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Evaluation of the Primary System as a Fission Product Barrier During a Depressurized Conduction Cooldown Accident in a VHTR

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1. Introduction

The mechanical source term (MST) mounts a significant challenge in the development of advanced non-light water reactors (non-LWRs), such as very high temperature reactors (VHTRs) [1]. Addressing this challenge requires physics-based models and simulations that capture fission product transport and off-site dose exposure under licensing basis events.

To support MST analyses, the Korea Atomic Energy Research Institute (KAERI) is developing a new computational code named MENTAS [2].

In a previous study [3], MENTAS was applied to a depressurized conduction cooldown (DCC) accident scenario in a 350 MWth VHTR. However, that study used conservative assumptions - namely, that fission products released from the fuel are immediately released into the reactor building, completely neglecting the role of the primary system as a retention barrier. In terms of the fission product barrier, the primary system (often called the primary circuit or primary loop) indicates the helium pressure boundary.

This study aims to provide a more realistic analysis by incorporating the primary system into the MENTAS simulation. The effects on fission product release and off-site dose exposure are quantitatively assessed.

2. Thermo-Fluid Phenomena During DCC

2.1 VHTR System and Existing GAMMA+ Results

The same VHTR configuration, GAMMA+ safety analysis results, and major assumptions used in reference [3] are retained in this study. A conceptual layout of the core is presented in Fig. 1.

The DCC accident considered here is initiated by a medium-size pipe break. The detailed accident scenario and GAMMA+ results are described in [4]. For this study, the GAMMA+ simulation was repeated solely for post-processing purposes.

Figure 2 shows the helium discharge flow predicted by GAMMA+. Initially, the flow is rapid and then quickly diminishes as pressures in the primary system and reactor building equalize. After pressure equalization, the remaining driving force is core heat-up with the primary coolant gas expansion and cooldown with the gas contraction. It should be noted that contribution of fission product release by diffusion within fluid would be much smaller during bulk gas expansion.

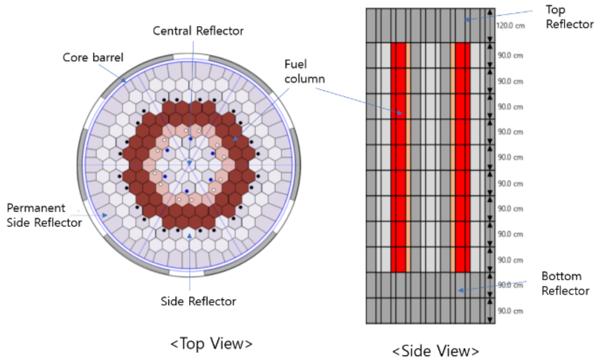

Fig. 1. Core layout of the VHTR [4].

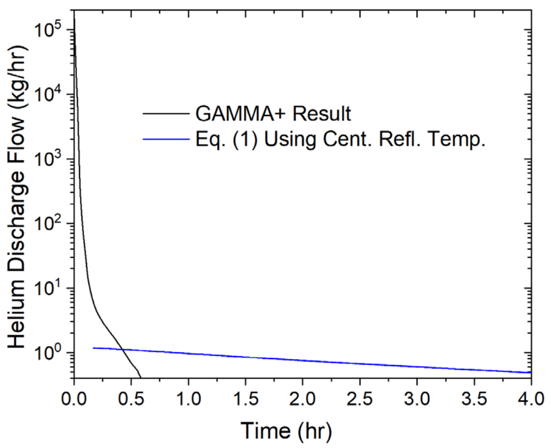

Fig. 2. Primary system discharge flow into the reactor building after the pipe break accident.

Figure 3 shows that the core temperature gradually peaks around 30 - 40 hours after the accident. During the blowdown phase (which ends before 600 seconds), fuel-based fission product release is minimal; most of the source term arises from circulating coolant activity and lift-off from plateout surfaces. Since fuel temperature directly influences release, significant fission product release is expected after blowdown. Thus, gas expansion leakage flow becomes the key mechanism for release.

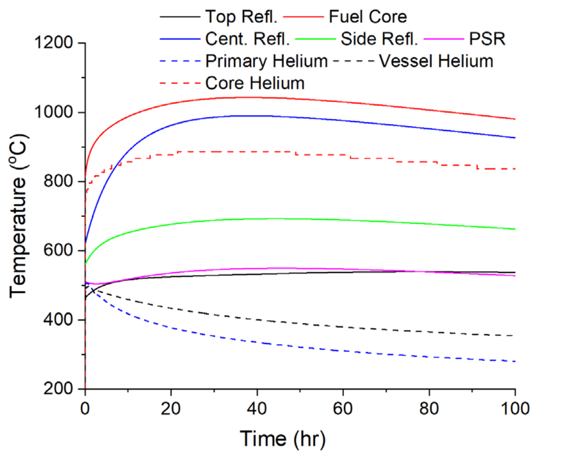

Fig. 3. Calculated temperature behavior after the pipe break accident.

