Nuclear Engineering and Technology 53 (2021) 2859–2865

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Analysis of severe accident progression and Cs behavior for SBO event during mid-loop operation of OPR1000 using MELCOR

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A R T I C L E I N F O

Article history:
Received 15 December 2020
Received in revised form
1 March 2021
Accepted 6 March 2021
Available online 15 March 2021

Keywords:
Mid loop operation
Full power operation
Severe accident
Cesium behavior
MELCOR
OPR1000

A B S T R A C T

One of the important issues raised from the Fukushima-Daiichi accident is the safety of multi-unit sites when simultaneous accidents occur at the site and recently a multi-unit PSA methodology is being developed worldwide. Since all operation modes of the plant should be considered in the multi-unit PSA, the accident analysis needs to be performed for shutdown operation modes, too. In this study, a station blackout during the mid-loop operation is selected as a reference scenario. The overall accident progression for the mid-loop operation is slower than that for the full-power operation because the residual heat per mass of coolant is about 6 times lower than that in the mid-loop scenario. Though the fractions of Cs released from the core to the RCS in both operation modes are almost the same, the amount of Cs delivered to the containment atmosphere is quite different due to the chemisorption in the RCS. While 45.5% of the initial inventory is chemisorbed on the RCS surfaces during the full-power operation, only 2.2% during the mid-loop operation. The containment remains intact during the mid-loop operation, though 83.9% of Cs is delivered to the containment.

1. Introduction

Since the Fukushima-Daiichi accident in 2011, concerns on simultaneous accidents at the multi-unit site of nuclear power plants (NPP) have been increased worldwide. Especially in Korea, four NPP sites are in operation, and at least five units are located at each site. Based on the total amount of power generated per plant site, Korea's all four NPP sites are ranked among the top 10 sites in the world [1]. Though the probabilistic safety assessment (PSA) technique has been developed and used to assess plant safety, it was mostly applied to the single unit case by now and recently a multi-unit PSA methodology is being developed and documented worldwide.

When multi-units are operating on the same site, some plants are scheduled to stop for an overhaul for preventive maintenance or corrective maintenance while others are in the full power operation mode. In other words, the accidents at the multi-unit site may occur either at the full power operation units or at the shutdown mode units. During the Fukushima-Daiichi accident, for example, Unit 4 was in a shutdown operation for planned maintenance. Fortunately, there was no damage to the fuel, but this Fukushima-Daiichi accident showed that a severe accident could occur even at a plant in shutdown operation. Therefore, when performing a multi-unit PSA, it will be more general to include the analysis for the units of low power and shutdown (LPSD) operation along with the full power units.

The configuration of the plant changes continuously during the LPSD operation, and typically 15 plant operational states (POS) are classified depending on the overhaul process [2]. Among these, an inspection of equipment in the reactor coolant system (RCS) and the eddy current test for u-tubes of the steam generators are performed during POS5. In this POS, the shutdown cooling system (SCS) removes the residual heat, maintaining the coolant level of the RCS at the center of the hot leg. Hence POS5 is also called the mid-loop operation. During POS5, even a small perturbation of water level in the RCS may cause the vapor to enter the SCS inlet pipe resulting in a loss of the SCS due to a pump failure. If the standby SCS does not work, the coolant temperature rises and eventually core damage occurs.

A couple of accidents were reported to occur during the mid-loop operation [3,4]. One is the loss of residual heat removal system at Diablo Canyon Unit 2 in 1987. The residual heat removal system failed about one and one-half hours when the plant was

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https://doi.org/10.1016/j.net.2021.03.006

shutdown with the RCS water level drained to approximately mid-level of the hot leg piping. The other is the loss of vital AC power and the residual heat removal system that occurred at Vogtle unit 1 in 1990. When the plant was in cold shutdown with reactor coolant level lowered to mid-loop for various maintenance tasks, all safety (vital) AC power was lost and the plant was out of control for 36 min. According to the PSA results, the core damage frequency (CDF) of POS5 accounts for 19.7% of the total LPSD CDF [2]. Because it takes a high portion of the total LPSD CDF, POS5 is selected as the representative state for the LPSD mode and the accident analyses are performed.

For the US plants, the mid-loop operation analysis was done in mid-1990. The analysis of thermal and hydraulic as well as the release fraction of fission products was performed at Grand gulf NPP for a large break loss of coolant accident and a station blackout (SBO) using MELCOR [5]. Also, level 3 probabilistic risk assessment was performed at the Surry NPP [6]. According to the report, the risk of early fatalities during the mid-loop operation was evaluated to be significantly lower than that of full-power operation and these results were caused by the short half-lives of iodine and tellurium, which affect the early fatality. On the other hand, the risk of latent cancer was found to be almost the same as that of full-power operation. For Korea plants, the thermal-hydraulic behavior under a loss of SCS during the mid-loop operation was analyzed using MARS 2.1 and RELAP5 for an optimized power reactor 1000 (OPR1000) [7,8], and the gravity feed was applied as the accident mitigation strategy. However, these studies were focused only on the timing of core damage, and the use of these studies was limited to level 1 PSA. Therefore, this study aims to analyze the severe accident progression and the behavior of fission products during mid loop operation, using MELCOR, which is a severe accident analysis code.

