Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 20-21, 2022

Preliminary MELCOR analysis for in-containment relief valve and pool scrubbing system to mitigate fission product bypass under thermally-induced steam generator tube rupture accident in OPR1000

Juhyeong Lee[a], Wonjun Choi[a], Byeonghee Lee[c], Kwang-Soon Ha[c], Sung Joong Kim[a,b*]
[a]*Department of Nuclear Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763*
Republic of Korea
[b]*Institute of Nano Science & Technology, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763*
Republic of Korea
[c]*Korea Atomic Energy Research Institute 111 Daedeok-daero, 989 Beon-gil, Yuseong-gu, Daejeon 34057, Republic of Korea*

[*]*Corresponding author: sungjkim@hanyang.ac.kr*

1. Introduction

During the bypass accident such as steam generator tube rupture, there exists a possibility that fission products (FPs) may be released into the environment through secondary system regardless of the containment integrity. Because of this unique characteristic of bypass accident, the containment safety features cannot function its key role and may result in environmental release of FPs. In the previous study, several mitigation strategies such as injecting feed water into the steam generator or depressurizing the primary system were evaluated and showed successful mitigation for steam generator tube rupture (SGTR) accident [1]. However, when the thermally-induced SGTR (TI-SGTR) accompanies a station black out (SBO) event, these mitigation strategies may be unavailable. Therefore, to prevent rapid environmental release of FPs under bypass accident induced by SBO, a new mitigation feature using a pool scrubbing tank has been proposed HYU and KAERI [2].

The new mitigation strategy is to create the release path from the steam generator (SG) to the containment, isolating the path to the environment. In the previous study, Kim et al. proposed an in-containment relief valve (ICRV), which releases the energetic steam generated in the SG to the containment [3]. The previous study showed that the ICRV can retain FPs inside the containment building and delay the FPs release into the environment. However, because of steam injection and accumulated FPs in the containment building, the ICRV could cause containment over-pressure and generation of a large amount of FP aerosol in the containment atmosphere. Therefore, an improved strategy was proposed to overcome the drawback of the ICRV. The main idea is to add a depressurizing and decontamination tank (D-tank) to the previous ICRV concept. In this study, the D-tank was designed for the Optimized Power Reactor 1,000 MWe (OPR1000).

The objective of D-tank is to capture the FPs by pool-scrubbing effect and to reduce the steam pressure released into the containment. However, the free volume of containment building of the OPR1000 is limited, so the installation location of the D-tank is limited as well. Thus, it is important to achieve high efficiency and to decrease facility size for D-tank design. To achieve high efficiency in limited space of containment, the coolant volume of the D-tank was designed by considering the enthalpy of injected steam. Additionally, to use coolant for decontamination of FPs, a pool scrubbing system was considered. An injection valve to enhance pool scrubbing was designed with multiple sparger nozzles. In this study, to analyze the decontamination effect of this injection valve and D-tank, the severe accident analysis was performed by MELCOR 2.2. Through the MELCOR results, a mass of decontaminated FPs, a decontamination factor, and the behavior of the FP were evaluated.

2. Numerical methodologies

2.1. Analysis code

To evaluate the new mitigation concept, MELCOR 2.2 code was utilized by assuming the accident progression of TI-SGTR. MELCOR has been developed by Sandia National Laboratories for the U.S. Nuclear Regulatory Commission to model the progression of severe accident phenomenon in light water (LWRs) [4]. MELCOR consists of various sub-packages to simulate accident progression in the nuclear power plants (NPPs). In the MELCOR simulation, various sub-packages calculate accident phenomena such as boiling, heat-up, oxidation, fission product release and transport, and relocation of the core, to mention the several key phenomena.

