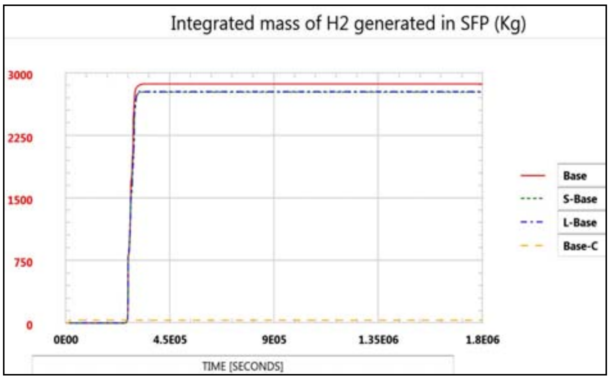

Fig. 6. Integrated Mass of H2 generated in Spent Fuel

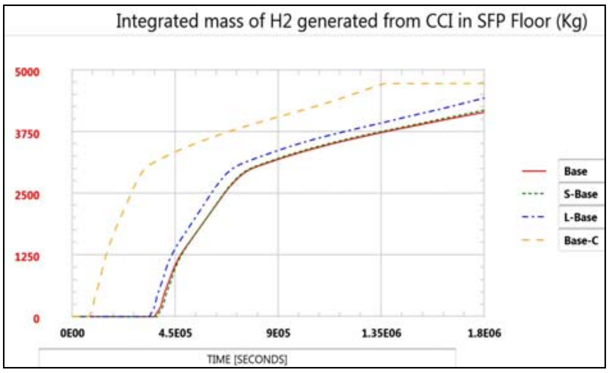

Fig. 7. Integrated Mass of H2 generated from CCI in SFP Floor

Figure 8 shows the concrete eroded depth due to MCCI for each case. And Figure 9 shows the sideward erosion distance due to MCCI for each case.

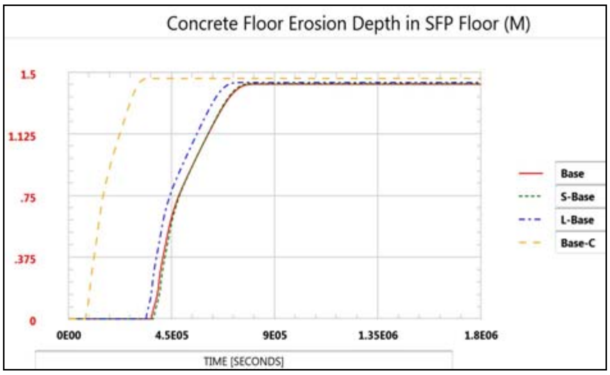

Fig. 8. Concrete Floor Erosion Depth in SFP

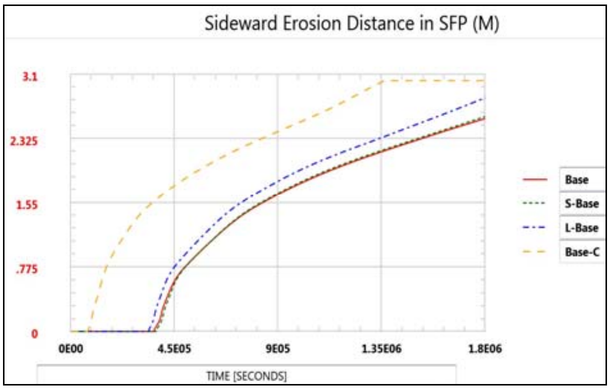

Fig. 9. Sideward Erosion Distance in SFP

After the fuel is melted, molten corium is relocated onto the SFP floor, and then the MCCI begins.

As described in the hydrogen generation graph, the Base case, the S-Base case, and the L-Base case show the similar behaviors. It is known that the enrichment is higher, the MCCI occurs somewhat earlier because the fuel melting is slightly fast. However, from the viewpoint of entire accident progression, it is judged that this difference is not meaningful.

Since the accident progression is fast in the Base-C case, the MCCI and the concrete erosion is started quickly. The downward concrete erosion is stopped around 1.5m since the thickness of heat sink is set to 1.5m. So, when the erosion depth reaches that point, it is judged that the BMT happens.

3. Conclusions

After the Fukushima accident, the severe accident phenomena in the SFP have been the great issues in the nuclear industry including Korea. Generally, it is known that the decay heat of the spent fuel in the SFP is not high enough to cause the severe accident qualitatively. However, there are some possibilities that can cause the severe accidents in the SFP if the loss of SFP cooling and integrity happens simultaneously. The severe accident phenomena in SFP themselves are not much different from those in the containment. However, since the structure of SFP cannot be isolated during the accidents like the containment, the consequence can be extremely significant. So, in terms of the establishment of the severe accident management strategy, it is necessary that the quantitative analysis for the severe accident progression in the SFP should be performed.

In this study, the general behavior which can be appeared during the severe accidents in the SFP was analyzed using the SFP model for OPR100 type NPP developed using MAAP 5.0.3.

As expected, the accident progression in the SFP is very slow if the SFP integrity in maintained. That means the there is enough time for operators to perform the recovery actions. However, if the SFP integrity is lost, the accident progression is fast. So, it is judged that the immediate SAMG strategies to cool the spent fuels should be performed.

For the SFP model and parameters, the more sensitivity study should be needed for more detailed and appropriate analysis.

REFERENCES

[1] Zion Parameter File in MAAP 5.0.3 Distribution Package, EPRI, August, 2014

[2] Dr. Chan Y. Paik, MAAP5 Spent Fuel Pool Model, Severe Accident Analysis Code Workshop, FAI, 2015.8

[3] Seo, Mi Ro, Shin, Jeong Min, “Overseas Business Trip report of Technical Advice Meeting for LPSD SAMG” 2015-50003339-전-0367TC, KHNP, 2015.08