2. Plant modeling and accident scenario

2.1. Plant nodalization

The OPR1000 nuclear power plant, which is a typical NPP of Korea, is selected as the reference plant. It is a pressurized water reactor with a core heat output of 2185 MWth. The RCS consists of two loops, and each loop has a hot leg and two cold legs. The pressurizer has the safety depressurization system (SDS) to rapidly depressurize the RCS and the pressurizer safety valve (PSV) to prevent RCS from over-pressurization [9].

The MELCOR 2.2 version developed by Sandia national laboratories is used in this study. MELCOR is an integrated computer code that can analyze the progression of the severe accidents of a light water reactor. It can be used to analyze the thermodynamic phenomena of an NPP and transport of fission products within the RCS and in the containment [10].

The MELCOR model developed in this study simulates the mid loop operation without the steam generator nozzle dam. Figs. 1 and 2 show the nodalization of the RCS and the containment of the MELCOR model, respectively. CV, FL, and CF mean control volume, flow path connecting each control volume, and control function which allows the user to define functions of variables, respectively [10]. As the manways of the pressurizer and the steam generators are always open (FL550, FL311, FL411) and the safety injection tanks (SIT) are isolated in POS5 [2], the pressurizer and the SITs are not modeled. Along with the mid-loop modeling, the full power model is also analyzed for the comparison of both power modes. In the model for the full-power operation, however, the pressurizer and the SITs are included and they are shown in blue lines in Fig. 1.

The containment is modeled with four control volumes including the reactor cavity in both models (see Fig. 2). The failure pressure of the containment is adopted from the results of the ultimate pressure capacity of the containment during the mid-loop operation, and the equipment hatch, which is the vulnerable part of the containment for mid loop operation, fails if the containment pressure exceeds 808.7 kPa(a) [11]. In the model for full-power operation, it is assumed that the containment fails at the cylindrical wall of it when its pressure exceeds 1328.6 kPa(a). The damaged area is assumed to be 1 ft^2 for both models [12].

Table 1 compares the major parameters and steady-state results for the mid loop operation and the full power operation. The steady-state simulation for the mid loop operation is performed based on the following assumptions. As the average time to enter POS5 after the reactor shutdown is 79.5 h, the residual heat of 12.183 MW is used as the initial power and modeled to decrease with time [2]. Though the residual heat is removed by the SCS heat exchanger during POS5 [2], the SCS heat exchanger is not modeled. Instead, 294.63 kg/s of water at 316.05 K is injected into the cold legs which is the maximum flow rate of the low pressure safety injection pump [13], and water flows out from the hot leg maintaining the center level in the hot leg. The coolant temperature of the hot leg is assumed to be the inlet temperature of the SCS heat exchanger, and the temperature of the cold leg is the discharge temperature of the heat exchanger [13]. The MELCOR model for full power operation is modeled by referring to the value of final safety analysis report (FSAR) [13]. As shown in Table 1, the error is evaluated lower than 1%, in other words, it can be said that the MELCOR model of the two operation modes simulates each operation mode well.

2.2. Reference scenario

According to the PSA report [2], CDFs of loss of off-site power (LOOP) and SBO occupy 10.4% and 36.5%, respectively, of the total LPSD CDF. Therefore, the reference accident during the mid-loop operation is selected as the SBO which results in the loss of SCS. It is assumed that the mitigation actions by the operator and the recovery of the power are not taken.

For the full power operation, the SBO is also assumed as an initiating event. If an SBO occurs, the reactor trips and reactor coolant pump and supply of the main feedwater are not available. So the residual heat removal using the secondary system fails. As a result, the pressure of the RCS increases due to residual heat, and when the pressure reaches 17.23 MPa(a), the PSV of the pressurizer repeatedly opens and closes to protect the RCS from over-pressurization. Even in a full power operation, it is assumed that the mitigation measures or power recovery failed. Only the SITs can supply the coolant to the RCS until the SIT is exhausted if the RCS pressure decreases below the set point of the SITs [9].

The accident scenarios for each operation mode of the mid loop operation and the full power operation are named MLO-SBO and FPO-SBO, respectively. It is assumed that an SBO occurs in 0 s and the accidents are analyzed for three days.