2.2. D-tank modeling

The conceptual design of D-tank is illustrated in Figure 1. To isolate by-passed Radio Nuclides (RNs) from the primary system to the SG secondary side, the D-tank was connected directly to the SG secondary side. The D-tank was installed in the annulus-1st of containment building and by-passed steam was released to the annulus through the D-tank. Because of the limited free volume of annulus, the dimension of the D-tank was scaled at 20 m^3 volume and 3 m height in cylindrical tank. In MELCOR input, the shape of D-tank was simplified as rectangular shape. Because the released steam from the primary system may exhibit high temperature and pressure during the severe accident, the D-tank may be exposed to the high enthalpy steam as well. To accommodate the high enthalpy steam, the D-tank was designed to contain sufficient coolant inventory pool inside. The volume of coolant pool was proposed as 10 m^3 considering the enthalpy of the steam. Because the tank shape was rectangular in MELCOR input, the pool was simulated in 1.5 m height. It is apparent that the coolant pool affects the RN behavior during steam injecting. To consider this effect, a pool scrubbing model was activated in MELCOR input. The decontamination effect by pool scrubbing is associated with bubble diameter, velocity, and water level above the bubble departure point. Thus, to ensure the submergence depth of bubble departure point, the flow path was located to 1 m below the surface of coolant pool. The flow path was designed to enhance decontamination efficiency by using multi-hole sparger that has 36 holes 1 inch in diameter.

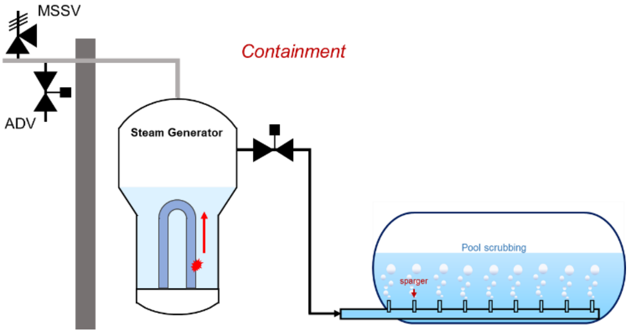

Fig. 1. A schematic of D-tank design and connection with steam generator secondary side

2.3. Reference accident case

To evaluate the passive mitigation performance of D-tank, a TI-SGTR accident induced by SBO was selected as a reference accident case [5]. In this accident case, only one SG was supplied with turbine-driven auxiliary feed water (AFW) for 4 hours and the other was assumed that AFW injection failed. Because of failed injection, the steam generator without AFW may be exposed to a pressure load with high temperature during severe accident condition. The pressure load can induce a creep rupture in the SG tube, and along to the creep rupture the SGTR was started. After the creep ruptured, the evaporated steam from primary system released into environment via ADV. Thus, to isolate the released steam, in the broken SG, the ADV was closed, and the D-tank valve was opened. Since opening the valve, the by-passed steam was released into the containment building and FPs were decontaminated by pool scrubbing. In this accident scenario, it was assumed that the lost power could not be returned on, and no additional mitigation strategies were available. Thus, finally RPV failure was predicted to occur at 17.93 hours. After RPV failure, because the primary steam was directly released to the containment, the steam from the primary system was not released to the D-tank. Thus, to evaluate the D-tank efficiency during steam injection, the accident was analyzed only until the RPV failure occurred. The detailed accident progression according to time is shown in **Table 1**.

Table 1: The major accident sequence of reference TI-SGTR case

Accident sequence	Time (hr)	Condition
Accident start	0	SBO
AFW start (ADV open)	0.83	Operator
AFW stop	4.83	
SAMG entrance	11.43	CET 923 K
Oxidation start	11.59	1100 K
Cladding melting	12.22	2100 K
UO2 melting	12.22	2800 K
SGTR	12.5	Creep rupture
Intact SG dry out	12.6	
D-tank valve open	12.79	Operator
Core dry out	14.01	
Broken SG dry out	14.53	
RPV failure	17.93	Penetration

3. Result and discussion

3.1. Radioactive nuclides behavior

Figure 2 shows the integrated mass of RNs inside the D-tank until RPV failure. UO_2 class shows the highest mass, and the rest shows the higher in the order of CsM, CsI, Te, and Cs class. However, because total injected mass of each class varies from class to class, evaluating the decontamination effect only with the total accumulated mass shows a limitation in method. Thus, to evaluate the specific behavior of RNs, 'FL-MACCS' record was added in MELCOR input.

