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Original Article

Effect analysis of ISLOCA pathways on fission product release at Westinghouse 2-loop PWR using MELCOR

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A R T I C L E I N F O

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A B S T R A C T

As the amount of fission product released from ISLOCA was overestimated because of conservative assumptions in the past, several studies have been recently conducted to evaluate the actual release amount. Among several pathways for the ISLOCA, most studies were focused on the pathway with the highest possibility. However, different ISLOCA pathways may have different fission product release characteristics. In this study, fission product behavior was analyzed for various pathways at the Westinghouse two-loop plant using MELCOR. Four pathways are considered: the pipes from a cold leg, from a downcomer, from a hot leg to the outlet of RHR heat exchanger, and the pipe from the hot leg to the inlet of RHR pump (Pathway 1—4). According to the analysis results, cladding fails at around 2.5 h in Pathways 1 and 2, and on the other hand, about 3.3 h in Pathways 3 and 4 because the ISLOCA pathways affect the safety injection flow path. While the release amount of cesium and iodine ranges between 20 and 26% in Pathways 1 to 3, Pathway 4 allows only 5% to the environment because the break location is submerged. Also, as more than 90% of cesium released to the environment passes through the personnel door, reinforcing the pressure capacity of the doors would be a significant factor in the accident management of the ISLOCA.

1. Introduction

The Interfacing-System Loss Of Coolant Accident (ISLOCA) is an accident in which a system that is connected to the Reactor Coolant System (RCS) ruptures outside the containment. This accident was first identified in the WASH-1400 [1]. The fission product can be released directly to the environment after core damage regardless of the containment integrity. So this accident may cause significant increases in the risk of the Nuclear Power Plant (NPP). The NUREG-1150 has also confirmed the ISLOCA as an important contributor to public health risk in a Pressurized Water Reactor (PWR) such as Surry and Sequoyah NPP, and checked improvements that could reduce the frequency of an ISLOCA [2].

Although the ISLOCA is an extremely low-frequency event, a large amount of fission product can be released early into the environment, bypassing the containment [3]. Therefore, it is important to predict the release amount as practical as possible to estimate ISLOCA's consequence realistically. In the past, fission products released from NPP due to the ISLOCA were overestimated because of the use of conservative assumptions in the accident analysis [4]. It was assumed that the safety injection and the containment spray system failed, and the reduction of nuclear fission product release due to flooding of the break-point or the deposition in the pipe were not taken into account. Also, fission products were assumed to be released directly to the environment bypassing the auxiliary building, too. As a result, CsI and CsOH were evaluated to be released 56.0 and 54.8% of the initial inventory, respectively, up to 24 h after the accident.

According to recent studies, however, a relatively small amount of cesium is released into the environment even for the ISLOCA scenarios [5]. This is because fission products are deposited on the pipings and auxiliary building structures, and scrubbed by the water pool formed in the Residual Heat Removal (RHR) pump room. The filters in the ventilation system of the auxiliary building also reduce the fission product release to the environment. Therefore, to get more realistic results, it is necessary to consider practical assumptions and conduct a detailed analysis of the phenomena that may actually occur under ISLOCA conditions.

The State-of-the-Art Reactor Consequence Analyses (SOARCA) Project has conducted a detailed analysis of an ISLOCA based on practical assumptions using MELCOR [5]. Sandia National

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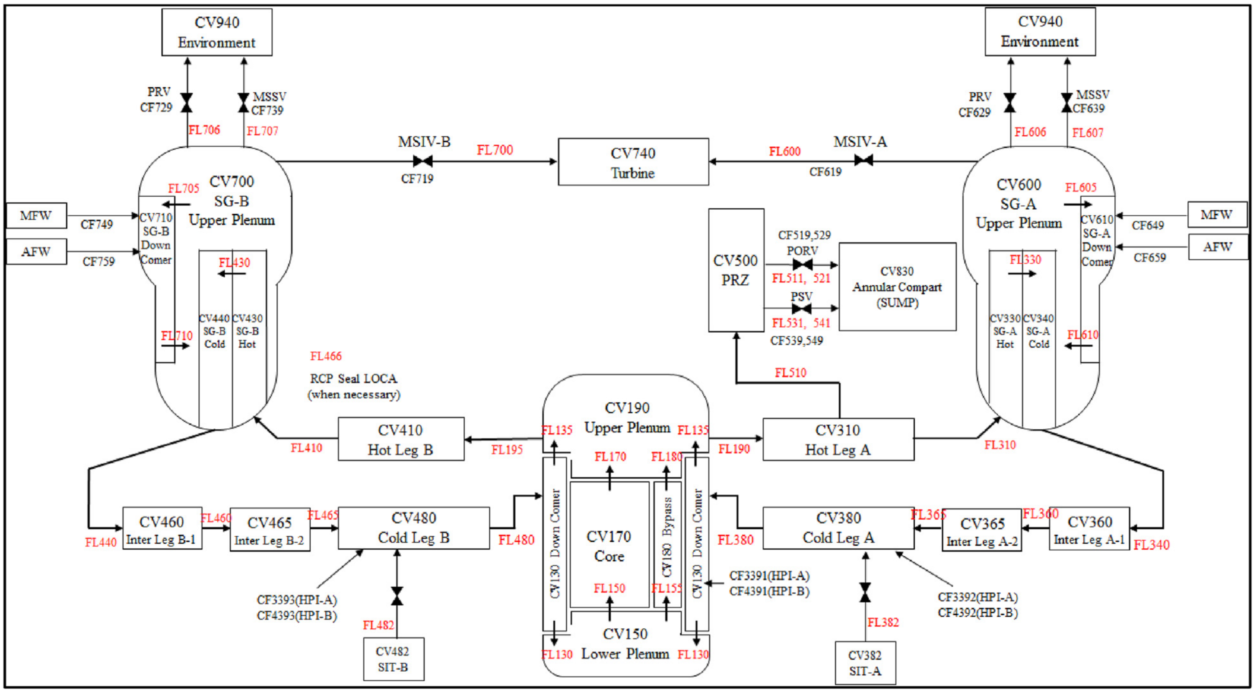

Fig. 1. Nodalization of RCS of the reference plant.

Table 1
Major design data for the reference plant.

Plant Design Data	
Plant Type	2-Loop PWR
Thermal Power	1876 MW
RCS Coolant Inventory	170.0 m^3
Accumulator Capacity	35.4 m^3
RWST Capacity	1170.0 m^3

Table 2
The result of simulation of steady-state using the MELCOR input model.

