Analyses of Aerosol Retention under SGTR Accident Based on ARTIST Experimental Data

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1. Introduction

A Steam Generator Tube Rupture (SGTR) event occasionally occurs during Pressurized Water Reactor (PWR) operation. It is one of the most serious accident sequences in PWRs since this event can cause a stuck-open safety relief valve and may create an open path into the environment. If core damage is not prevented during this accident, a significant amount of fission products will be released into the environment.

The Korean regulatory authority has declared an amendment of the "Nuclear Safety Act" to strengthen the legal framework of the severe accident management strategies. In accordance with this amendment, Probabilistic Safety Assessment (PSA) results shall satisfy the risk target values such as frequency of Cs-137 release of more than 100 TBq. Therefore, it is important to analyze the amount of fission product release in an optimal method.

In general, the applicant in Korea has used Modular Accident Analysis Program (MAAP) [1] for the analysis. However, this analysis code conservatively estimates the amount of fission product release during the SGTR accident. Thus, this study suggests a best-estimated methodology to evaluate fission product release based on the results of the international AeRosol Trapping In STeam generator (ARTIST) research program [2]. The objective of this research program was to investigate the aerosol retention in the SG during the SGTR.

2. Background and Modeling

2.1 Description of the MAAP5

The MAAP5 is a useful tool for analyzing the consequences of a wide range of postulated plant transients and severe accidents. Thermal hydraulic behavior of the Reactor Coolant System (RCS) and the SG regions can be reasonably well analyzed by using the MAAP5. However, this code does not take a credit for aerosol retention with the tube bundle effects in SGTR sequence due to the absence of empirical data and the complexity of the SG geometries. Thus, the MAAP5 assumes that the aerosol Decontamination Factor (DF) for steam generator tube rupture releases is 1.0 under the SG dry conditions. It means that there is no aerosol retention in the break vicinity of the SG secondary side. When the SG is under wet conditions, the code calculates the DF based on lookup table generated from SUPRA [3] results. Since this lookup table provides the DF in bare pool, the effect of the flooded bundle does not take into account. Therefore, the MAAP5 may overestimate the amount of the fission product releases into the environment. Thus, the results of the ARTIST tests have been used for optimal analysis by the MAAP5. In this study, version 5.03 of the MAAP was used.

2.2 Application of the ARTIST Data

The Paul Scherrer Institute (PSI) has led the ARTIST project between 2003 and 2011, which aimed to thoroughly investigate various aspects of aerosol removal in the secondary side of a breached SG [2]. The ARTIST project consisted of eight distinct phases. Among the phases, Phase II, Phase VII and Phase V were focused in this study. Each phase is summarized as follows.

Phase II: The aerosol retention in the break vicinity under dry conditions. The ARTIST Phase II shows that the DF is 2 with an Aerodynamic Mass Median Diameter (AMMD) of 0.7 μm (SiO_2 particles).

Phase VII: The aerosol retention in the whole model SG under dry conditions. The Phase VII shows the following results: (1) the DF is 5.2 with an AMMD of 1.4 μm (SiO_2 particles); (2) the DF is 19 with an AMMD of 3.7 μm (SiO_2 particles).

Phase V: The aerosol retention in the bundle section under flooded SG secondary side conditions when the break location is submerged in the water. The Phase V shows the results described in Table 1.

Table 1. The DF for the ARTIST Phase V tests in the flooded bundle [4, 5].

Particles	Gas flow rate	Sub-mergence [m]	DF average
1.15 μm TiO_2	Low	3.6	2,100
0.35 μm TiO_2	High	3.0	335
1.4 μm SiO_2	Low	0.3	53
3.7 μm SiO_2	Low	0.3	1,370
1.4 μm SiO_2	High	0.3	1,210
3.7 μm SiO_2	High	0.3	2,780

Based on the results of the Phase II and the Phase VII, an empirical correlation for the aerosol decontamination was derived for the dry SG conditions as illustrated in

Fig. 1. For the plant applications, the only parameter of this correlation is the aerosol particle AMMD, d_p (μm).

$$DF_{dry} = -21.52 + 20.72 \cdot \exp(0.1813 \cdot d_p) \quad (1)$$

This equation is validated in the range of the AMMD of 0.7 ~ 3.7 μm. Since the gas flow rate of the Phase V test is approximately 360 kg/h (0.1 kg/s) and this value is sufficiently small when it is compared with the real situation with an open area corresponding to the inner cross-section area of one tube, Eq. (1) is conservative enough.

