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Analyses of Fission Product Retention under ISLOCA using MELCOR for APR1400

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1. Introduction

An Interfacing System Loss-of-Coolant Accident (ISLOCA) is one of bypass scenarios considered in Nuclear Power Plants (NPPs). This accident can occur due to an unisolated rupture (outside of containment) of a piping connected to Reactor Coolant System (RCS). Since there are not appropriate strategies to prevent core damage during the ISLOCA, it is assumed that the probability of the initial event is as same as the Core Damage Frequency (CDF) of the ISLOCA in Probabilistic Safety Assessment (PSA). Even though the CDF for the ISLOCA is considerably low, this can lead to a significant and direct release of fission products from the RCS into the environment. Therefore, it is important to estimate the behavior of the fission products during the ISLOCA.

The U.S. Nuclear Regulatory Commission (NRC) has carried out the State-of-the-Art Reactor Consequence Analyses (SOARCA) project to develop best estimates of the offsite radiological health consequences for potential severe accidents [1]. In this project, various scenarios were analyzed with MELCOR [2] to estimate the accident progression and the behavior of the fission products. Especially, the state-of-the-art modeling approach was used to simulate the ISLOCA appropriately. Auxiliary buildings including the drain system and the ventilation system to influence the behavior of the fission products were modeled in detail. In addition, the mechanisms such as the aerosol deposition and the pool scrubbing during the ISLOCA piping were considered.

The SOARCA project was performed for two pilot plants: Peach Bottom and Surry. Peach Bottom is a Boiling Water Reactor (BWR) and Surry is a Pressurized Water Reactor (PWR). Among the pilot plants, the ISLOCA scenarios were analyzed for the Surry NPP only. Although Surry is the Westinghouse PWR, differences between the Surry NPP and the NPPs in Korea exist in plant-specific design such as the structure of the auxiliary building. Because the results of the ISLOCA analysis of the SOARCA project are not generally applicable to the NPPs in Korea, the ISLOCA analyses were performed on the Advanced Power Reactor 1400 MWe (APR1400) in this study. Analysis methodology and modeling approach were established based on best practices of the SOARCA project in this study.

2. Modeling

The major mechanisms of the fission product retention during the ISLOCA are follows.

1. Deposition within the piping connecting the RCS to the auxiliary building
2. Scrubbing of fission products in the accumulated water pool and deposition on the surface of the walls and the components in the auxiliary building
3. Filtration within the ventilation system of the auxiliary building

To estimate the amount of the fission product retention according to each above-mentioned mechanism, the MELCOR version 2.2 [2] was utilized in this study. The modeling details are discussed in the following subsections.

2.1 Deposition within ISLOCA Piping

According to the result of the PSA for the APR1400, the piping section with the highest possibility of the ISLOCA was evaluated as the suction line of the Shutdown Cooling System (SCS). The SCS piping between the hot leg and shutdown cooling pump is around 100 m in length. Even though the rupture to cause the ISLOCA can occur in anywhere in this piping, it is assumed that the rupture occurs in the piping section with the smallest schedule and the largest diameter. The piping judged as most susceptible to rupture is located near the shutdown cooling pump in the basement of the auxiliary building.

This piping model for the MELCOR consists of 6 volume nodes and 6 heat structures with around 20 bends to simulate the deposition of aerosols on pipe surfaces. The turbulent deposition model which is the primary mechanism for the fission product deposition was selected as the following default model of the MELCOR.

1. Straight piping: Wood’s model for rough pipes [3]
2. Bends: Idaho National Laboratory model [4]

On the other hands, all parts of the SCS piping are insulated. Thus, the heat transfer to the outside of the piping was not simulated conservatively in terms of the re-vaporization of the deposited fission products due to high temperature of the piping wall. However, some parts of the SCS piping can be submerged under ISLOCA conditions, and the submerged part is around 10 m in length. Thus, this segment was simulated to enable heat transfer through the outside of the piping when it was submerged.

2.2 Pool Scrubbing and Deposition

The scrubbing of the fission product vapor and aerosols in the pool is calculated with the MELCOR. The pool scrubbing model is based on the SPARC-90 code [5]. The pool scrubbing decontamination factor mainly depends on the break submergence depth. The pool depth can be defined as the distance between the break location and the flooding elevation of the auxiliary building under the ISLOCA condition. Therefore, the detail modeling of the auxiliary building is required based on the specific design.