Parameter	Unit	FSAR [11]	MELCOR	Error
Reactor Core heat Output				
Thermal Power	W	1.88E+09	1.88E+09	0.00%
Fission Power	W	1.76E+09	1.76E+09	0.00%
Decay Heat	W	1.20E+08	1.20E+08	0.00%
Coolant Temperature				
Average in Core	K	581.5	581.6	0.02%
Average Rise in Core	K	39.6	40.4	2.02%
Average in Vessel	K	579.3	579.8	0.09%
Average Rise in Vessel	K	37.3	36.8	−1.34%
Reactor Vessel Inlet	K	560.6	561.4	0.14%
Reactor Vessel Outlet	K	597.9	598.2	0.05%
Coolant Flow				
Total Reactor Thermal Flow Rate	kg/sec	8.83E+03	8.96E+03	1.47%
Effective Flow Rate for Heat Transfer	kg/sec	8.27E+03	8.06E+03	−2.54%
Pressure				
Primary System Pressure	Pa(a)	1.55E+07	1.55E+07	0.00%
Steam Generator				
Feedwater Rate/SG	kg/sec	500.0	512.7	2.54%
Feedwater Temperature at SG Inlet	K	494.3	494.3	0.00%
Steam Flow/SG	kg/sec	500.0	512.7	2.54%
Steam Pressure at SG Outlet	Pa(a)	6.03E+06	6.04E+06	0.17%

Laboratory (SNL) analyzed ISLOCAs at Surry Nuclear Power Plant through the SOARCA Project sponsored by Nuclear Regulatory Commission (NRC) [5]. SNL assumed a break at the inlet of the RHR pump and the safety injection system operation was successful for the injection mode only. Besides, the deposition of the fission products on the piping and the fission product scrubbing by overlying water above the break location was considered, and the auxiliary building was modeled in detail. The flow paths from the auxiliary building to the environment were considered via the ventilation system of the auxiliary building or the opening of the personal door. Also, fission products trapping by a filter in the ventilation system were taken into account. As a result, it was estimated that cesium and iodine were released to the environment about 2% and 15% of the initial inventory, respectively. When applying a mitigation strategy of the opening of the Power Operated Relief Valve (PORV), the amount of cesium and iodine release was reduced to 1.4% and 11%, respectively. If the High-Pressure Safety Injection (HPSI) pump was assumed to operate with the minimum injection flow rate, the progress of the accident could be delayed as long as the Refueling Water Storage Tank (RWST) inventory was available (~30 h).

Korea Atomic Energy Research Institute (KAERI) also analyzed the ISLOCA at an Optimized Power Reactor 1000 (OPR1000) with MELCOR [6]. They also assumed the inlet of the Shutdown Cooling System (SCS) pump was broken. Though the fission product deposition on the pipings was considered, the auxiliary building was modeled roughly and the filters in the ventilation system and the submergence of the break location were not considered. As a result, it was evaluated that 40% of CsI and 33% of CsOH were released to the environment up to 24 h.

Table 3
The characteristics of each pathway for the reference scenario.

		Pathway 1	Pathway 2	Pathway 3	Pathway 4
ISLOCA route		CL[a] → RHR HX	DC[b] → RHR HX	HL[c] → RHR HX	HL[c] → RHR Pump
Characteristic of Pipeline	HP Pipe[d]	8″ SCH1 60, 18.28 m	6″ SCH1 60, 18.25 m	6″ SCH1 60, 18.31 m	8″ SCH1 60, 22.34 m
	LP Pipe[e]	8″ SCH80, 12.56 m	8″ SCH80, 12.56 m	8″ SCH80, 12.56 m	12″ SCH80, 22.67 m
Break Location		RHR HX Room	RHR HX Room	RHR HX Room	RHR Pump Room
Break-part Flooded		X	X	X	O
Break Size		8.11E-3 m^2 (4in break)			
HPSI Injection		Success			
HPSI Recirculation		Failure			
Ventilation System		Success			

[a] Cold Leg.
[b] Downcomer.
[c] Hot Leg.
[d] High-pressure Pipe.
[e] Low-pressure Pipe.

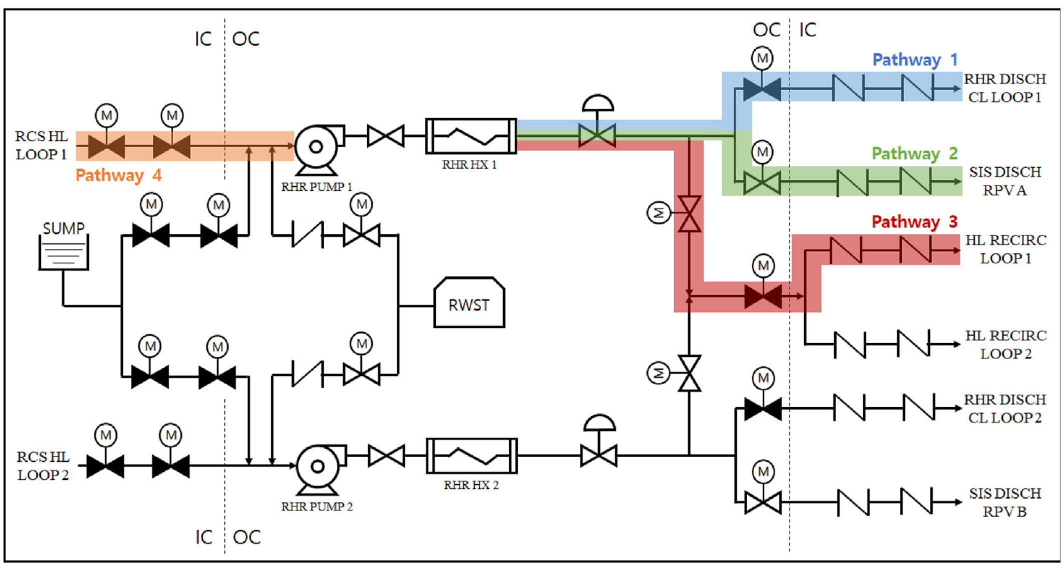

Fig. 2. Potential ISLOCA pathways for the reference plant.

The ISLOCA in the Advanced Power Reactor 1400 (APR1400) was also studied with MELCOR [7]. The suction pipe of SCS pump was assumed broken and the safety injection system was successful, but recirculation failed as in the case of the SOARCA project. Besides, piping deposition, pool scrubbing, and ventilation system filtration were considered. According to this reference, among 17 classes of fission product, the cesium molybdate(Cs_2MoO_4) class contains 90% of the total cesium initial core inventory, and about 2% of Cs_2MoO_4 was estimated to be released to the environment. When a mitigation strategy with the Containment Spray System (CSS) and Cavity Flooding System (CFS) was applied, the release was reduced by half. This is because CSS and CFS prevent re-vaporization of aerosols in ISLOCA piping. If CSS and CFS are operated, the containment temperature decreases, and the temperature of the part of the ISLOCA piping inside the containment decreases (ISLOCA piping is not insulated). Therefore, the aerosols deposited in the piping do not re-vaporize, and the amount of the fission product release to the environment decreases.