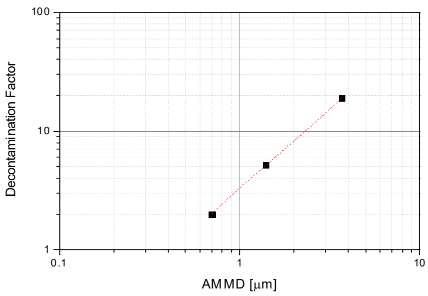

Fig. 1. The ARTIST DF under dry conditions as a function of the AMMD.

In case of flooded bundle of tubes conditions, an empirical correlation [5] was suggested by research group in PSI as follow based on the results of the ARTIST Phase V.

$$DF_{wet} = (1237 \cdot \ln((0.00094 \cdot m_g)^{1/2}) + 1947) \cdot \exp(0.385 \cdot (L - 0.3)) \quad (2)$$

The aerosol DFs can be calculated only with two parameters, which are the mass flow rate of gases, m_g (kg/h), and the submergence of the break, L (m), by the above correlation. When Eq. (2) was derived by the research group in PSI, it was assumed that the representative aerosol particle size is an AMMD of 1.4 μm. Since it is assumed to be the represent size of the aerosol particle for severe accidents and the mass fraction of particles that is larger than an AMMD of 1.4 μm, which is approximately 80% of the total amount according to the MAAP5 calculation, this assumption is reasonable and conservative. Meanwhile, Eq. (2) is validated in the range of the mass flow rate of approximately 50 ~ 660 kg/h.

By using Eq. (1) and Eq. (2), it was possible to obtain reasonable estimates of the aerosol decontamination in dry and wet SG conditions.

2.3 The MAAP5 Modeling

The MAAP5 input model for the Advanced Power Reactor 1400 MWe (APR1400) has been used in this study. And, simulations have been performed for an unmitigated sequence and a mitigated sequence to refill the faulted SG secondary after the core damage to investigate the aerosol retention under the dry and wet SG conditions. The major assumptions to simulate the SGTR accident are follows.

(1) The break size of the SG tube was assumed as an open area corresponding to the inner cross-section area of one tube. This assumption is consistence with the ARTIST test and the tube inside diameter of the ARTIST mock-up, 16.87 mm, is almost the same as APR1400.

(2) It was assumed that the break occurs at 0.25 m above the tube sheet as with the ARTIST test.

(3) It was assumed that the stuck-open of one Main Steam Safety Valve (MSSV) in the faulted SG and the break happen simultaneously.

(4) It was assumed that the main feedwater was tripped off when the reactor was tripped.

(5) Failure of all safety system such as Safety Injection System (SIS) and Auxiliary Feed Water System (AFWS) was assumed.

(6) In case of the mitigated sequence, it was assumed that the SG secondary would be refilled at 30 minutes after the core exit temperature exceeds 1,200 ^{o}F.

(7) The injection flow rate by a mobile pump was assumed as 250 gpm which is a lower performance compared with the auxiliary feedwater pump.

Based on above assumptions, the SGTR accidents were simulated by using the MAAP5.

3. Analyses Results

3.1 General Description of Accident

Table 2 summarizes the timing of the key events in the SGTR without mitigation strategies. As assumed in Section 2.3, the accident would be initiated with a rupture of one SG tube and stuck-open of one MSSV. After 1,236 seconds, the reactor successfully trips due to low pressure of the pressurizer. However, all safety system and operator actions were not successful for cooling the RCS to permit operation of the Shutdown Cooling System (SCS) and isolating the faulted SG.

After the reactor trip, the RCS pressure was decreased to about 8 MPa, which was similar to the pressure of the intact SG as shown in Fig. 2. In case of the faulted SG, the pressure decreased rapidly after reactor trip due to the stuck-open of a MSSV. Figure 3 shows the mass flow rate through the SG tube break. Before about 7,000 seconds, it was estimated that the most liquid fluid was released through the break, and then the gaseous fluid was released. The mass flow rate of the gases was about 10,000 kg/h, which was larger than the amount of the ARTIST test conditions.