The auxiliary building model for the APR1400 consists of 19 nodes as shown in Fig. 1. The auxiliary building is divided into 4 quadrants, and each quadrant is designed not to allow flooding to spread. Since the piping which is likely to cause the ISLOCA in the APR1400 is included in Quadrant A, Quadrant A was modeled in detail. The compartments on the 1st floor of Quadrant A, where flooding can occur, were modeled in the most detail with 7 nodes. The compartments on the 1st floor of other quadrants (Quadrants B, C, and D) were modeled with 1 node. The auxiliary building model from the 2nd floor up to 4th floor consists of 2 nodes on each floor. On the 5th floor and 6th floor, one node was used to represent each floor. The fuel handling area existing in Quadrant B was composed of one node in consideration of the size and characteristics of this compartment. In this analysis, the node containing the ruptured piping is Node CV022.

Among the flow paths between the compartments, the fire and water doors (which are expected to be intact) were not modeled as flow paths. The normal doors which can be influenced by the ISLOCA were modeled to be opened when pressure difference between the adjacent compartments exceeds a defined opening pressure. In addition, the floor drainage system including the bottom drainpipe and the emergency flow paths was modeled with several flow paths.

The conditions, such as the water level, temperature, pressure, and etc., of the 1st floor of Quadrant A were calculated by using this auxiliary building model. And the pool scrubbing of the fission products was estimated based on the calculated conditions. To estimate the deposited fission products on the surface of the wall and the components in the auxiliary building, around 100 heat structures were modeled for all the compartments.

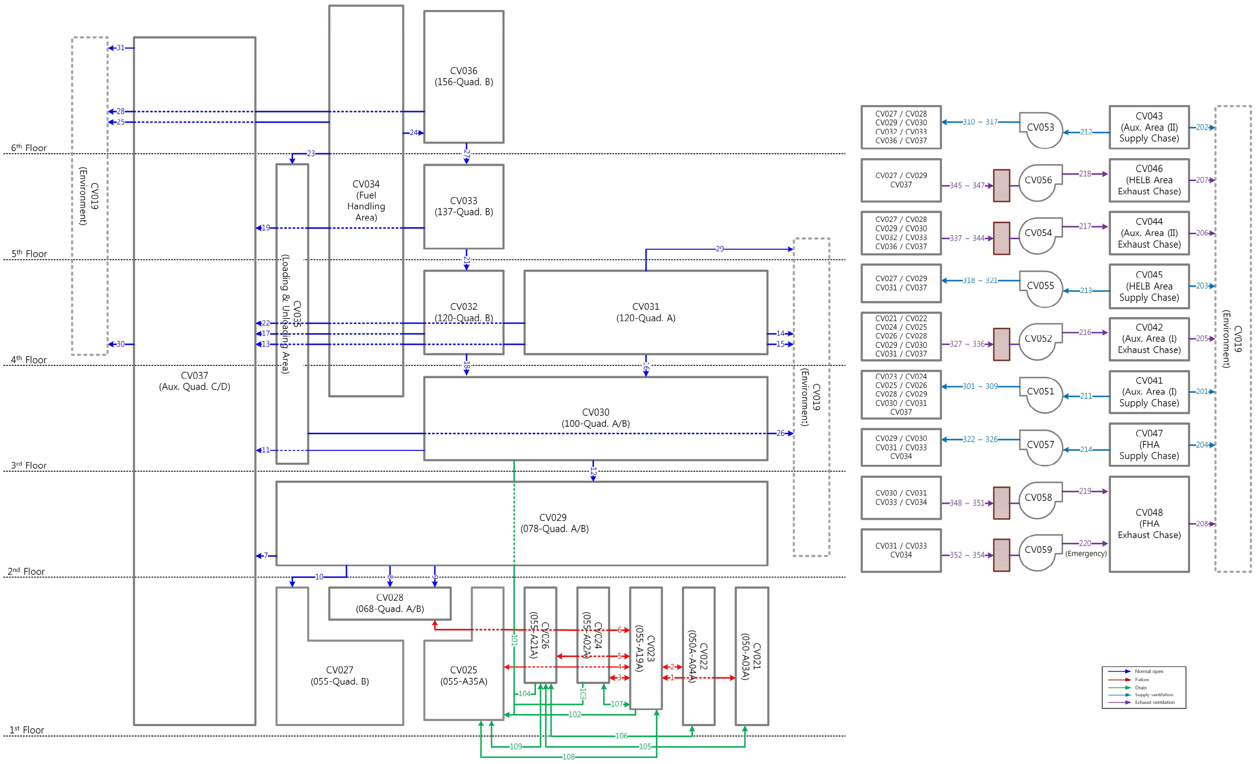

Fig. 1. Diagram of ARP1400 auxiliary building model constructed for us with the MELCOR