The MAAP5 code was also used for the ISLOCA analysis for a 1300 MWe PWR [8]. In this reference, the effect of the detailed modeling of pipes, pool scrubbing, and ventilation system on fission product release was analyzed. When all three were not modeled, 62.0% of cesium was released, but the release was reduced to 0.3% by modeling the phenomena and the system.

These previous studies were focused on the single ISLOCA scenario, however, there are several pathways (hereinafter ‘ISLOCA pathway’) where ISLOCA is likely to occur in an NPP and the release characteristics of fission product may depend on ISLOCA pathways. Hence the purpose of this study is to analyze the accident progression for various ISLOCA pathways and to compare the fission product release characteristics with MELCOR.

2. Methodology

The MELCOR code version 2.2 is used as the analysis code. MELCOR is a computer code for the analysis of severe accidents, which deals with the thermo-hydrodynamic phenomena, core damage, and the behavior of fission products in NPP. Also, piping deposition, pool scrubbing, and filter models are included in the code [9,10].

2.1. Modeling of the reference plant and a scenario

Westinghouse 2-loop Pressurized Water Reactor (hereinafter

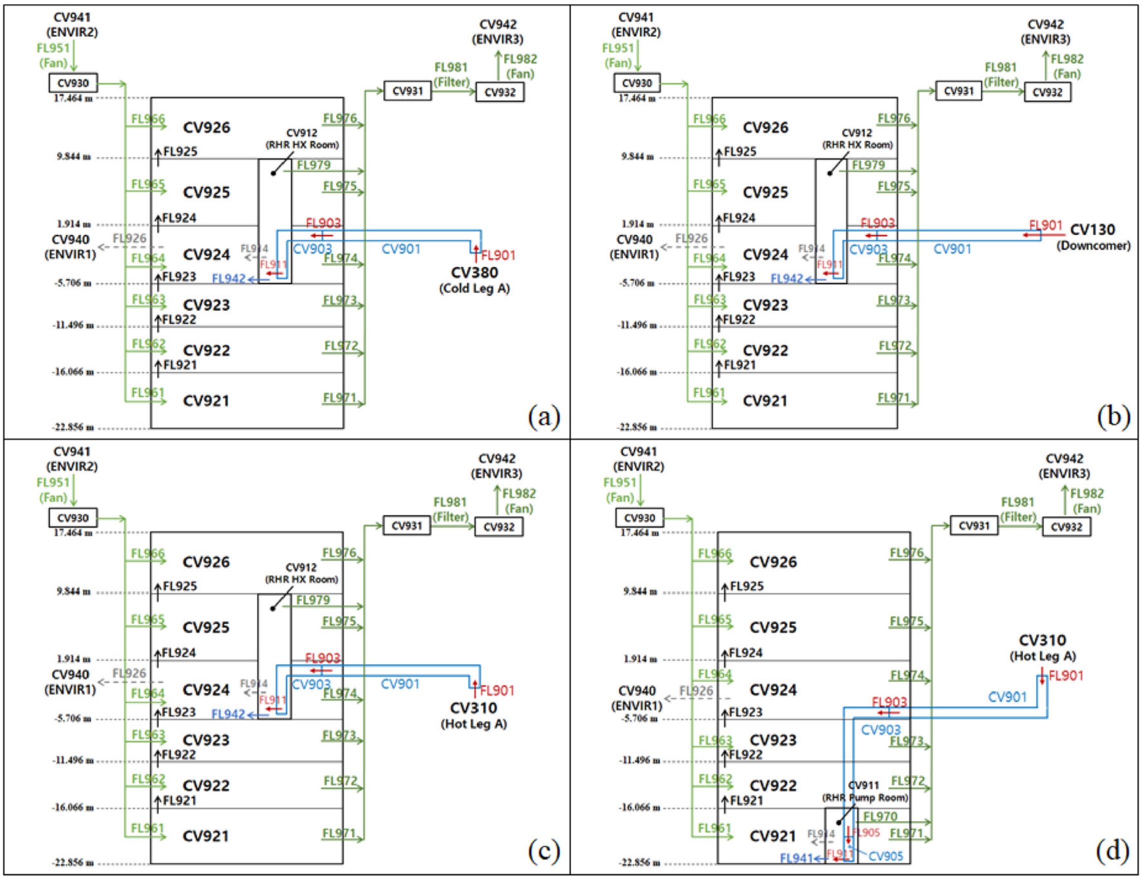

Fig. 3. Nodalization of ISLOCA piping and auxiliary building for (a) Pathway 1, (b) Pathway 2, (c) Pathway 3, and (d) Pathway 4.

'WH600') plant is selected as the reference plant in this study. Fig. 1 shows the RCS nodalization of the MELCOR input model for the reference plant, and Table 1 summarizes the major design data [11]. The results of simulating the steady-state using the input model are shown in Table 2. The difference between the result of the MELCOR calculation and the design data of the major variables of the reference plant is less than 3%, which means that the input model can simulate the reference plant appropriately.

For the ISLOCA simulation, a 4-inch diameter pipe break, which is based on the previous studies [7,8], is assumed to occur at 0 s. The safety injection by two HPSI pumps is successful but the recirculation mode fails because the safety injection water is drained into the auxiliary building through the ISLOCA break. The operation of the ventilation system in the auxiliary building is assumed to be successful. The ventilation system of the auxiliary building is always operated during a normal operation to keep the auxiliary building at negative pressure. However, under the Emergency Operation Processor (EOP) condition, the ventilation system is stopped to isolate the auxiliary building. However, if the accident gets worse and enters the Severe Accident Management Guideline(SAMG) condition, and radioactive material is detected in the auxiliary building, the system is re-operated by the decision of the operator. There are two fans with 100% capacity in the system, so the probability of failure to restart is extremely slim. When ISLOCA occurs, the RCS water inventory including water sources from the accumulators and the RWST is drained to the auxiliary building. At this time, a water pool can be formed on the lowest floor of the auxiliary building, and the break location may be submerged in the pool. Table 3 summarizes the characteristics of four pathways for the reference scenario.

Table 4
Mass Fraction of Each Compound compared to Initial Core Inventory.

Radionuclides	Compound	Mass Fraction[a]
Cesium	CsOH	69.63%
	CsI	7.89%
	Cs_2MoO_4	22.48%
Iodine	I_2	0.77%
	CsI	99.23%

[a] The mass fraction of only Cs or I nuclides in the mass of the compound.