3. Results and discussion

3.1. Comparison of accident progression

Tables 2 and 3 show the time sequence of the major events and the calculation results of both accidents. In the MELCOR calculations of this study, the influence of natural convection in the RCS is neglected. In MLO-SBO, the SCS is lost due to the SBO in 0 s. Since the residual heat of the core cannot be removed, the temperature of the coolant in the core rises to the saturation temperature in 0.22 h (777 s), and the coolant in the core begins to boil. The evaporated coolant is discharged to the inner shell of the containment through

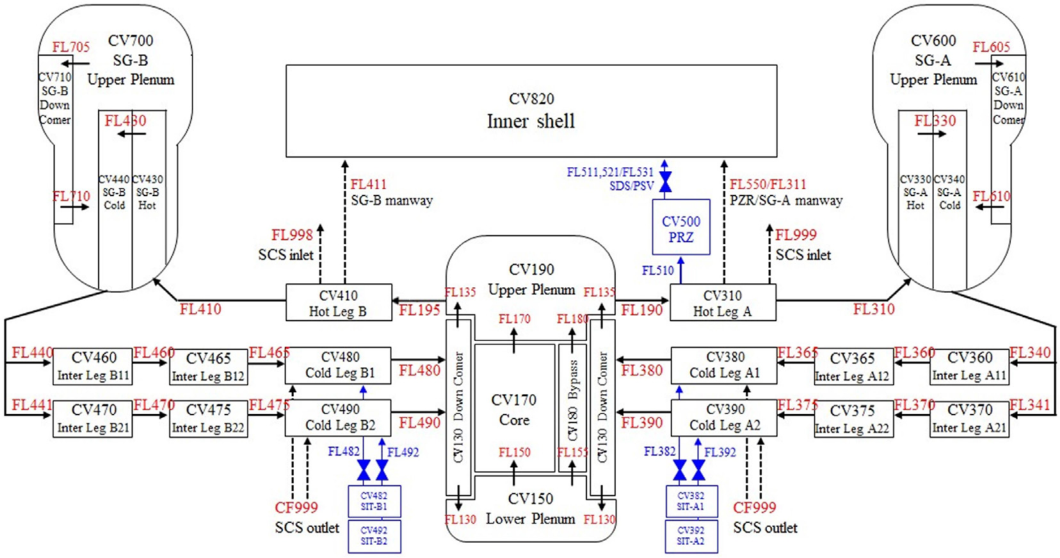

Fig. 1. The RCS nodalization of OPR1000 MELCOR model.

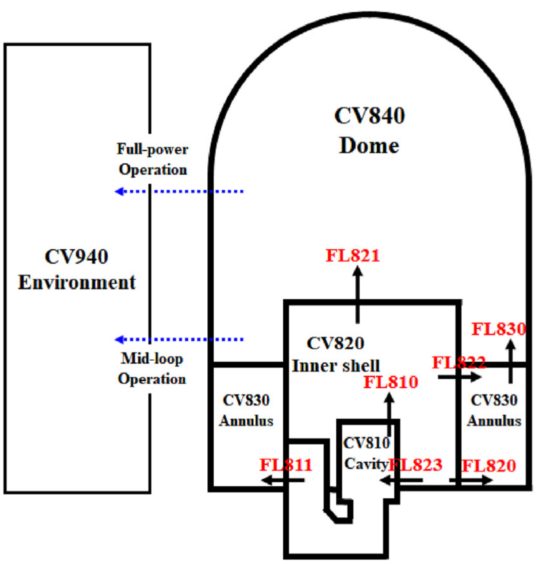

Fig. 2. The containment nodalization of OPR1000 MELCOR model.

Table 2
Time sequence of the major events in MLO-SBO and FPO-SBO.

Event	MLO-SBO [hr]	FPO-SBO [hr]
Initiating event	0.0	0.0
SG dryout	–	0.79
PSV first open	–	1.08
Boiling starts in the core	0.22	1.13
Active core uncovery	2.55	1.67
Oxidation starts in the core	3.58	1.96
Gap release[a)]	3.63	1.99
RPV failure	8.57	3.97
SIT injection	–	4.00
Reactor cavity dry out	20.75	37.33
Containment failure	–	39.24

[a] Fission products are released from the gap of the fuel rods.

the manways and the active core is exposed in 2.55 h. When the FPO-SBO occurs, on the contrary, the RCS pressure reaches the PSV set point in 1.08 h and the coolant of the core starts to boil in 1.13 h (4080 s) as the residual heat is removed by the steam generators. As a result, boiling starts later in the core of FPO-SBO than MLO-SBO. Fig. 3 shows the coolant temperatures of the core and its saturation temperatures for both cases. Since the initial residual heat per RCS coolant mass of FPO-SBO is about 6 times more than that of MLO-SBO, the overall accident progression is faster in FPO-SBO. The

Table 1
Major parameters and steady-state results for mid loop operation and full power operation.

Parameter	Mid loop operation			Full power operation		
	Reference value	MELCOR	Error [%]	Reference value	MELCOR	Error [%]
Decay heat/Core heat output [MW]	12.183	12.183	0.00	2185	2185	0.00
RPV inlet coolant flow rate [kg/sec]	294.63	294.63	0.00	15311	15252	−0.39
Hot leg coolant temperature [K]	324.85	325.94	0.33	600.45	602.39	0.32
Cold leg coolant temperature [K]	316.05	316.03	−0.01	568.95	572.12	0.56
RCS pressure [kPa(a)]	101.33	101.37	0.05	15513	15504	−0.06
Manway diameter [m]	0.4064	–	–	–	–	–
RCS coolant mass [ton]	92.72	–	–	212.5	–	–
SIT volume [m^3]	–	–	–	52.6	–	–
Containment failure pressure[a)] [kPa(a)]	808.7	–	–	1328.6	–	–

[a] It was assumed by sing the evaluation results of the ultimate pressure capacity for the containment according to each operation mode.