2.2 Leakage Flow Due to Helium Expansion

Following pressure equalization, only thermal expansion of the primary helium coolant enables radionuclide transport to the reactor building. The mass flow rate due to thermal expansion, ($\dot{m}$), is given by:

$$\dot{m} = \frac{PV}{RT^2}\frac{dT}{dt} \qquad (1)$$

Where P = pressure, V = volume, R = helium gas constant, T = temperature, t = time. Unlike the core region, coolants in the primary system and reactor vessel cool down more rapidly (see Fig. 3). Figure 4 illustrates helium expansion flow rates calculated using various temperatures shown in Fig. 3. The figure shows that the most conservative estimate is based on the central reflector temperature. Therefore, the expansion flow rate using the central reflector temperature (=blue curve in Fig. 4) is used as the reference boundary condition in subsequent MENTAS calculation. In order to compare with the GAMMA+ result, the same curve is plotted in Fig. 2 with a logarithmic scale.

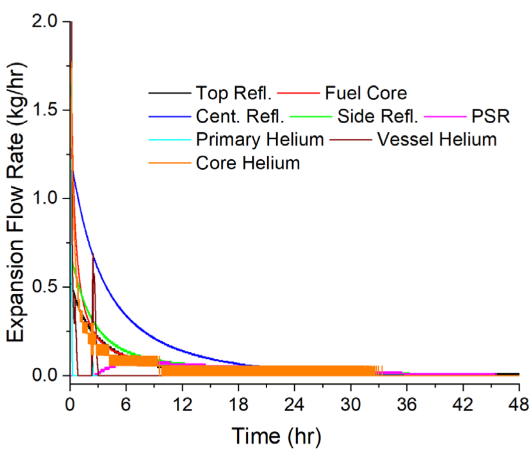

Fig. 4. Helium expansion flow rate using Eq. (1) and various temperatures.

3. MENTAS Results

A leak rate equivalent to 100% volume per day is applied at the reactor building. Nuclide decay is considered only within the primary system and reactor building; decay in the environment is neglected for conservatism.

Figure 5 shows the result of the MENTAS calculation for the fission product release rate from the core. The figure is not changed from [3] as core release is independent of primary system modeling.

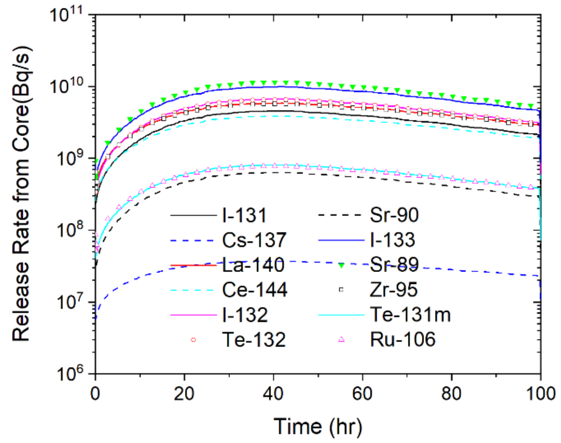

Fig. 5. Fission product release rate from core under DCC accident of VHTR.

Figures 6 and 7 present I-131 and Cs-137 activities, respectively, within the primary system, reactor building, and environment. Only a small fraction of radionuclides escapes the primary system. Initially, reactor building activity increases but peaks around 20 hours, then declines as helium expansion flow diminishes (see Fig. 4). It means that after the peaks, entering nuclides are less than exiting nuclides at the reactor building. Environmental accumulation, however, continues due to the absence of removal mechanisms. After all, the activities at the environment exceed the amounts at the reactor building after ~ 30 hours.

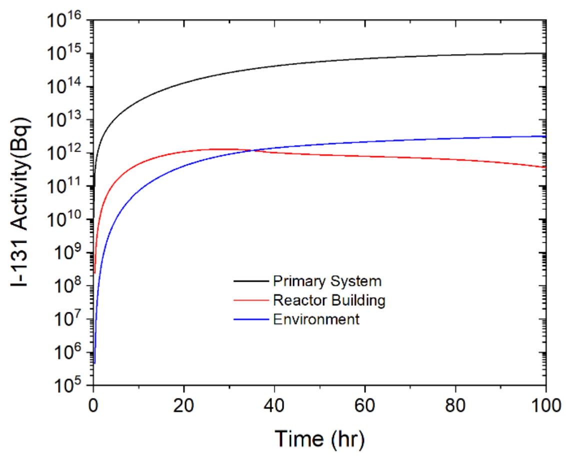

Fig. 6. I-131 release under DCC accident of VHTR.