2.3 Filtration within the ventilation system

When the fission products are released to the auxiliary building, airborne aerosols can be collected in the ductwork of the auxiliary building ventilation system. The ventilation system draws air from the auxiliary system, let it pass it through filters, and discharges it to the environment. Since the operation of the auxiliary building ventilation system determines the flow characteristics of the fission products and the aerosols can be decontaminated by the filters of the ventilation system, the amount of fission products released into the environment can be strongly influenced by the modeling of the ventilation system. Therefore, the following air handling units in the radiation management area were modelled.

(1) Auxiliary Building Controlled Area (I) Supply
(2) Auxiliary Building Controlled Area (I) Exhaust
(3) Auxiliary Building Controlled Area (II) Supply
(4) Auxiliary Building Controlled Area (II) Exhaust
(5) High Energy Line Break Area Supply
(6) High Energy Line Break Area Exhaust
(7) Fuel Handling Area Supply
(8) Fuel Handling Area Normal Exhaust
(9) Fuel Handling Area Emergency Exhaust

In order to simulate each duct connected to the air handling unit, around 70 flow paths were used. The normal operation design flow rate of each duct was simulated by adjusting the flow area of each flow paths. Considering that one handling unit is connected to various compartments by the ducts, virtual nodes (CV051 ~ CV059) were modeled to collect the fluid from each duct. The total flow rate of each air handling unit was simulated using the fan function of the MELCOR. The air handling unit is finally connected to the environment through the chase (CV041 ~ CV048) for the auxiliary building ventilation system.

On the other hands, only High-Efficiency Particulate Air (HEPA) filters were modeled among the various types of the filters installed in the ventilation system of the APR1400 conservatively. Since the integrity of the HEPA filters for Surry is maintained under the ISLOCA condition in accordance with the analysis results of the SOARCA project, it was assumed that the function of the filters is maintained in this analysis for the APR1400.

2. Analysis Results

2.1 Sequence Definition

Simulations have been performed for an unmitigated sequence and a mitigated sequence to inject the water into the reactor cavity with the Emergency Containment Spray Backup System (ECSBS) and Cavity Flooding System (CFS) to mitigate Molten Core Concrete Interaction (MCCI) after reactor vessel failure. Additional assumptions to simulate the ISLOCA are follows.

(1) The rupture size to cause the ISLOCA is 4 inch diameter.
(2) It is assumed that one safety injection pump located in Quadrant A is not available due to the influence of the ISLOCA. Thus, three safety injection pumps are available among four safety injection pumps.
(3) All four Safety Injection Tanks (SITs) are available.
(4) Failure of the strategy to refill the In-containment Refueling Water Storage Tank (IRWST) is assumed.

Base on above assumptions, the ISLOCA were simulated by using the MELCOR.

2.2 General Description of Accident

Table 1 summarized the timing of the key events in the ISLOCA without the mitigation strategy. The accident would be initiated with a rupture of the SCS piping outside the containment. After 63 seconds, the reactor successfully tripped due to the low pressure of the pressurizer. Three safety injection pumps initiate, and then the IRWST was depleted at 24,800 seconds. Thus, the safety injection pumps stopped. The fluid in the RCS were continuously released into the auxiliary building through the ruptured piping, so that the core was uncovered at 28,950 seconds after the accident happened and the core exit temperature exceeded 1,200 ^{o}F at 31,200 seconds. And the reactor vessel was failed at 41,300 seconds.

Table 1. The timing of key events for the unmitigated sequence

Event description	Time [s]
ISLOCA	0
Reactor trip	63
Safety Injection (SI) initiates	103
IRWST exhausted (SI stops)	24,800
Core uncover	28,950
Core exit temperature > 1,200 ^{o}F	31,200
Reactor vessel failure	41,300

As described above, the general trends of the RCS is similar with the LOCA. However, the phenomena in the containment and the auxiliary building are considerably different. In the early phase of the accident, the transient in the containment is not large because there is no discharge of the mass and energy into the containment. But, various behaviors occur in the auxiliary building.