Table 3
Important parameters of accident progression in MLO-SBO and FPO-SBO three days after the accident.

Parameters	MLO-SBO	FPO-SBO
Hydrogen mass generated in the core [kg]	417.5	467.6
Hydrogen mass generated in the reactor cavity [kg]	1183.0	1126.9
Total debris mass ejected to the reactor cavity [ton]	132.0	132.4
Zirconium mass ejected to the reactor cavity [ton]	11.4	10.8
Stainless steel mass ejected to the reactor cavity [ton]	21.3	20.8
Axial eroded depth of concrete in the reactor cavity [m]	1.26	2.75
Peak containment pressure [kPa(a)]	541.5	1328.6[a)]

[a] Containment failure pressure for full power operation.

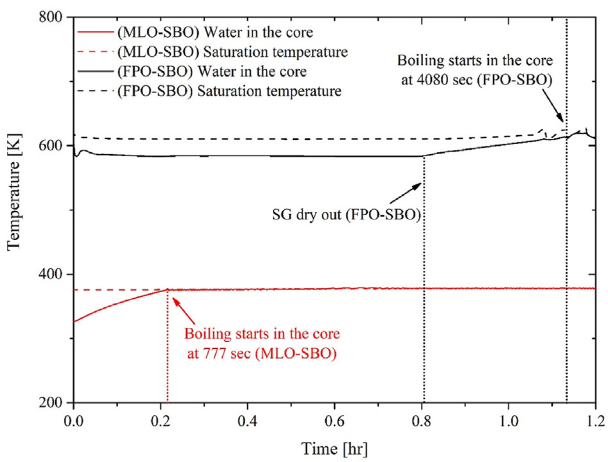

Fig. 3. Saturation temperatures and water temperatures of the core.

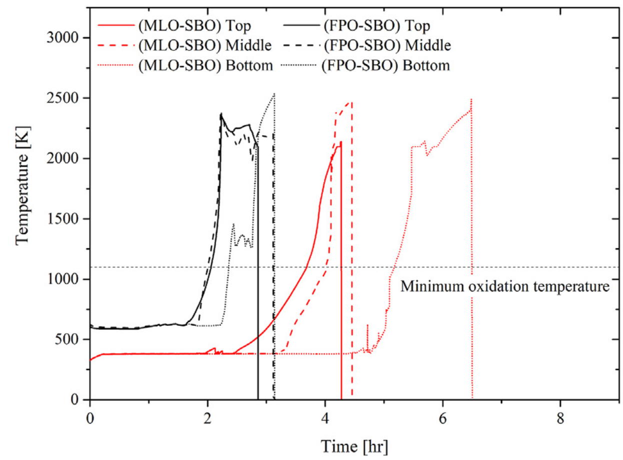

Fig. 4. Cladding temperatures at the center ring of the core.

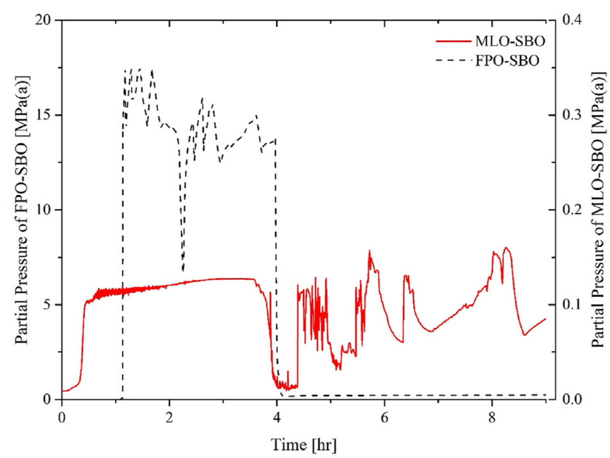

Fig. 5. Partial pressure of steam in the core.