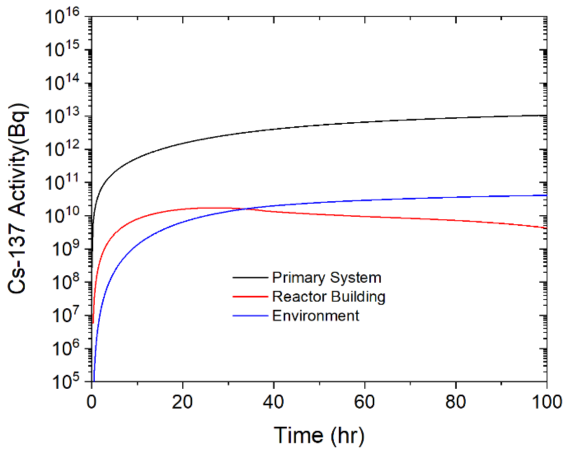

Fig. 7. Cs-137 release under DCC accident of VHTR.

Figures 8 and 9 illustrate the impact of the primary system on cumulative environmental release and the accumulated dose at the Exclusion Area Boundary (EAB). They show that the fission product release and the off-site dose exposure are significantly reduced by the primary system. The results clearly demonstrate the primary system's significant mitigating effect.

The helium expansion flow rate is one of the key parameters affecting the off-site dose. Additional calculations explored the sensitivity of off-site dose to helium expansion flow rate. Using the flow rate at 600 seconds as the “high flow rate,” Figure 10 shows that dose exposure increases with higher expansion flow, approaching results from the simulation without primary system (see Fig. 9).

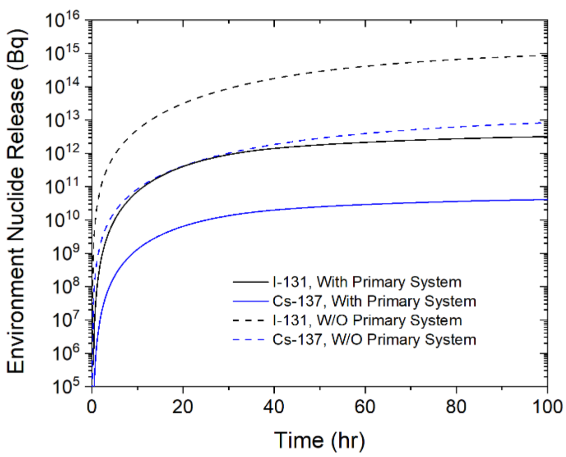

Fig. 8. Effect of primary system on cumulative nuclide release to environment under DCC accident of VHTR.

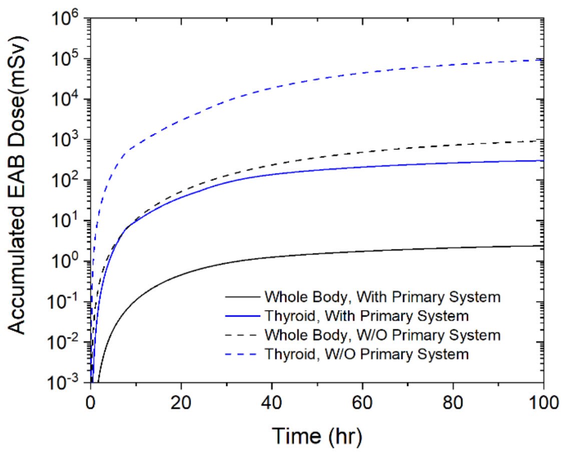

Fig. 9. Effect of primary system on accumulated EAB dose under DCC accident of VHTR.

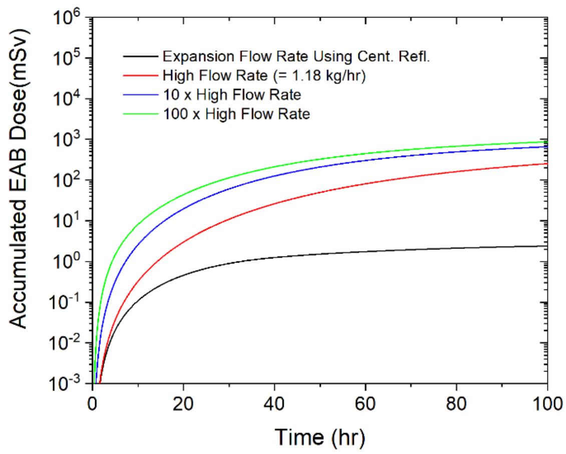

Fig. 10. Effect of helium expansion flow rate on accumulated EAB whole body dose.

4. Conclusions

This study evaluates the role of the primary system as a barrier against fission product release during a DCC accident in a VHTR. MENTAS simulation results indicate substantial reductions in environmental release and off-site dose when the primary system is considered.

This barrier is expected to play an even more critical role during a pressurized conduction cooldown (PCC) scenario. For realistic MST evaluations, inclusion of the primary system is essential.

Future works should add prompt source terms for off-site dose exposure. In addition, the authors emphasize the need for comprehensive verification and validation efforts for licensing applications of MST analyses.

Acknowledgements

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