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A Study on Fission Product Behavior during a Severe Accident at APR1400 Nuclear Power Plants

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1. Introduction

As a part of a research project, KINS planned to investigate the fission product behavior during a severe accident at APR1400. As shown in the results from our previous study [1], we applied a criterion of risk, which consists of the probability and consequence of the accidents of interest, to selection of the representing sequences for the APR1400. Therefore, Probabilistic Safety Assessment (PSA) for Shin-Kori 3·4 nuclear power plants [2], which are APR1400 type reactors, were reviewed. After all, the representing scenarios were determined to be the sequences with station blackout (SBO), interfacing system LOCA (ISLOCA), and steam generator tube rupture (SGTR), which are similar to those of the U.S.NRC's State-of-the-Art Reactor Consequence Analyses (SOARCA) study [3-5]. Among those sequences, SBO occupies the largest portion of the risk from severe accidents, and was selected to be analyzed at first about the fission product behavior in the containment. It includes events such as failure of the alternative AC power generator following a blackout event, successful operation of turbine-driven auxiliary feed water (AFW) pump, late recovery of off-site power before containment failure, in-vessel injection and successful actuation of cavity flooding system and spray system, and failure of hydrogen mitigation system [1].

In this study, calculations have been carried out for a SBO sequence similar to the selected scenario, but a faster one with simple assumptions. Instead, a sensitivity study was carried out to take into account the effects of such differences on the fission product behavior. We use MELCOR 1.8.6 [6] with the 35- and 2-cell compartment models of the containment. Since MELCOR does not treat organic iodide, we tried to make the results up by MELCOR-RAIM [7] which is the MELCOR code coupled with RAIM, a stand-alone code developed for evaluation of the iodine behavior.

2. Analysis Methods

The scenario chosen to be analyzed is a SBO sequence with assumptions such that the AFW pump is unavailable from the beginning of the accident, and electricity is not recovered; therefore, in-vessel injection and the spray system do not work for this sequence. However, the three-way valve for protection of the IRWST from hydrogen explosion and the cavity flooding system (CFS) were assumed to be operable, relying on the battery power. The effects of AFW pump operation, in-vessel injection, CFS actuation, the number of compartments in the containment, and iodine chemistry models on the fission product (FP) release were analyzed as a sensitivity analysis. The reactor coolant system (RCS) was modeled as shown in Fig. 1, and the 35-cell containment model is shown in Fig. 2.

MELCOR v1.8.6 with the 35-cell model was mainly used, but for some cases its pool chemistry model (PCM) was activated with the 2-cell model. Some of these calculations were compared with those with MELCOR-RAIM which also used the 2-cell model.

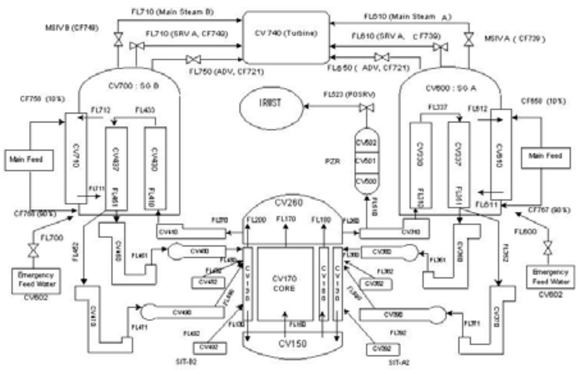


Fig. 1. Nodalization for the reactor coolant system.

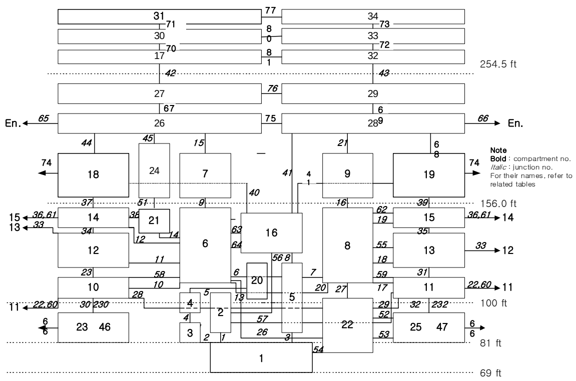


Fig. 2. Nodalization for the containment system with 35 compartments.

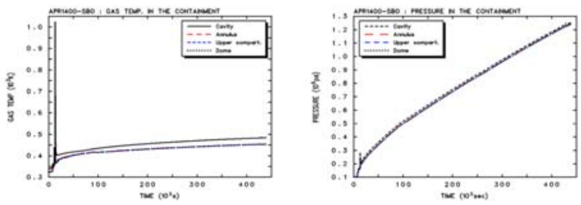
3. Analysis Results

3.1 Fission product behavior for the base case

Table I shows the timing of key events. Figs. 3 (a) shows that temperature in the containment atmosphere rises rapidly at the time of the reactor vessel failure. The containment pressure increases continuously after a peak at that time and may threaten the integrity of the containment at about 5 days after the initiation of the accident (Fig. 3 (b)). The following figures, Figs. 4-5, show that volatile elements, such as noble gas, cesium, and iodine in the form of CsI, release up to approximately 90% by the time of the reactor vessel failure, while a large part of Te releases are from the reactor cavity after that time.