Figure 2 shows the water level of the compartments located in the basement of Quadrant A. The water level of most compartments in the basement of Quadrant A decreased rapidly. In the case of Node CV022 including the ruptured piping, since the pressure was higher than that of the other compartments, the water level was maintained relatively low. These behaviors in the auxiliary building are closely related to the fission product retention. The details regarding the behavior of the fission products are discussed in the following section.

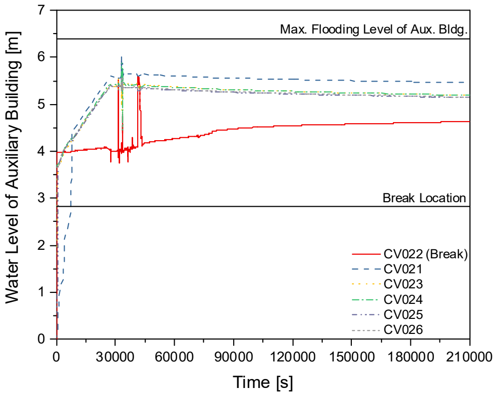

Fig. 2. The water level of the auxiliary building for the unmitigation sequence

2.3 Behavior of Fission Products

The amount of fission products released from the RCS into the environment can be reduced through the three mechanisms described in Section 2. The MELCOR treats the fission product with 17 classes. Among these classes, the cesium molybdate (Cs_2MoO_4) class contains about 90% of the total cesium in the core inventory. Thus, in this paper, the behavior of the fission products is discussed based on the mass fraction (compared to total core inventory) of the cesium molybdate.

Figure 3 shows the mass fraction of the cesium molybdate deposited within the ISLOCA piping. This value does not take into account the amount of the re-vaporization. As presented in Fig. 3, the major deposition mechanism of the cesium molybdate was the turbulent deposition in the pipe bends. This pattern was similar with most fission product classes of the MELCOR analysis.

The fission products deposited within the piping could be re-vaporized when the surface temperature of piping reached to a value which is sufficient to re-vaporize the volatile fission products such as the cesium molybdate. Figure 4 shows the vapor temperature inside the ISLOCA piping and the heat structure temperature of each segment of the piping. The piping walls except the submerged segment were calculated to exceed the temperature of the vapor flowing through the ISLOCA piping due to the influence of the fission product decay power. And, in case of the cesium molybdate, the amount deposited within the ISLOCA piping initiated to re-vaporize at around 80,000 seconds when the piping wall temperature exceeded around 1,400 K as shown in Figs. 4 and 5. After around 120,000 seconds, the cesium molybdate remained only in the segment which was submerged. The amount of the cesium molybdate in the deposited state was estimated to be about 1% of the total core inventory.

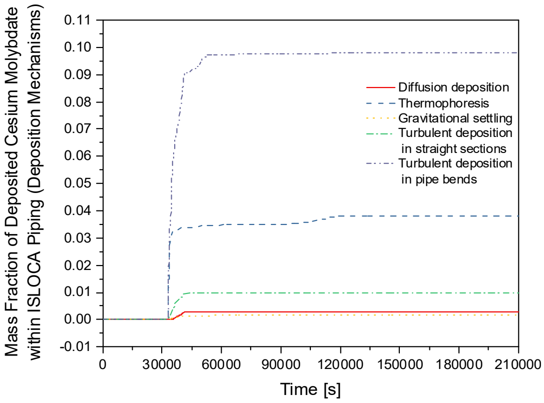

Fig. 3. The mass fraction of the deposited cesium molybdate according to each deposition mechanism within the ISLOCA piping for the unmitigation sequence

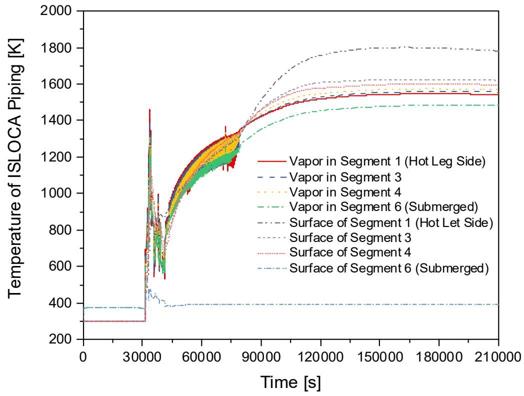

Fig. 4. The temperature of the vapor and the surface of each segment of the ISLOCA piping for the unmitigation sequence