The fluids in the RCS and the faulted SG were continuously released into the environment through the open MSSV, so that the core was uncovered at 7,818 seconds after the accident happens and the core exit temperature exceeded 1,200 ^{o}F at 8,712 seconds. In case of the unmitigated sequence, the reactor vessel was failed at 15,395 seconds. On the other hand, in the mitigated sequence, water was injected into the faulted SG at 10,512 seconds, and the water level of the faulted SG was restored as shown in Fig. 4.

Table 2. The timing of key events for the unmitigated sequence

Event description	Time [s]
SGTR	0
MSSV stuck-open	0
Reactor trip	1,236
Faulted SG dry	2,426
Intact SG dry	4,916
Core uncovery	7,818
Core exit temperature > 1,200 °F	8,712
First fission product gap release	8,866
Relocation of core materials	14,974
Reactor vessel failure	15,395

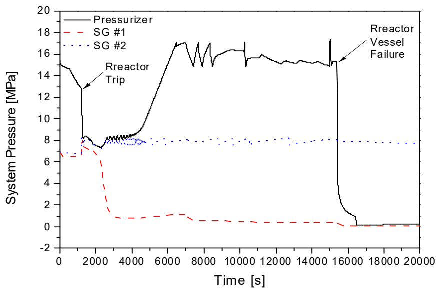

Fig. 2. The RCS and the SG pressure in the unmitigated sequence.

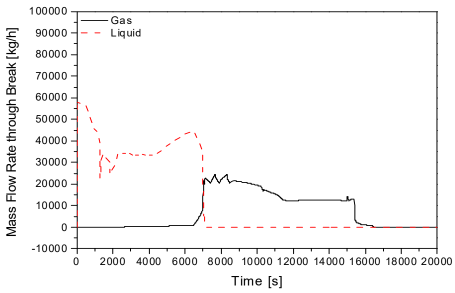

Fig. 3. The mass flow rate through the SG tube break in the unmitigated sequence.

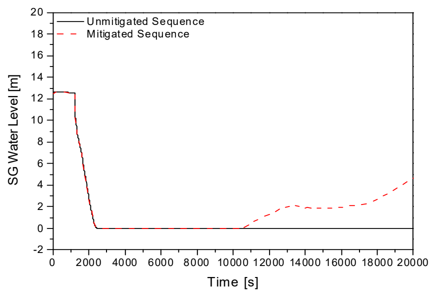

Fig. 4. The water level of the faulted SG.

3.2 Aerosol Retention under Dry SG Condition

The MAAP5 does not consider the aerosol retention for the SGTR releases when the SG is in a dry condition. Thus, the DF calculated by the code was always 1.0 for the unmitigated sequence. When the DF was 1.0, the mass fraction of the Cesium released to the environment was 4.2% as shown in Fig. 5.

To evaluate the effect of the aerosol retention in the SG secondary side using the ARTIST results, the DF was calculated based on Eq. (1). Figure 6 shows the particle size distribution (at 10,000 seconds) calculated by the MAAP5. The average density of the aerosol including the Cesium was assumed as 4.5 g/cm^3 to obtain the AMMD. When calculating the average DF of various particle size bins, it was conservatively assumed that the mass fraction of the particles smaller than 0.7 μm is zero and the DF of the particles larger than 3.7 μm is 19 which was the maximum value in the ARTIST Phase VII test. And, the DF with the AMMD between 0.7 μm and 3.7μm were calculated from the mass fraction of each bin and Eq. (1). The calculated average DF is shown in Fig. 7. The mass fraction of the Cesium released to the environment was reduced to 0.43% when the ARTIST results were reflected, as illustrated in Fig. 5.

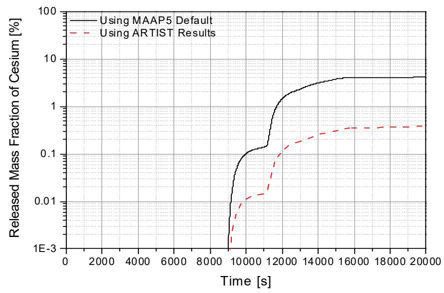

Fig. 5. The released mass fraction of Cesium in the unmitigated sequence.