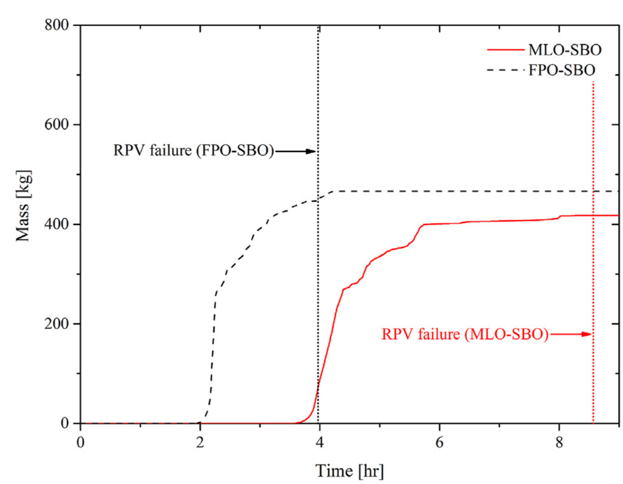

Fig. 6. Cumulative hydrogen masses generated in the core.

time to the active core uncovery and the reactor pressure vessel (RPV) failure in FPO-SBO is 1.67 h and 3.97 h, respectively, and they are 0.88 h and 4.6 h earlier than those of MLO-SBO (refer to Table 2).

Figs. 4 and 5 depict the temperatures of the cladding and partial pressure of steam in the core. Fig. 6 shows the cumulative hydrogen masses generated in the core for both scenarios, respectively. The core consists of 10 axial levels and 5 radial rings. In MLO-SBO, steam and metal in the cladding interact to generate hydrogen around 3.58 h, and the cumulative hydrogen mass produced in the core is evaluated to be 417.5 kg. During the full power SBO sequence, hydrogen starts to be generated in 1.96 h and reached 467.6 kg. About 50 kg of hydrogen is produced more from FPO-SBO because of the fast core heat-up process and high partial pressure of steam for the cladding oxidation in the core.

The damaged core is eventually relocated to the bottom of the RPV and the molten corium in the lower plenum is relocated to the reactor cavity after the RPV failure. For MLO-SBO, the RPV fails in 8.57 h, and 11.4 ton of zirconium and 21.3 ton of stainless steel are relocated to the reactor cavity, producing 1183 kg of hydrogen from the reactor cavity for the first three days of the accident. In the meantime, about 1127 kg of hydrogen is generated in FPO-SBO. Comparing the total hydrogen mass produced in the core and reactor cavity, about 1600 kg of hydrogen are generated, in both MLO-SBO and FPO-SBO (refer to Table 3).

The initial debris mass relocated to the reactor cavity in MLO-SBO and FPO-SBO is 132.0 ton and 132.4 ton, respectively. Though this value is much similar in both sequences, the amount of decay heat in the corium is quite different, as shown in Fig. 7. Hence, 2.75 m of the bottom concrete at the reactor cavity is ablated in FPO-SBO for the first three days of the accident, which is 1.5 m deeper than that in MLO-SBO.

Figs. 8 and 9 show the containment pressures and coolant mass in the reactor cavity in MLO-SBO and FPO-SBO sequences. As the coolant in the reactor cavity is completely depleted around 20.75 h in MLO-SBO, the pressure buildup rate suddenly decreases after cavity water depletion. Hence the containment pressure reaches about 540 kPa(a) after three days, which is still lower than the

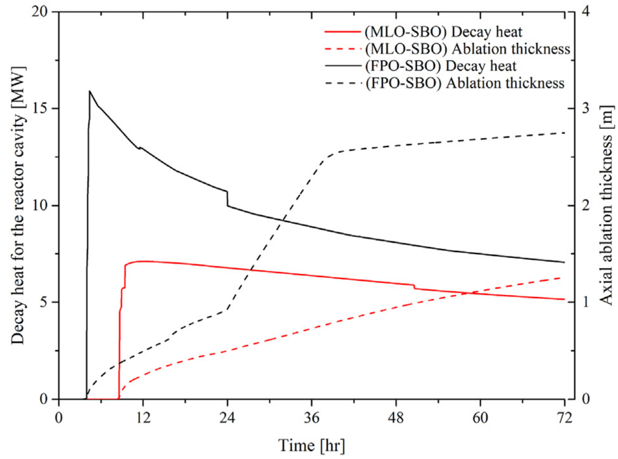

Fig. 7. Decay heat rates for the reactor cavity and axial ablation thicknesses of the reactor cavity.

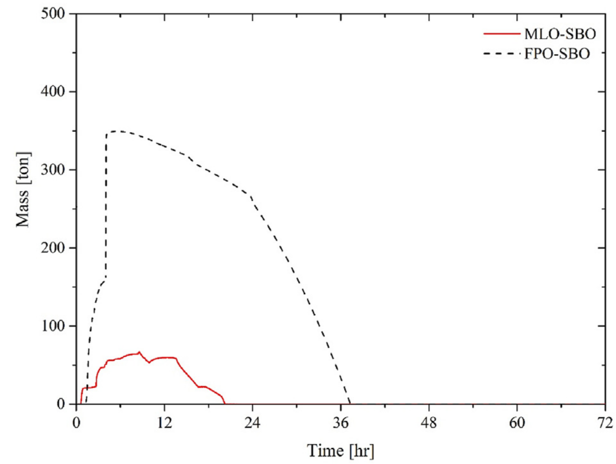

Fig. 9. Coolant mass in the reactor cavity.