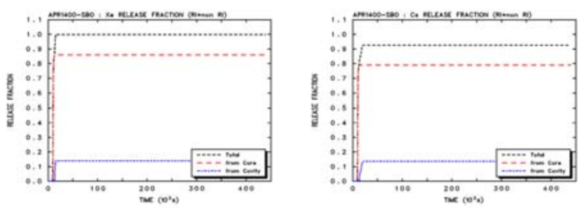
Table I: Timing of Key Events

Event	Time (s)
Rx/ MFW/ RCP Trip	0.0
SG Dryout	3,700
SRV Open	5,552
Core Uncovered	7,548
CET > 922 K (SAMG initiation)	8,635
Gap Release	8,849
Start Fuel Melt	9,220
Core Dryout	9,671
Actuate CFS @ 30 min. after SAMG initiation	10,435
Fuel Relocation	12,813
RPV Penetration Fail	12,913
MCCI Start	12,913
SIT Injection Start	13,131
SIT Exhausted	13,456
Calculation Terminated	440,000



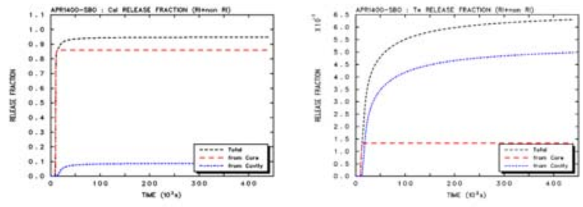
(a) (b)

Fig. 3. Containment temperature (a) and pressure (b).



(a) (b)

Fig. 4. Release fraction of the core inventory: Xenon (a), Cesium (b).



(a) (b)

Fig. 5. Release fraction of the core inventory: CsI (a), Te (b).

3.2 Effects of containment modeling and accident management measures

The effect of the number of compartments and different MELCOR versions such as MELCOR-RAIM is shown in Fig. 6 (a) and (b). The containment pressure and volatile FP release were not much different from each other.

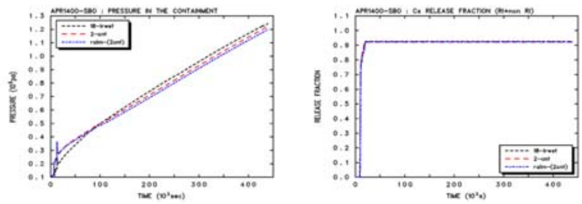


Fig. 6. Effect of the number of compartments and different codes on the containment pressure (a) and fission product (Cs) behavior in the containment (b).

The effect of the AFW pump operation is shown in Fig. 7 (a) and (b). By this measure the accident sequence can be delayed by about 14 hours. Nevertheless, the thermal hydraulic- and the FP behavior are very similar to the case without AFW system when they are compared with Fig. 3(a) and Fig. 4(b).

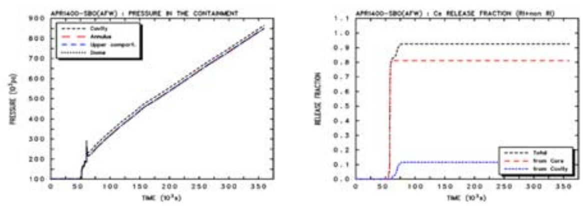


Fig. 7. Effect of the AFW pump operation on the containment pressure (a) and fission product (Cs) behavior in the containment (b).

The effect of external injection of emergency cooling water on the thermal hydraulic- and the FP behavior is shown in Figs. 8-9. They show that while the containment pressure can be greatly reduced, there could be immersion of instrumentation due to flooding. Furthermore, perhaps due to high fuel temperature, slightly more amounts of FPs could release.

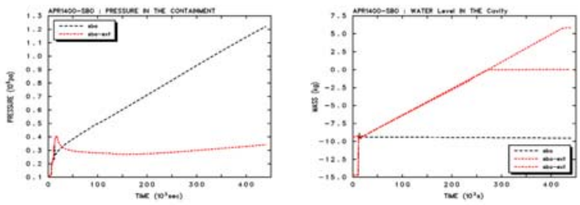


Fig. 8. Effect of the external injection of emergency cooling water on the containment pressure (a) and the cavity water level (b).