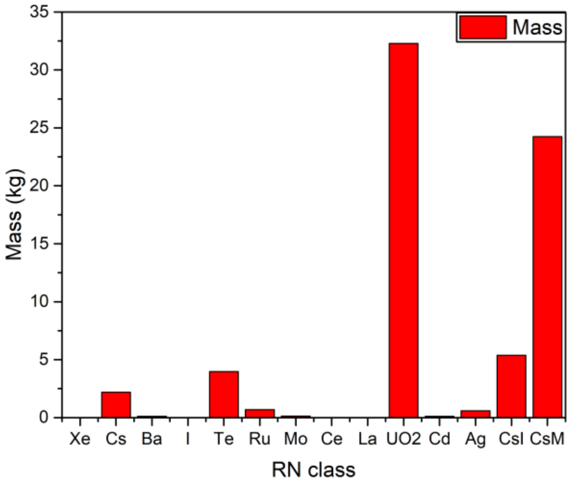

Fig. 2. Total integrated mass of each RN class at the RPV failure time

ʹFL-MACCS’ record was added for two flow paths. The first flow path is the line connecting SG-2nd to D-tank and the second one is D-tank to annulus. By using these two records, the transferred mass of each RN was evaluated based on the D-tank. **Table 2** shows transferred mass of CsM, CsI, Te, and Cs class until RPV failure. In MELCOR output for MACCS, each RN class has one vapor state and five aerosol sections. Five aerosol states were divided by aerosol size and aerosol 1 is the smallest size and aerosol 5 is the biggest one. In this study, the maximum aerosol size was 5.0e-4 m and minimum size is 1.0e-7 m. The results of **Table 2** are illustrated in **Figures 3** and **4**, for tank inlet and outlet, respectively.

Table 2: MELCOR mass [kg] output for MACCS of Cs, Te, CsI, and CsM class according to RN state

		Cs	Te	CsI	CsM
Vapor	Tank in	5.869	4.659	11.055	0.035
	Tank out	1.712	0.322	3.540	0.043
Aerosol1	Tank in	0.000	0.023	0.000	0.239
	Tank out	1.440	0.496	0.804	0.646
Aerosol2	Tank in	0.000	2.077	0.001	17.837
	Tank out	0.466	2.335	0.860	3.272
Aerosol3	Tank in	0.000	1.196	0.000	8.951
	Tank out	0.006	0.732	0.251	1.148
Aerosol4	Tank in	0.000	0.373	0.000	2.468
	Tank out	0.000	0.043	0.017	0.087
Aerosol5	Tank in	0.000	0.021	0.000	0.128
	Tank out	0.000	0.000	0.000	0.000