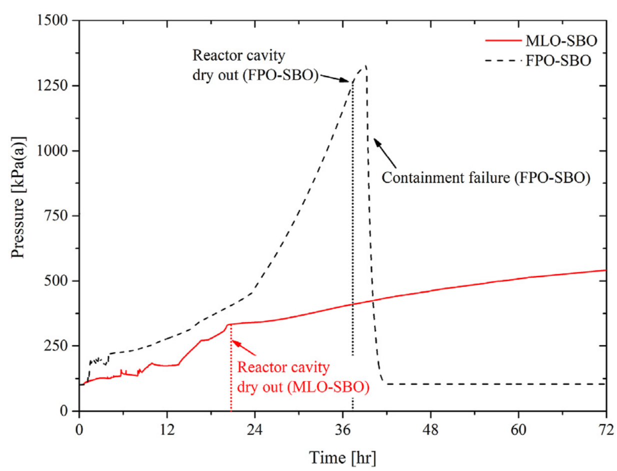

Fig. 8. Containment pressures.

Table 4
Distribution of Cs in MLO-SBO and FPO-SBO at three days after the accident occurred.

Parameters	MLO-SBO	FPO-SBO
Initial inventory of the Cs[a)] [kg]	112.61	112.66
Total Cs fraction released from the core[b)] [%]	99.97	99.96
Total Cs in the RCS [%]	16.1	58.3
Airborne fraction [%]	0.0	0.1
Liquid fraction [%]	0.2	0.5
Deposited fraction on heat structures [%]	13.7	12.2
Chemisorbed fraction on heat structures [%]	2.2	45.5
Total Cs in the containment [%]	83.9	31.8
Airborne fraction [%]	0.5	2.4
Liquid fraction [%]	0.0	0.0
Deposited fraction on heat structures [%]	83.4	29.3
Total Cs in the environment [%]	0.0	9.8

[a] Member elements of Cs are Cs^{137}, Cs^{136} and $Cs.^{134}$.
[b] Total Cs includes the Cs compounds such as CsOH, CsI and Cs_2MoO_4.

failure pressure of 808.7 kPa(a) [11]. For the FPO-SBO sequence, however, the containment fails in 39.24 h after the accident due to the larger RCS water inventory and the water from the SITs. In 1.08 h, the opening of PSV causes the first pressure jump, as shown in Fig. 8. In 24 h, as the evaporation rate of the coolant in the reactor cavity increased, the containment pressure buildup rate increases suddenly. This is because the corium pool components changes from heavy mixture layer to light oxide layer due to the oxidation of all metals in the corium pool and light oxide layer transfers heat to the coolant more faster.

3.2. Analysis of Cs behavior in the RCS and containment

The initial inventory and distribution of Cs for both operation modes in the RCS and the containment are shown in Table 4. The initial Cs inventory of the OPR1000 is calculated using the Origen-Arp [14]. The same methodology and assumptions as the previous study are used for the initial inventory calculation [15]. It is assumed that an accident occurs at the end of the cycle. The initial fission product inventory is calculated in 0 s after the reactor trip for the full power operation mode and 79.5 h after shutdown for mid loop operation mode [2]. Though a long half-life of Cs affects the initial inventory, its difference is negligible.

According to the MELCOR calculation, more than 99% of Cs is released from the core for both scenarios. Since the manways are always open in MLO-SBO, the fission products escaped from the fuel are released to the containment right away. In FPO-SBO, however, fission products are released to the containment through the PSVs, which open and close repeatedly depending on the RCS pressure. The difference in the plant operation mode affects the fission product distribution in the containment. While 58.3% of Cs is kept inside the RCS in FPO-SBO, only 16.1% of Cs stays in the RCS in MLO-SBO (refer to Table 4).

In the RCS, Cs may exist in the air, in liquid, deposited, or chemisorbed on the surfaces of heat structures. Figs. 10 and 11 show the fractional distribution of Cs in the RCS of each accident. Depending on the operation mode, it is found that there is a large difference in the amount of Cs chemisorbed on the surfaces of the heat structures. In MELCOR, chemisorption of Cs is modeled to occur on the surface of stainless steel, and the chemisorbed Cs does not re-vaporize [16]. Studies on the Cs chemisorption indicates that the chemisorption rate is affected by temperature, the concentration of CsOH in gas phase, surface condition, etc. [17,18], and the chemisorption rate increases with the surface temperature exponentially [16]. The chemisorbed fraction is evaluated to be 2.2% and 45.5%, respectively, for the MLO-SBO and the FPO-SBO cases (refer to Table 4). One of the main reasons for such a big difference is the different temperatures of the RCS heat structures for both cases. Fig. 12 shows the surface temperatures of the guide tube, the wall of the upper plenum, and the u-tubes of the steam generator, which