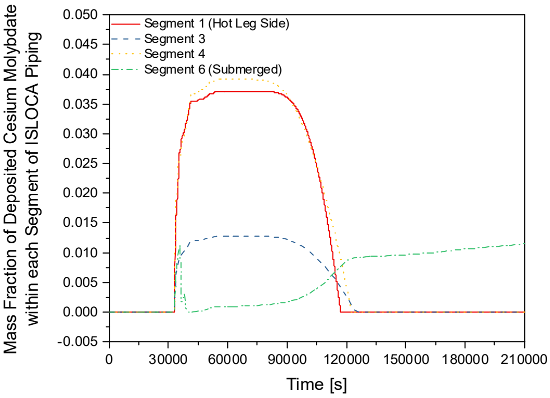

Fig. 5. The mass fraction of the deposited cesium molybdate within each segment of the ISLOCA piping for the unmitigation sequence

On the other hands, the re-vaporization behavior of the fission products within the ISLOCA piping was different when the mitigation strategy using the ECSBS and CFS was implemented. Since the MCCI was mitigated after the water was injected into the reactor cavity, the vapor and wall temperature was evaluated to be relatively low as presented in Fig. 6. Thus, Fig. 7 shows that the once deposited cesium molybdate remained in the piping without the re-vaporization. The mass fraction of the cesium molybdate to maintain the deposited state was estimated to around 12% of the total core inventory.

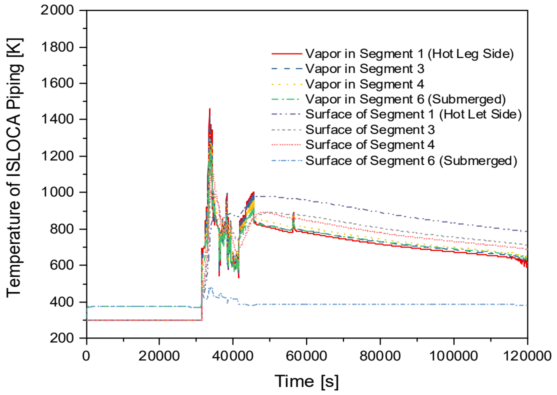

Fig. 6. The temperature of the vapor and the surface of each segment of the ISLOCA piping for the mitigation sequence

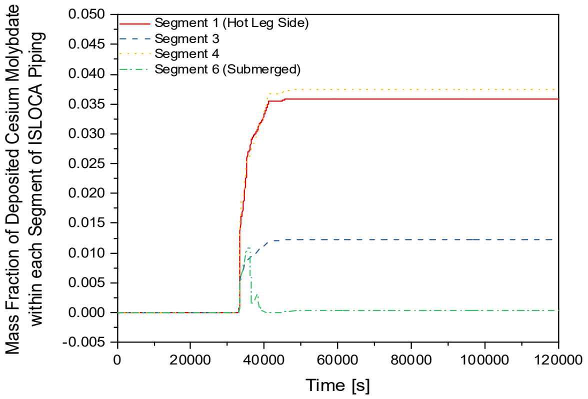

Fig. 7. The mass fraction of the deposited cesium molybdate within each segment of the ISLOCA piping for the mitigation sequence

The fission products that are not deposited in the SCS piping and released through the rupture can be removed by the scrubbing effect if the break is submerged. In addition, the fission products can be deposited in the wall and components in the auxiliary building. Figure 8 shows the mass fraction of the cesium molybdate in each compartment located in the basement of Quadrant A and all other compartments in the auxiliary building. Most of the cesium molybdate remaining in the auxiliary building was contained in the water accumulated in the basement of Quadrant A. The break submergence depth was about 1 ~ 1.5 m as presented in Fig. 2, and it was evaluated that a sufficient scrubbing effect could be expected under this condition. It was estimated that 33% of the core inventory were contained in the basement and only 1.7% were present in the other compartment.