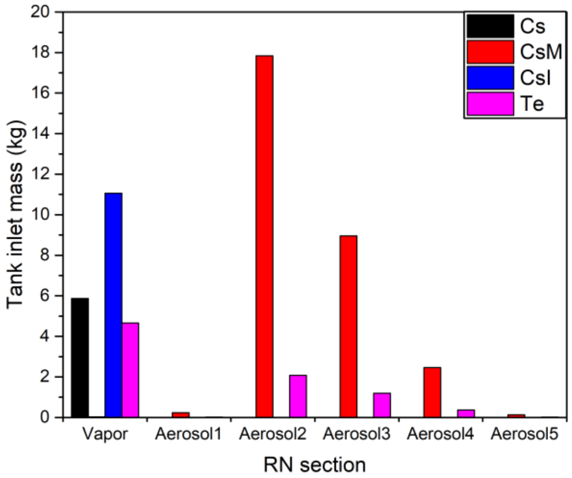

Fig. 3. Integrated mass of D-tank inlet according to RN class and RN state

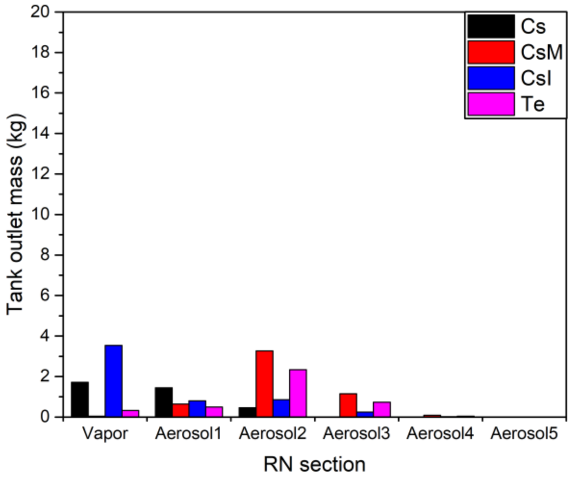

Fig. 4. Integrated mass of D-tank outlet according to RN class and RN state

Depending on RN class, the mass of RN state was showed different distributions. Cs, CsI, and Te classes show considerable mass as vapor state on the inlet side. However, CsM class shows small-scale mass as vapor state (0.035 kg) and significant mass as aerosol 2 state (17.837 kg). On the outlet side, mass of vapor state was reduced in all RN classes. However, Cs, CsI, and Te classes show increased mass than inlet side in the aerosol state 1 and 2. In the D-tank, there is no RN generation. Thus, it is expected that the injected vapor state turned into aerosol state during pool scrubbing process, and partially captured in the pool. For CsM class, outlet aerosol states are decreased in state 2, 3 and 4. Vapor state and aerosol 1 state show increased mass by 0.005 kg and 0.407 kg each in outlet side than inlet side. It is evaluated that the aerosol state 2, 3, and 4 were decreased by total 24.749 kg by pool scrubbing. However, additional study is needed for the reason of increased mass in vapor state and aerosol state 1.

To figure out total decontamination effect, a decontamination factor (DF) was calculated by Eq. (1)

$$DF = \frac{Total\ FP\ released\ to\ the\ D - tank}{Released\ FP\ to\ the\ containment} \qquad (1)$$

Table 3 shows total injected and released mass of D-tank and calculated DF of each RN class. CsM class show the highest DF value 5.708 and 2.125 for Te class, 2.021 for CsI, and 1.620 for Cs. The high DF of CsM could be attributed to the fact that the 99% of inlet RN mass is aerosol state. Whereas, in CsI, Cs, and Te classes, it is analyzed that significant mass of vapor state affects relatively low DF of RN class.

Table 3: Total inlet outlet mass [kg] and DF of Cs, Te, CsI and CsM class

	Cs	Te	CsI	CsM
Total in	5.870	8.349	11.057	29.658
Total out	3.624	3.928	5.472	5.196
DF	1.620	2.125	2.021	5.708

4. Conclusion

In this study, a new mitigation system, D-tank was evaluated by using MELCOR 2.2 code. The transferred RN mass was analyzed by using output for MACCS and DF was calculated with integrated injected and released mass. The major results are summarized as follows.

- The D-tank utilizing the pool scrubbing shows decontamination effectiveness. The D-tank could isolate the RNs inside the pool until RPV failure.
- In terms of the RN mass state, CsM class shows 99% of aerosol state on the inlet side. However, Cs, CsI, and Te classes show high fraction of vapor state.
- On the outlet side of the D-tank, the vapor state of Cs, CsI, and Te classes decreased more than inlet side and they were transferred into aerosol state by pool scrubbing effect. The calculated DF by using integrated mass are 5.708, 2.125, 2.021, and 1.620 for CsM, Te, CsI, and Cs, respectively. The high DF of CsM could be possible because the injected mass of vapor state is almost 0 and most of injected mass is in aerosol state.

ACKNOWLEDGMENTS

This research was supported by the National Research Foundation of Korea (NRF) and funded by the ministry of Science, ICT, and Future Planning, Republic of Korea (grant numbers NRF-2021M2D2A2076382)and the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (Ministry of Trade, Industry and Energy) (No.KETEP-20181510102400).

REFERENCES

[1] Wonjun Choi, Hwan-Yeol Kim, Rae-Joon Park, Sung Joong Kim, "Effectiveness and adverse effects of in-vessel retention strategies under a postulated SGTR accident of an OPR1000," Journal of Nuclear Science and Technology, 54:3, 337-347, (2017).

[2] Byeonghee Lee and Kwang Soon Ha, "Aerosol Retention Test in Water-Filled Tank for Bypass Accident Mitigation System", Proceedings of the Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 19-20, (2022)

[3] Taeseok Kim, Wonjun Choi, Joongoo Jeon, Nam Kyung Kim, Hoichul Jung, Sung Joong Kim, "Investigation on Fission Products Release Mitigated by In-Containment Relief Valve Under SGTR Accident," Proceedings of the 2018 26th International Conference on Nuclear Engineering, Volume 7: Decontamination and Decommissioning, Radiation Protection, and Waste Management; Mitigation Strategies for Beyond Design Basis Events, London, England, July 22–26, (2018).

[4] SNL, "MELCOR Computer Code Manuals, Vol. 1: Primer and Users' Guide. Version 2.2," SAND2017-0455, Sandia National Laboratories, Albuquerque, NM (2017).

[5] Y. Liao, K. Vierow, "MELCOR Analysis of Steam Generator Tube Creep Rupture in Station Blackout Severe Accident," Nuclear Technology, 152:3, 302-313, (2005).