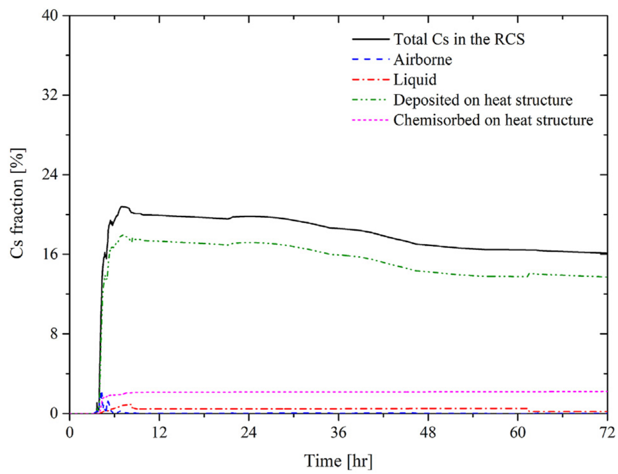

Fig. 10. Cs distribution in the RCS of MLO-SBO.

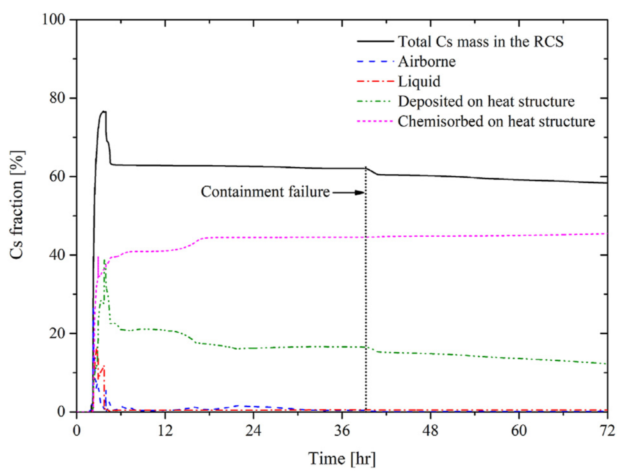

Fig. 11. Cs distribution in the RCS of FPO-SBO

are the representative RCS surfaces. As seen in the figure, the RCS heat structure temperatures during the FPO-SBO accident are generally higher than those during the MLO-SBO accident, resulting in an about 21 times bigger mass of chemisorbed Cs. In summary, about 58.3% of Cs stays in the RCS structure for the FPO-SBO case mainly due to the chemisorption effect and about 16.1% for the MLO-SBO.

Within the containment, Cs can exist in air, in liquid, or deposited on the surface of the containment structures. Unlike in the RCS, there is no chemisorbed Cs mass because the chemisorption model of Cs on the paint and concrete is not included in MELCOR. Figs. 13 and 14 show the distribution of Cs in the containment for each accident. Fig. 15 depicts the surface temperature of representative components in the reactor cavity, where A is a component made of stainless steel and B is a component of carbon steel. In MLO-SBO, about 83.9% of the initial inventory is released to the containment after cladding failure. Initially, most of Cs stays in the air, but the airborne Cs experiences the sedimentation process and settles down to the water collected in the containment. When the reactor cavity dries out in 20.75 h, Cs dissolved in the reactor cavity water still stays on the cavity concrete heat structures and some fraction is re-vaporized on the surfaces such as A component and then settles down again. Hence most Cs released to the containment are deposited on the containment heat structures. In FPO-SBO, about 38.0% of Cs is released to the containment and 9.8% of the initial inventory is released to the environment after the containment failure in 39.24 h. After 60 h, Cs re-vaporized from the surfaces such as component B in FPO-SBO. On the other hand, in MLO-SBO, re-vaporization on surface of component B does not occur, because the surface temperature of component B is maintained at about 600 K, as shown in Fig. 15.

4. Conclusion

The MELCOR model for the mid loop operation of OPR1000 has been developed, and the accident progression and the behavior of Cs both in the RCS and in the containment for an SBO scenario are analyzed. The results are compared with those for the full power operation to get an insight for the mid-loop operation mode.

The initial amount of coolant and the residual heat induces a significant effect on the accident progression in both accidents. Compared to FPO-SBO, the residual heat per mass of coolant is about 6 times lower in MLO-SBO, resulting in a slow progression of the accident. Hence the cladding and the RPV fail about 1.64 h and 4.60 h, respectively, later than those times in FPO-SBO. The mass of hydrogen produced in the core in MLO-SBO is 417.5 kg, which is about 50 kg less than that in FPO-SBO because the heat up process of cladding is slower in MLO-SBO. The mass of hydrogen produced

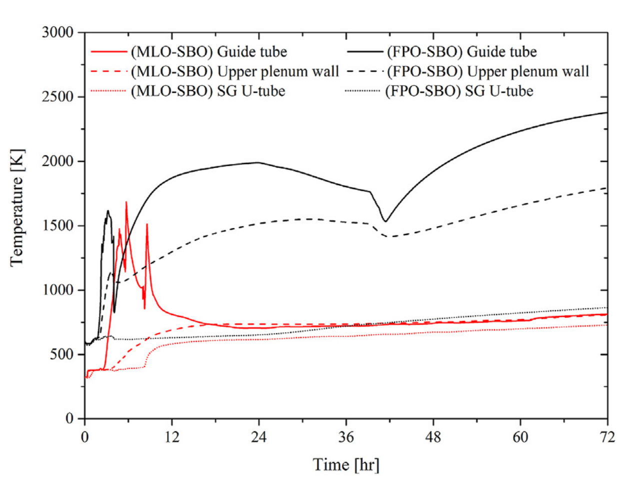

Fig. 12. Surface temperatures of heat structures in the RCS.