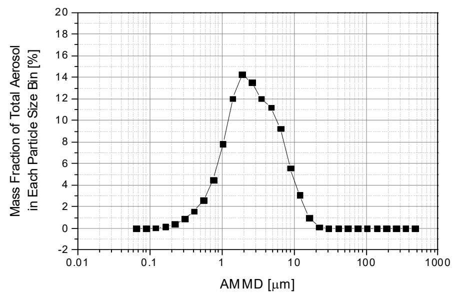

Fig. 6. The particle size distribution calculated by the MAAP5 at 10,000 seconds

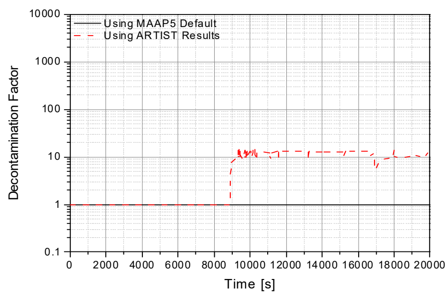

Fig. 7. The calculated DF in the unmitigated sequence

3.3 Aerosol Retention under Flooded SG Condition

The MAAP5 calculates the DF for the SGTR releases into the flooded SG secondary side based on the bare pool condition. Since the effect of the flooded bundle is not considered, this code may underestimate the DF under the flooded SG condition. The calculated DF by the MAAP5 is shown in Fig. 8. Before the SG water level rises above the break position, the DF is 1.0. And, the DF increases as the steam generator level increases as shown in Fig. 4. The mass fraction of the Cesium released to the environment was 0.77% as shown in Fig. 9.

To evaluate the effect of the aerosol retention under the flooded SG using the ARTIST results, the DF was calculated based on Eq. (2). Since the ARTIST Phase V test were performed with submergence of 0.3 m above the tube break, the DF, which was calculated by Eq. (2), was applied to the case when the SG water level rise 0.3 m above the break position. And, considering that the test was carried out within the mass flow rate range of approximately 50 ~ 660 kg/h, the mass flow rate applied to Eq. (2) was limited to 600 kg/h. And, the DF calculated according to Eq. (1) was applied before the SG is flooded. The calculated DF is shown in Fig. 8. By reflecting the ARTIST results, the mass fraction of the Cesium released to the environment was reduced to 0.017% as shown in Fig. 9.

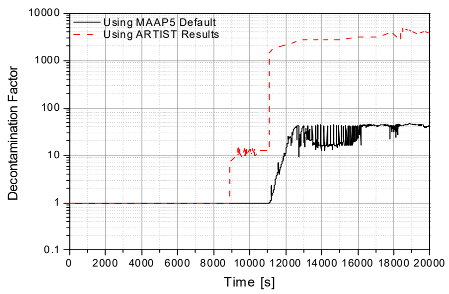

Fig. 8. The calculated DF in the mitigated sequence

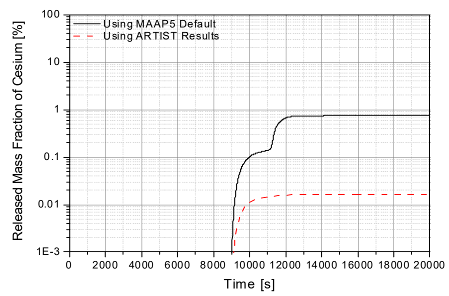

Fig. 9. The released mass fraction of Cesium in the mitigated sequence.

4. Conclusions

Analyses using the MAAP5 were performed for the SGTR with the stuck-open of the MSSV. The main purpose was to examine the influence of the aerosol DF obtained from the ARTIST tests in reducing the release of radioactive materials to environment. The analyses indicated that the aerosol retention in the SG secondary side is likely much higher than the predictions using model currently implemented. In particular, if the mitigation strategy to inject water into the faulted SG was implemented at an appropriate timing, it was shown that the release of the Cesium could be significantly reduced. Assuming that the initial core inventory of Cs-137 was 500,000 TBq, the analysis for the mitigated sequence was estimated to release thousands of TBq of Cs-137 if the ARTIST results were not reflected. However, the release of Cs-137 was not exceeded 100 TBq in the analysis after reflecting the ARTIST results.

The phenomenon regarding the aerosol retention in the SG secondary side has various uncertainties. And, in applying the ARTIST results to the analyses, the test results until now were insufficient. If the tests are carried out under more various conditions such as the working fluid, the mass flow rate, the particle size, and etc., it would be possible to obtain a deeper insight and analyze the aerosol retention more accurately.

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