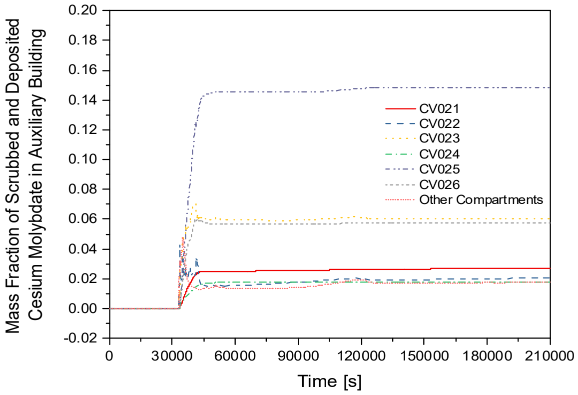

Fig. 8. The mass fraction of the scrubbed and deposited cesium molybdate in the auxiliary building for the unmitigation sequence

Fission products that do not remain in the auxiliary building are released into the environment. However, if the auxiliary building ventilation system is operating, the aerosol of fission products can be removed by the filters. The aerosol removal capability of the HEPA filters installed in the ventilation system is a typical efficiency of 99.7% at 0.3 μm particles. Thus, in this analysis, the Decontamination Factor (DF) of the filters was applied as around 3,000 only when the particle size was larger than 0.3 μm. According to the analysis results, the mass fraction of the filtered cesium molybdate was continuously increased as shown in Fig. 9. The amount of the cesium molybdate released into the environment without being filtered by the ventilation system was also continuously increased, but the final release fraction was estimated to be less than 2%.

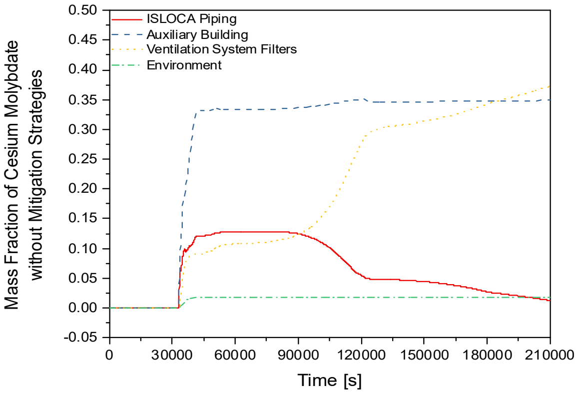

Fig. 9. The distribution of the cesium molybdate for the unmitigation sequence

On the other hands, the major difference between the unmitigation and mitigation sequences was the amount of the fission product deposited in the ISLOCA piping as described above. As shown in Fig. 10, the cesium molybdate once deposited in the piping was not released to the auxiliary building through the break, so that the mass fraction of the cesium molybdate filtered by the ventilation system did not increase continuously. There was no significant difference between the unmitigation and mitigation sequences in terms of the release fraction into the environment, but this was because the fission products were decontaminated by the ventilation system just before releasing into the environment. Considering that the integrity of the filters in the ventilation system can be loss, implementation of the strategy to mitigate the MCCI is required.

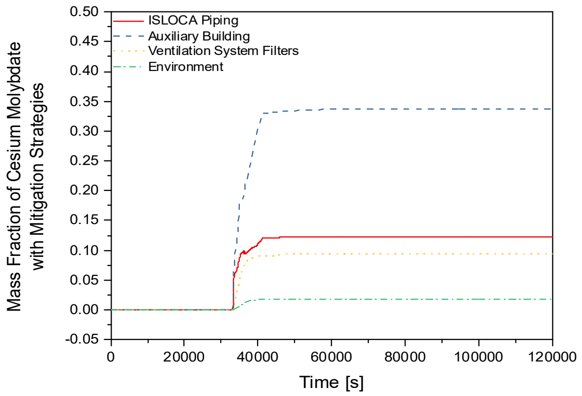

Fig. 10. The distribution of the cesium molybdate for the mitigation sequence

3. Conclusions

Analyses using the MELCOR were performed for the ISLOCA in the APR1400 based on best practices of the SOARCA project [1]. Considering the design characteristics of the APR1400, the rupture of the piping to cause the ISLOCA is likely to occur at the basement of the auxiliary building. And it was evaluated that the break was submerged more than 1 m in depth. In this analysis, the developed methodology was used to investigate the impact of (1) the deposition within the piping, (2) scrubbing of fission products in the accumulated water pool, and (3) the filtration within the ventilation system. According to analysis results, the amount of the cesium deposited in the SCS piping has increased when the strategy to inject into the reactor cavity was implemented to mitigate the MCCI. And, it was evaluated that the considerable amount of the cesium was scrubbed by the water accumulated in the basement of the auxiliary building. In addition, if the filters in the auxiliary ventilation system were available, the environment release fraction of the cesium could be decreased significantly. This study contributed to the safety analysis of the NPPs by providing a best-estimate methodology to assess the release fraction for a containment bypass event.

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