2.2. Modeling of ISLOCA pathways and auxiliary building

According to the Probabilistic Safety Analysis (PSA) report of the reference plant, the ISLOCA might occur through four different routes, and they are shown in Fig. 2 [4]. In this study, these ISLOCA pathways are analyzed regardless of their occurrence frequencies.

- Pathway 1: route from the RHR discharge on the cold leg to the outlet of the RHR HX

A pipe break at RHR Heat Exchanger (HX) outlet with failure of two check valves and one motor-driven valve (MOV) may occur. Its frequency is 1.318E-10/yr. The RHR HX is in the RHR HX room, which occupies a part of the first and the second floors of the auxiliary building.

- Pathway 2: route from SIS discharge at the RPV downcomer to the outlet of the RHR HX

Table 5
The accident progression sequence for each pathway.

Event	Pathway 1		Pathway 2		Pathway 3		Pathway 4	
	sec	hr	sec	hr	sec	hr	sec	hr
ISLOCA Start	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Reactor Trip	10.5	0.0	13.0	0.0	20.2	0.0	12.9	0.0
HPSI Injection	10.5	0.0	13.0	0.0	20.2	0.0	12.9	0.0
RWST Exhaust	6477.6	1.8	6483.6	1.8	6487.9	1.8	6481.7	1.8
SAMG Entry	8494.8	2.4	9197.3	2.6	11,420.1	3.2	10,713.2	3.0
Gap Release	8799.1	2.4	9508.7	2.6	11,839.3	3.3	11,073.0	3.1
Release to Environ.	8805.3	2.4	9514.6	2.6	11,842.4	3.3	11,076.4	3.1
Relocate to LH[a]	11,680.0	3.2	11,920.0	3.3	17,513.7	4.9	14,299.2	4.0
RPV Failure	17,378.0	4.8	18,252.1	5.1	22,456.0	6.2	19,297.0	5.4

[a] The timing of molten UO_2 first relocation to Lower Head of RPV.

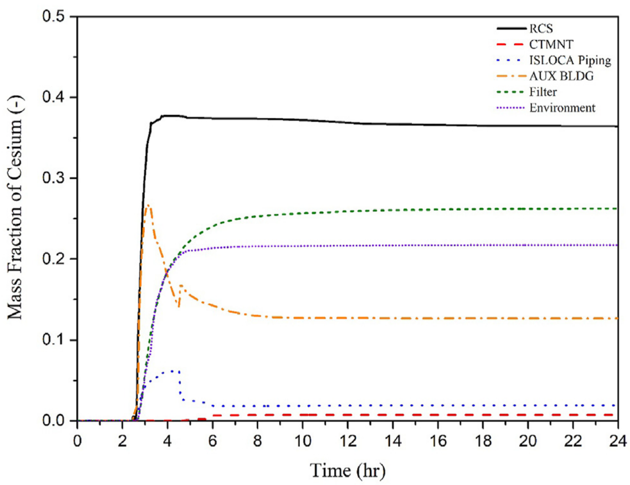

Fig. 4. Cesium behavior for Pathway 1.

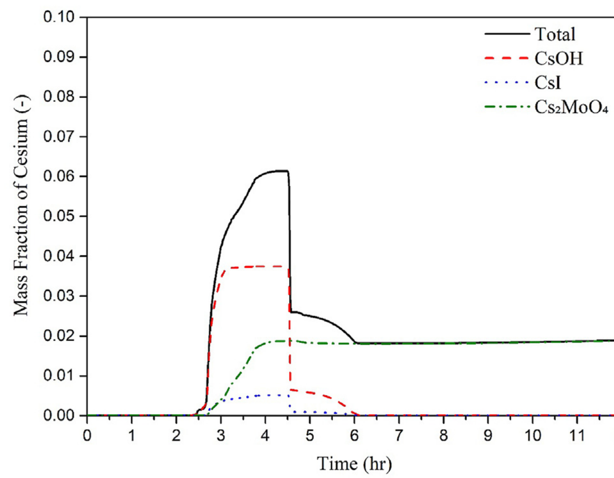

Fig. 5. Cesium behavior on ISLOCA piping for Pathway 1.

In WH600, the Emergency Core Cooling System (ECCS) injects the coolant directly into the Reactor Pressure Vessel (RPV) through the downcomer. A break at the RHR HX outlet with failure of two check valves may occur, and its frequency is 4.22E-8/yr. This pathway has the highest possibility of ISLOCA occurrence in the reference plant.

- Pathway 3: route from the hot leg recirculation to the outlet of the RHR HX

A break at the RHR HX outlet with failure of two check valves and one MOV is considered. Its frequency is 1.32E-10/yr, and this route connects from the top of the hot leg.

- Pathway 4: route from the hot leg to the inlet of RHR Pump

This route is connected from the bottom of the hot leg. A break at the suction line of the RHR pump with failure of two MOVs may occur. Its frequency is 7.08E-12/yr. As the RHR Pump is installed in the RHR Pump Room, which is located on the bottom floor of the auxiliary building, the break location can be submerged depending on the scenario.

Three main mechanisms affect the decontamination of fission product under the ISLOCA condition. The first mechanism is deposition on ISLOCA piping, which is mainly deposited by turbulent deposition and impaction. These are calculated using the wood's model and the INL model respectively in MELCOR [10]. The second is the pool scrubbing phenomenon caused by the submergence of the broken part, which is analyzed using the SPARC model

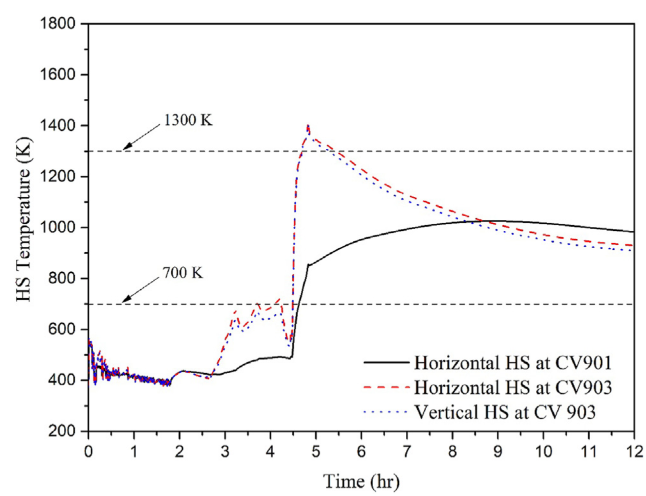

Fig. 6. Temperature of heat structures on ISLOCA piping for Pathway 1.