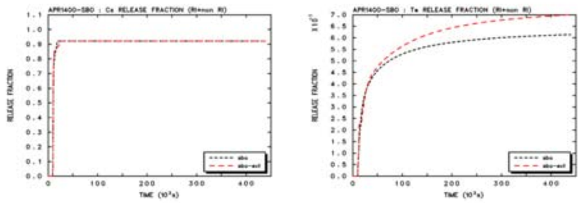


Fig. 9. Effect of the external injection of emergency cooling water on the fission product behavior in the containment: Cs (a), Te (b).

Fig. 10 shows that without the cavity flooding system (CFS), the release of Cs and CsI, which are water-soluble, greatly increases when the coolant in the cavity dries out. After release into the containment atmosphere, the concentrations of FPs slowly decrease by deposition.

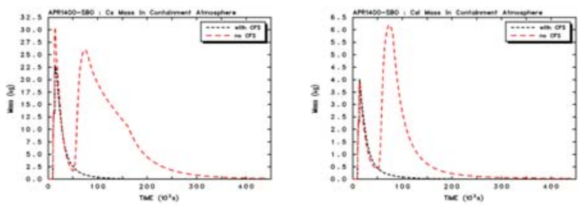
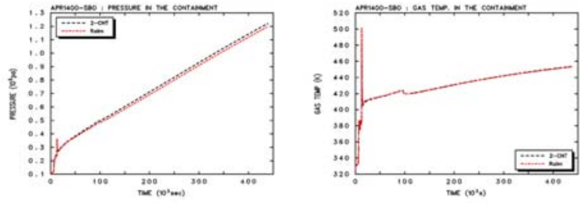


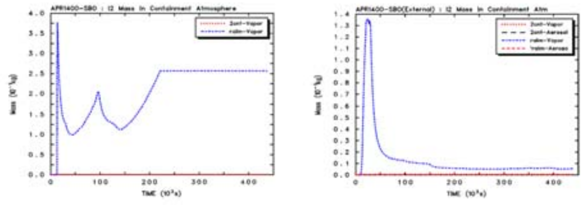
Fig. 10. Effect of the cavity flooding system operation on the fission product behavior in the containment: Cs (a), CsI (b).

MELCOR-RAIM and MELCOR with PCM estimates the similar thermal-hydraulic behavior, but much larger amounts of molecular and organic iodine in the containment, as shown in Figs. 11-12 with comparison to Figs. 3-4. When the temperature of the reactor cavity water increases up to 425 K, the RAIM model stops running. For the case with external injection of cooling water, RAIM estimates a decrease in the amount of I_2 and a continuous increase in the CH_3I production, as shown in Fig. 12.

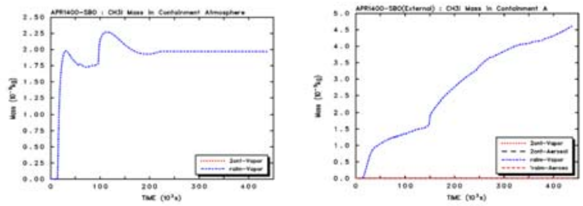


(a) (b)

Fig. 11. Effect of activation of the iodine chemistry models on the containment pressure (a) and temperature (b).



(a) (b)



(c) (d)

Fig. 12. Effect of activation of the iodine chemistry models on the fission product behavior in the containment: I_2 mass (a), I_2 mass with external injection of cooling water (b), CH_3I mass (c), CH_3I mass with external injection of cooling water (d).

4. Conclusions

In order to investigate the fission product behavior during a severe accident at APR1400, we have selected the representing scenarios with SBO, ISLOCA and SGTR. Among them, a SBO sequence similar to the selected scenario, but a faster one with simple assumptions, was analyzed using MELCOR v1.8.6 with 35-cell models of the containment. In addition, a sensitivity study was carried out to take into account the effects of different containment models and iodine chemistry models, and implementation of several accident management measures on the fission product behavior. For the sensitivity analysis, we use the 2-cell containment model and the codes with the iodine chemistry model such as MELCOR with PCM and MELCOR-RAIM. With regard to the accident management measures, we considered auxiliary feedwater supply, external cooling water injection, and reactor cavity flooding.

The results of the analysis show that volatile elements such as noble gases, cesium, and iodine release into the containment mostly at the time of the reactor vessel failure, while a large amount of tellurium release occurred from the reactor cavity after that time. The concentrations of FPs in the containment, excluding noble gases, slowly decrease by deposition. The sensitivity study shows the following results;

- The number of compartments do not make much different thermal hydraulic- and FP release behavior in the containment.
- The AFW pump operation delays the accident proceeding by about 14 hours; nevertheless, the thermal hydraulic- and the FP behavior are similar to the case without AFW system.
- External injection of cooling water may reduce the containment pressure greatly, but it could cause immersion of instrumentation and release of slightly more amounts of FPs.
- Without the cavity flooding system (CFS), the release of Cs and CsI increases greatly when the water in the cavity dries out.
- Iodine chemistry models estimate much larger amounts of molecular and organic iodine in the containment.

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