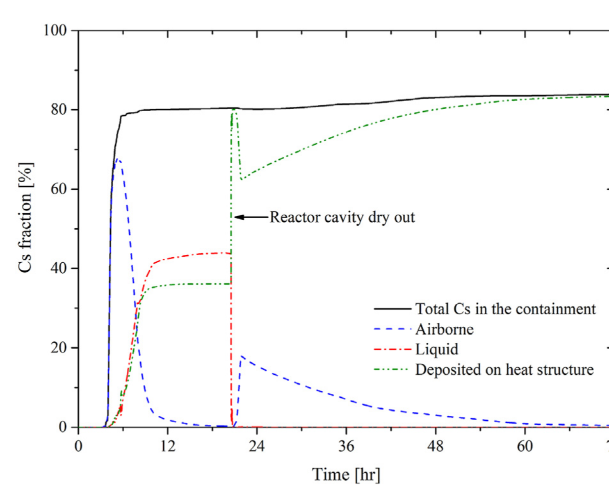

Fig. 13. Cs distribution in the containment of MLO-SBO.

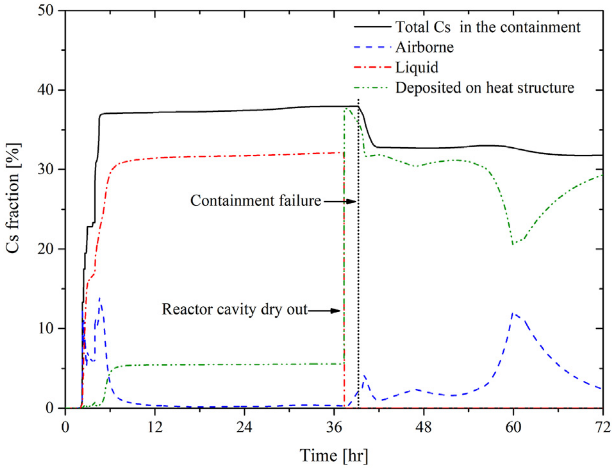

Fig. 14. Cs distribution in the containment of FPO-SBO

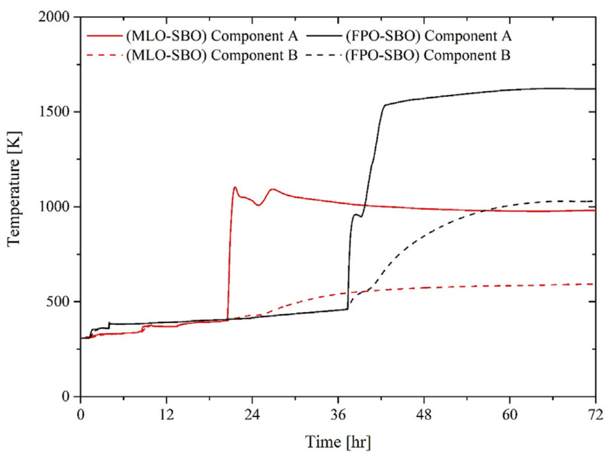

Fig. 15. Surface temperatures of heat structures in the reactor cavity.

in the reactor cavity in MLO-SBO is 1183 kg, about 56 kg bigger than that in FPO-SBO. But the sum of cumulative hydrogen mass produced in the core and reactor cavity is much similar in both accidents. The concrete ablation thickness in FPO-SBO is 2.75 m, and it is 1.5 m deeper than that in MLO-SBO. This difference is caused by the smaller decay heat in the corium pool in MLO-SBO than in FPO-SBO.

One of the main differences between two accidents is the different Cs mass released from the RCS to the containment. As the chemisorption phenomena is strong for the high surface temperature range, more than 58% of the initial inventory is chemisorbed on the RCS heat structures in FPO-SBO, and 32% of Cs is allowed in the containment. In MLO-SBO, on the contrary, only about 16.1% of the initial inventory is chemosorbed in the RCS and the rest goes to the containment because the RCS temperatures are relatively lower in MLO-SBO. Though 2.6 times more Cs is delivered to the containment in MLO-SBO than in FPO-SBO, there is no Cs release to the environment as the containment is intact during the accident. Less water inventory in the MLO-SBO plant configuration does not threaten the containment integrity. However, in FPO-SBO, the containment fails in 39.24 h and about 9.8% of Cs is released to the environment.

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.

Acknowledgements

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KOFONS), granted financial resource from the Multi-Unit Risk Research Group (MURRG), Republic of Korea (No. 1705001).

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