[10]. Lastly, it is filtration by the filter of the auxiliary building ventilation system. There are fans and filters in the ventilation system, which are modeled using the FANA model and the Simple Filter model, respectively [10].

Considering the ISLOCA pathway and three mechanisms, ISLOCA piping and auxiliary building were modeled as shown in Fig. 3. The ISLOCA piping is modeled with two control volumes (CV) of a high-pressure pipe (CV901) and a low-pressure pipe (CV903). In Pathway

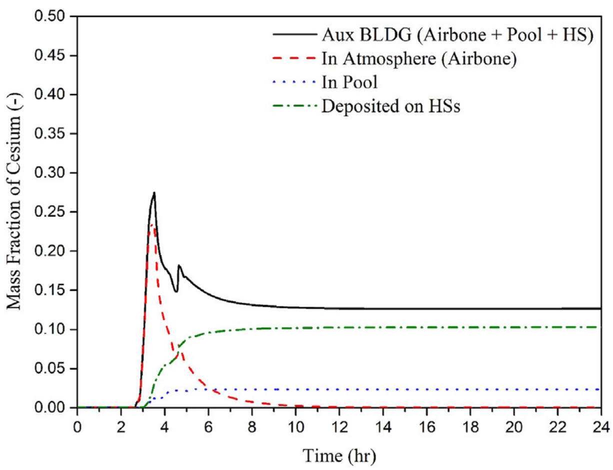

Fig. 7. Cesium behavior in the auxiliary building for Pathway 1.

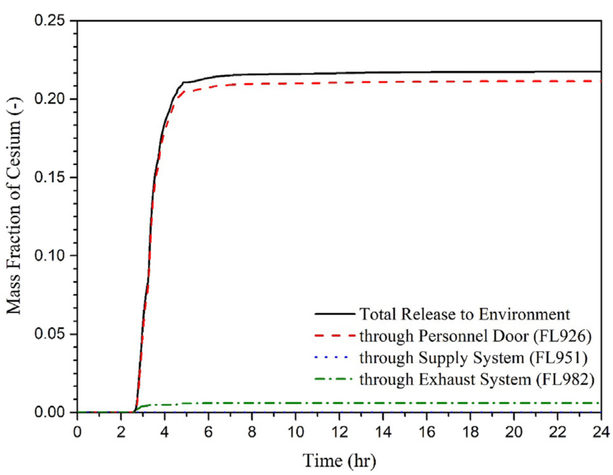

Fig. 8. Cesium release fraction for Pathway 1.

4, a submerged pipe (CV905) is newly added to consider the cooling effect from the water pool. The fission product deposition caused by turbulent deposition, impaction, gravitational settling, thermophoresis, and diffusiophoresis, as well as the pool scrubbing phenomenon is simulated with the MELCOR models.

The auxiliary building structure of the reference plant is composed of 6 stories, 3 stories underground (CV921~923), and 3 stories above ground (CV924~926). The RHR HX room (CV912) and the RHR pump room (CV911) are located on the fourth floor (ground level) and the first floor (the lowest floor) of the auxiliary building, respectively. Besides, it is assumed that each room has drain pipes that are connected to the adjacent rooms, and doors that can open when the differential pressure exceeds a certain set value. Additionally, the ventilation system including the fan and the filter is modeled in the auxiliary building. Based on the Final Safety Analysis Report (FSAR) of the reference plant, the filtration efficiency of the High-Efficiency Particle Absorption (HEPA) filter in the exhaust system is 99.97% for aerosols with a diameter of 0.3 μm or more [11], so the Decontamination Factor (DF) of the filter is set to 3333.3.

There are three flow paths for the fission product to be released from the auxiliary building to the environment. Potential release flow paths may be the supply system (FL951) and the exhaust system (FL982) of the ventilation system, and the personnel door (FL926). They are shown in Fig. 3. The supply system blows air into the auxiliary building using a fan. When the pressure difference between the auxiliary building and the environment is higher than the maximum pressure head of the fan, the air could flow backward and fission products could be released to the environment. The exhaust system has a filter, but if the aerosol accumulates and exceeds a certain pressure difference (1.5 psig), the filter could be damaged and fission products could be released to the environment. Also, even if the integrity of the filter is maintained, gaseous fission product and small-sized aerosol can be released to the environment. Finally, the personnel door can open when the pressure difference between the auxiliary building and the environment exceeds a certain value. In this study, the pressure difference is assumed as 1-inch H_2O (249.1 Pa(d)), which was used for Surry NPP in the SOARCA project [5], because finding the data of the pressure difference for the reference plant is difficult. And the opening area of the door is assumed as 0.5 m^2 because there is little difference in the amount of fission product release in the open area of 0.5 m^2 or more, based on the sensitivity analysis.

3. Result and discussion

In this study, accident progression and fission product behavior are analyzed for all four pathways. As the phenomenon of each

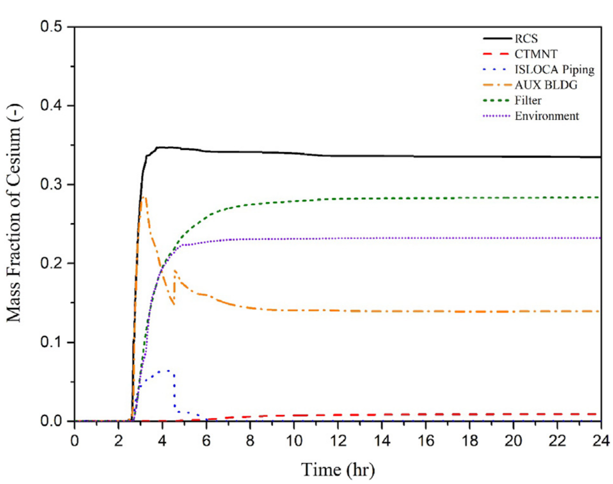

Fig. 9. Iodine behavior for Pathway 1.

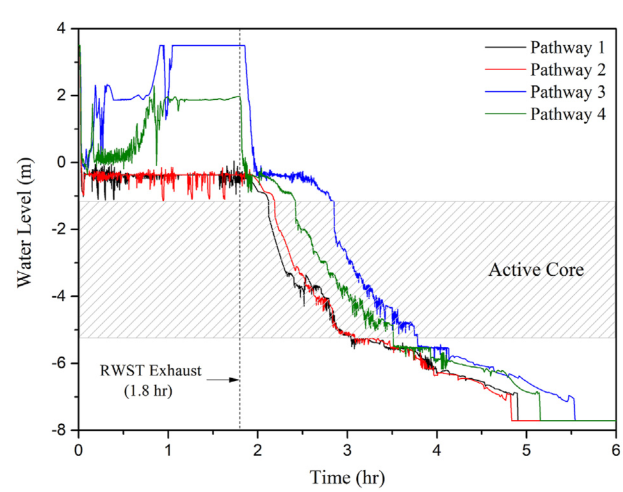

Fig. 10. Water level of Core for each pathway.

Table 6
Cesium distribution in 24 h for each pathway.

	RCS	CTMNT	ISLOCA Piping[a]	AUX BLDG	Environment	Filter
Pathway 1	36.41%	0.75%	6.14 → 1.92%	12.67%	21.74%	26.25%
Pathway 2	28.69%	1.89%	5.93 → 1.40%	15.82%	20.79%	30.87%
Pathway 3	6.50%	0.80%	5.91 → 0.72%	32.84%	24.93%	33.25%
Pathway 4	7.34%	1.25%	7.65 → 1.41%	37.52%	4.96%	46.40%

[a] ISLOCA Piping: Maximum Deposition Fraction → Deposition Fraction in 24 h.

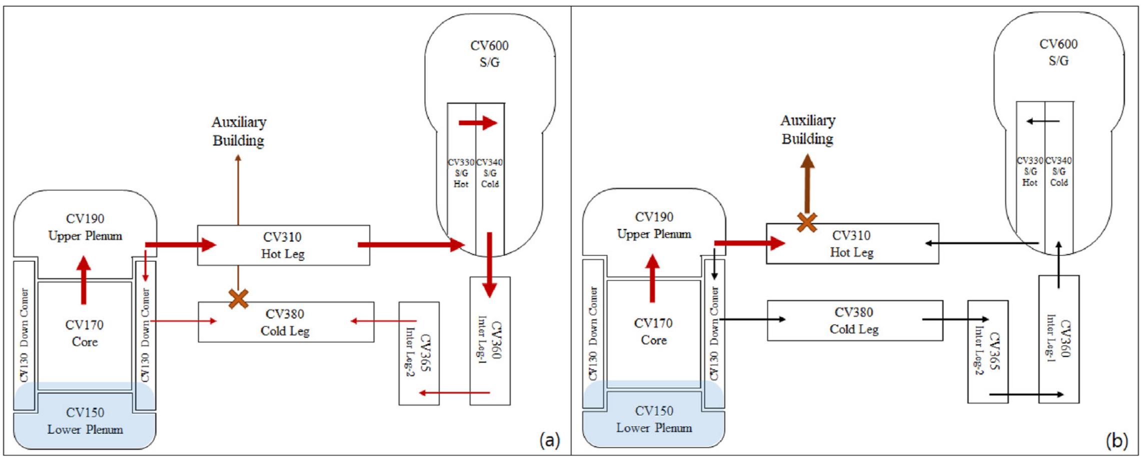

Fig. 11. Cesium release path to the auxiliary building from RCS during ISLOCA condition for (a) Pathway 1 & 2 and (b) Pathway 3 & 4.

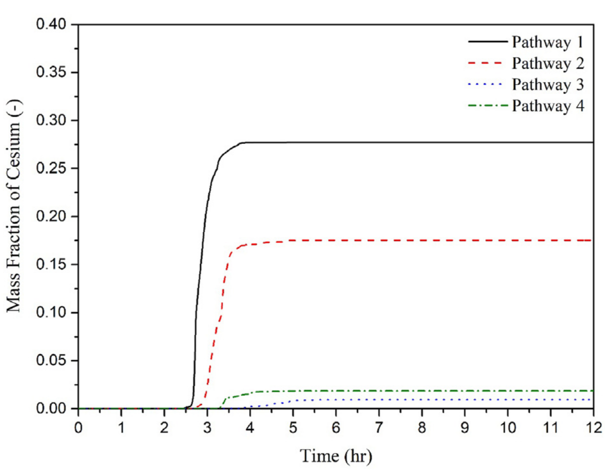

Fig. 12. Deposition fraction of cesium on SG u-tubes for each pathway.

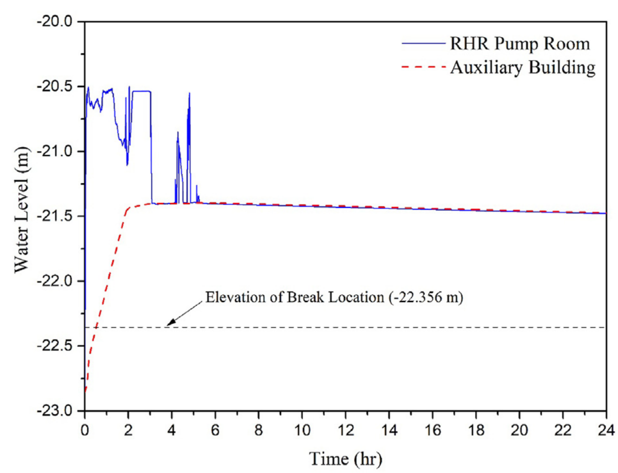

Fig. 13. The water level of RHR pump room and auxiliary building for Pathway 4.

accident is similar in pathways 1–4, the detailed results are given for Pathway 1, and differences are described for other pathways. Cesium and iodine are selected as the representative nuclide for the fission product analyses. Cesium (especially, Cs-137) is the nuclide that has the greatest impact on the latent cancer risk and is present in the form of CsOH, CsI, and Cs_2MoO_4 during the accident. Iodine (especially, I-131) is a significant contributor to the early fatality and exists in the form of I_2 (elemental iodine), CH_3I (organic iodine), and CsI [12,13]. In this study, the transfer calculation of the fission product is performed by dividing cesium into CsOH, CsI, Cs_2MoO_4, and iodine into I_2 and CsI. In the MELCOR code, it is assumed that radionuclides exist in elemental form (e.g., Cs, I, Mo) in the nuclear fuel [9]. Once released from fuel, some mass of radionuclides is converted into compounds form (e.g., CsOH, CsI, Cs_2MoO_4) based on the core release model. In this study, the core release is calculated using the CORSOR-M model [14], and as a result, about 70, 8, and 22% of the initial core inventory of elemental cesium are present in the form of CsOH, CsI, and Cs_2MoO_4, respectively, and about 0.77 and 99.23% of elemental iodine are evaluated to exist in the form of I_2 and CsI, respectively (refer to Table 4). CsOH, CsI, and Cs_2MoO_4 all exist in aerosol form, and aerosol dynamics (e.g., diffusion, agglomeration, sedimentation, and deposition) within the MELCOR Code are calculated by the MAEROS model [15]. Since almost all of the iodine exists as CsI, the behavior of iodine follows that of CsI. Although the calculations for the I_2 behavior are also performed in MELCOR, a detailed analysis of the I_2 behavior is not performed because the result does not significantly affect the iodine release.

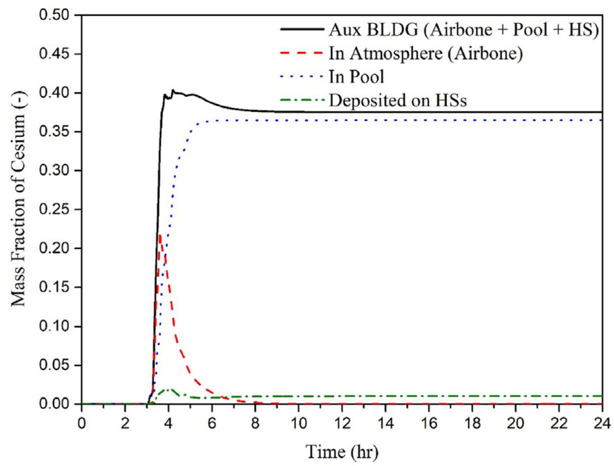

Fig. 14. Cesium behavior in the auxiliary building for Pathway 4.

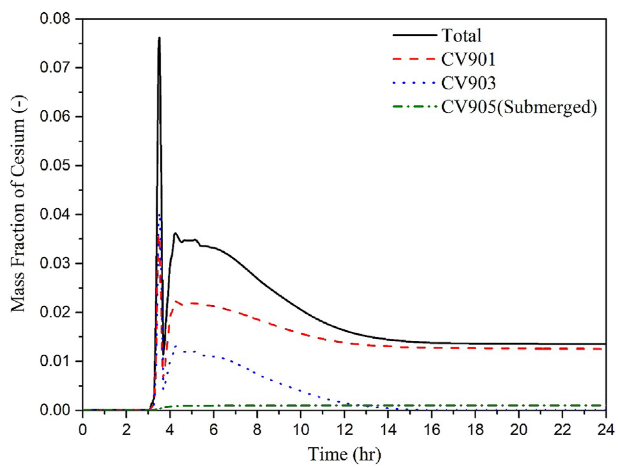

Fig. 15. Cesium behavior on ISLOCA piping for Pathway 4.

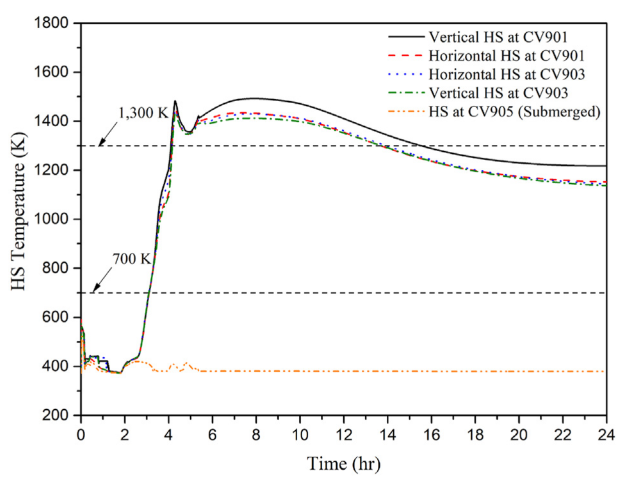

Fig. 16. Temperature of heat structures on ISLOCA piping for Pathway 4.

3.1. Analysis of accident progression and fission product behavior for Pathway 1

Table 5 shows the progression of the accident for Pathway 1. When a break of 4-inch equivalent diameter pipe occurs near RHR HX at 0 s, the reactor is tripped in 10.5 s and the safety injection begins by the low-pressure signal of the pressurizer (the pressure of the pressurizer < 1870 psig). The safety injection stops when the RWST is exhausted in 1.8 h, and the plant enters the Severe Accident Management Guide (SAMG) condition in 2.4 h, followed by cladding failure and a gap release. Since it is a bypass accident, fission products in the core begin to be released to the environment directly through the auxiliary building regardless of the containment integrity. The corium is relocated to the lower head of RPV in 2.6 h, and RPV fails in 4.8 h.

In the auxiliary building, the door of the RHR HX room and the personnel door on the ground floor open immediately after the accident due to the pressure buildup. Therefore, fission products leaked into the RHR HX room through the ISLOCA piping are released to the environment directly through the open doors, even though the ventilation system is properly working.

Fig. 4 shows the cesium distribution for Pathway 1. About 36.4% of the cesium of the initial inventory remains in the RCS, 12.7% stays in the auxiliary building, 26.3% is captured by the filter, and 21.7% of the inventory escapes to the environment 24 h after the accident. When the RPV fails in 4.8 h, some of the cesium in the RCS will escape to the containment building and its fraction is about 0.75%. Up to 6.1% of cesium is deposited on the ISLOCA piping (CV901, 903), and at that time, about 16 and 82% of the deposited cesium is evaluated as deposited by turbulent deposition and impaction, respectively. However, only 1.9% of cesium's initial core inventory remains in the piping 24 h after the accident occurs because of the re-vaporization of CsOH and CsI. Mass fraction of Cs compounds on the ISLOCA piping and the temperatures of the heat structures of the piping are shown in Fig. 5 and Fig. 6, respectively. CsOH and CsI are re-vaporized when the surface temperature of heat structures in the pipes reaches about 700 K. The sudden temperature rise in 4.5 h is due to the water depletion in the ISLOCA piping. On the other hand, cesium molybdate (Cs_2MoO_4) does not re-vaporize because its re-vaporization temperature is about 1300 K or higher [16].

As shown in Fig. 7, the cesium in the auxiliary building is initially present in the atmosphere as an aerosol, but the airborne aerosols settle down on the bottom (~10%) or in the water pool (~3%) through agglomeration and sedimentation 24 h after the accident. Fig. 8 indicates the cesium release fraction to the environment, showing a significant portion of the cesium is released to the environment through the personnel door. Only 0.60% passes through the exhaust system unfiltered.

In the MELCOR analysis results, iodine exists in the form of 99.99% of CsI and 0.01% of vapor iodine (such as elemental iodine and organic iodine). As most of the iodine exists in the form of CsI, iodine behavior under the ISLOCA conditions follows the trend of CsI behavior. The iodine behavior for Pathway 1 can be seen in Fig. 9, and it is much similar to cesium behavior (refer to Fig. 4). About 33.5% of the iodine of the initial inventory remains in the RCS, 13.9% stays in the auxiliary building, 28.4% is captured by the filter. One different point is that the deposit amount of iodine in the pipings in 24 h is almost 0 because almost of CsI is re-vaporized from the piping. Eventually, 23.2% of iodine releases to the environment 24 h after the accident.

3.2. Comparison of accident progression

Table 5 summarizes the progression of accidents for each pathway. The RWST, which is the water source for HPSI, is exhausted in 1.8 h for all cases. However, the rate of core degradation is faster in Pathways 1 and 2, compared to Pathways 3 and 4. This difference can depend on whether the safety injection flow

Table 7
Cesium release fraction depending on release ways in 24 h.

	Total Release	Personnel Door (FL926)	Supply System (FL951)	Exhaust System (FL982)
Pathway 1	21.74%	21.14%	0.00%	0.60%
Pathway 2	20.79%	20.09%	0.00%	0.70%
Pathway 3	24.93%	22.83%	0.00%	2.10%
Pathway 4	4.96%	3.54%	0.00%	1.42%

Table 8
Iodine distribution in 24 h for each pathway.

	RCS	CTMNT	ISLOCA Piping[a]	AUX BLDG	Environment	Filter
Pathway 1	33.47%	0.90%	6.40 → 0.00%	13.93%	23.24%	28.37%
Pathway 2	23.90%	2.20%	6.23 → 0.11%	17.65%	22.37%	33.57%
Pathway 3	2.20%	0.93%	1.04 → 0.00%	35.89%	25.64%	34.52%
Pathway 4	4.64%	1.33%	8.31 → 0.08%	37.42%	5.32%	50.14%

[a] ISLOCA Piping: Maximum Deposition Fraction → Deposition Fraction in 24 h.

passes the core or not. That is, if the ISLOCA occurs at the pipes connected to the cold leg and downcomer (Pathways 1 and 2), some of the coolant injected by HPSI would be immediately discharged to the auxiliary building without cooling the core. The core water levels, which are shown in Fig. 10, indicate that Pathways 1 and 2 have less water inventory in the core because of injected coolant loss before reaching the core, causing an early SAMG entry condition and core damage.

However, comparing Pathway 3 and Pathway 4, the core water level in Pathway 4 remains lower than that in Pathway 3. This difference comes from the different locations where ISLOCA pipes are connected to the hot leg. While the RHR HX is connected to the top of the hot leg in Pathway 3, the RHR pump is to the bottom of the hot leg in Pathway 4. Therefore, it is relatively easy to deliver the coolant from the hot leg into the auxiliary building through the broken pipe in Pathway 4. For this reason, the overall accident progression in Pathway 3 is slower than Pathway 4, resulting in RPV failure about 0.8 h late.

3.3. Comparison of fission product behavior

The distribution of cesium is given in Table 6 on a location basis for each pathway 24 h after the accidents. The characteristics of cesium behavior are related with the accident progression which depends on ISLOCA pathways. Fig. 11 shows a cesium release path from the core to the auxiliary building for Pathways 1 & 2 and Pathways 3 & 4. As Pathways 1 and 2 have a cesium release path from the core to the cold leg, about 36.4% and 28.7% of cesium are kept in the RCS, respectively. On the contrary, about 7% of cesium remains in the RCS for Pathways 3 and 4 because of the direct release path from the core to the hot leg without passing the steam generators and the cold leg. Fig. 12 plots the deposition fraction of cesium on the steam generator u-tubes for each pathway. From this figure, it is noted that the cesium distribution during ISLOCA sequences is affected by the release path. As a result, the cesium fraction in the auxiliary building is much larger in Pathways 3 and 4 than in Pathways 1 and 2.

Regardless of the release path for Pathways 1, 2, and 3, the release fraction to the environment is similar and it ranges between 20 and 25%. However, Pathway 4 allows only 5% of cesium to be released to the environment because of the pool scrubbing. Fig. 13 shows the water level in the RHR pump room in the auxiliary building and the break location is covered by the coolant in the room. As shown in Fig. 14, about 36% out of 37.5% of cesium in the auxiliary building is kept in the pool for Pathway 4. This suggests that the fission product removal by the deposition on the auxiliary building structures is not effective in controlling cesium release to the environment. Instead, the effect of pool scrubbing in the auxiliary building seems to be important in reducing the amount of cesium released to the environment. Also, in Pathway 4, cesium behavior in ISLOCA piping is different from that of other pathways. In Fig. 15, while the amount of cesium in CV901 and 903 is reduced because of re-vaporization, the deposited cesium in CV905 does not decrease because the piping is submerged. The temperatures of ISLOCA piping heat structures are shown in Fig. 16.

Table 7 summarizes the fraction of cesium released to the environment depending on release locations for each pathway. The fraction of cesium released to the environment through the personnel door exceeds 90% for Pathway 1 to 3 and 70% for Pathway 4. That means the amount of cesium that is released through the door is the most critical release path to the environment under the ISLOCA conditions.

The distribution of iodine is given in Table 8 for each pathway 24 h after the accidents. As mentioned earlier, the iodine distribution is similar to that of cesium in all pathways because most of the iodines exist in the form of CsI. In Pathways 1, 2, and 3, the release fraction to the environment is 23.2, 22.4, and 25.6%, respectively. Lastly, only 5.3% is allowed to be released in Pathway 4 due to the pool scrubbing and the filtering.

4. Conclusion

In this study, the differences of the accident progression and the amount of fission product release to the environment are analyzed for various ISLOCA pathways. When a break occurs on the pipe connecting the cold leg and the downcomer to the RHR HX, gap release starts in around 2.5 h, and about 21% of the initial inventory of cesium and 23% of iodine are released to the environment. When an accident occurs at a specific location on the route from the hot leg to RHR HX, cladding fails around 3.3 h, and about 24.9% of cesium and 25.6% of iodine are released to the environment. However, when an accident occurred on a pipe connected from a hot leg to an RHR pump, the released amount of cesium and iodine is evaluated to be 5.0 and 5.3%, respectively, which is the least among all cases. This result means that the characteristics of the accident strongly depends on the ISLOCA pathways. In the previous analyses of ISLOCA, however, an accident through the most likely pathway was selected as the representative study, and the source term was evaluated only for that scenario. Based on this exemplary study result, it deduced that ISLOCA needs to be analyzed with various possible scenarios to meet the analysis objective, in addition to the most frequent case.

Among the several release paths to the environment, the most critical release path of cesium and iodine is focused to be the personnel door. On the other hand, the amount of cesium that is released through the ventilation system is relatively low due to the filters. Unlike the containment building, the doors of the auxiliary building are not designed to withstand the ultimate internal pressure. Hence reinforcing the pressure withstand capacity of the doors and other openings would be a significant mitigating factor in accident management of the ISLOCA.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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