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A Verification Methodology for Safety Evaluation of RCPB Leakage Detection Technology in i-SMR

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1. Introduction

The innovative small modular reactor (i-SMR) currently under development in Korea adopts a differentiated design concept from conventional large-scale nuclear power plants, featuring an integral reactor vessel that accommodates major primary system components, a fully passive safety system, and a boron-free core. These innovative characteristics make the i-SMR highly attractive in terms of installation flexibility, economic efficiency, and safety. However, such design features also create notable discrepancies when applying existing safety standards and evaluation methodologies that were established for large-scale reactors.

When a leak occurs in the reactor coolant pressure boundary (RCPB) of the i-SMR, identifying the leakage location is challenging due to the integral configuration. Moreover, because the containment vessel is maintained under vacuum conditions during normal operation, conventional leak detection methods commonly used in large reactors—such as sump monitoring—cannot be directly applied. Therefore, it is necessary to propose leak detection approaches that are suitable for the i-SMR operating environment. Furthermore, to validate the feasibility of the proposed detection approaches and to provide technical evidence for future regulatory licensing reviews, it is essential to establish a quantitative safety assessment methodology that reflects the unique thermal–hydraulic characteristics of the i-SMR.

Accordingly, this study aims to provide a quantitative Accordingly, this study aims to provide a quantitative analysis basis for evaluating the effectiveness of the leak detection system under vacuum containment conditions. Specifically, leakage scenarios of 1 gpm and 0.05 gpm are assumed at the lower region of the reactor vessel, and the corresponding leakage mass flow rates are evaluated using the MARS-KS system thermal-hydraulic code. The MARS-KS calculations show that the leakage mass flow rate remains nearly constant over a long duration (up to 100,000 s); therefore, the MARS-KS-derived values are imposed as constant inlet boundary conditions in the CFD simulations to preliminarily reproduce the internal containment response during coolant leakage, including steam transport behavior and pressure/temperature/humidity distributions. This coupled approach enables the virtual reproduction of sensor response signals under representative operating conditions and provides technical evidence to support verification of the sensitivity and reliability of the leak detection system. [1]

2. Numerical Methodology

2.1 Computational Domain

The present analysis aims to evaluate the overall steam transport behavior and concentration distribution inside the i-SMR steel containment by considering a flow diffusion domain that includes the entire containment volume and the outer surface of the reactor vessel. Therefore, complex internal structures within the reactor vessel, which have a negligible impact on the containment flow field, were omitted and the geometry was simplified. Since the target model is symmetric, simulations were performed on a half-domain (1/2 geometry).

Because the region of interest is not the near-field micro-scale flow immediately after the break, but rather the global diffusion behavior of steam throughout the containment, an equivalent effective discharge surface was assumed at a location where the complex phase-change and diffusion processes following the break are completed and the leakage can be treated as behaving as an ideal gas. Accordingly, a hemispherical inlet with a radius of 20 mm was specified on the outer wall of the lower region of the reactor vessel as the inlet boundary condition. The entire computational domain was meshed with approximately 1.87 million unstructured polyhedral elements.

2.2 Boundary Conditions

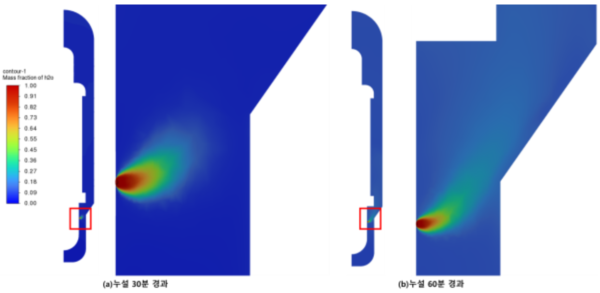
The CFD simulations were performed using ANSYS Fluent as three-dimensional transient analyses. The fluid inside the containment was modeled as a binary ideal-gas mixture of air and water vapor, and the species transport equations based on mass fractions were solved. Adiabatic (thermally insulated) wall boundary conditions were applied to all solid surfaces. For turbulence modeling, the URANS-based SST k–ω model was adopted, and the steam dispersion behavior was simulated for up to 1 h. At the start of the simulation, the containment was initialized as lowpressure dry air at 0.1 bar and 150°C. [2] At the inlet, leakage mass flow rates of 0.047 kg/s (1 gpm) and 0.00238 kg/s (0.05 gpm) were imposed.

3. Results

3.1 Analysis of Leaked Steam Dispersion Based on Mass Fraction

For both the 0.05 gpm and 1 gpm scenarios, the fundamental dispersion mechanism of the leaked steam was the same: because the leaked steam has a lower density than the air in the containment, it is driven by buoyancy and disperses upward, opposite to the direction of gravity. However, under the 0.05 gpm condition, the leakage amount was extremely small relative to the containment volume; thus, even after 1 h, the water-vapor mass fraction remained close to zero in most regions except in the vicinity of the leak source, as shown in Fig. 1.

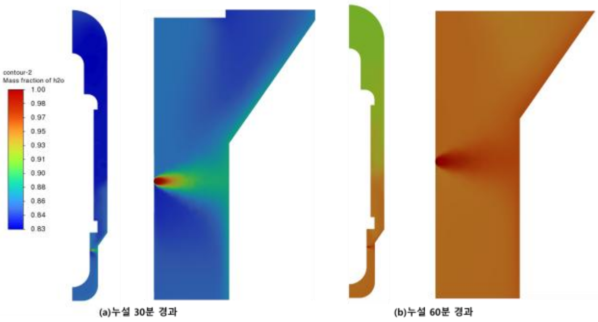
In contrast, under the 1 gpm condition—where the leakage amount was increased by a factor of 20—the leaked coolant mixed actively from the early stage, and a wide region in the upper part of the containment became filled with water vapor at mass fractions above 0.8, as shown in Fig. 2.



(a)누설 30분 경과

(b)누설 60분 경과

Fig. 1. H2O mass fraction for the 0.05gpm leak.



(a)누설 30분 경과

(b)누설 60분 경과

Fig. 2. H2O mass fraction for the 1gpm leak.

3.2 Leak Detection Assessment Based on Virtual Sensor Locations

As shown in Fig. 3, five virtual leak-detection sensors were placed at selected locations inside the containment, and the time histories of the water-vapor mass fraction were converted to ppmv (parts per million by volume) for analysis. Even under the 0.05 gpm micro-leak condition, the sensors located along the major circulation path (P2, P3, and P5) exhibited an approximately linear cumulative increase, capturing a meaningful concentration rise within 1 h (up to approximately 220,000 ppmv). In contrast, the sensors located in stagnant-flow regions—P4, which is positioned in an upper region but outside the main circulation path, and P1, which is located in a lower stagnant region—failed to detect the leak even under the 1 gpm condition, as shown in Fig. 4. These results suggest that sensor placement should not be determined solely by vertical elevation; rather, it is necessary to pre-identify the steam transport pathways through CFD-based analyses of flow and dispersion patterns.pulses that propagate through potential detector channels. This model is useful for optimizing the detector and the resolution for application to neutron monitoring in the Generation IV power reactors.

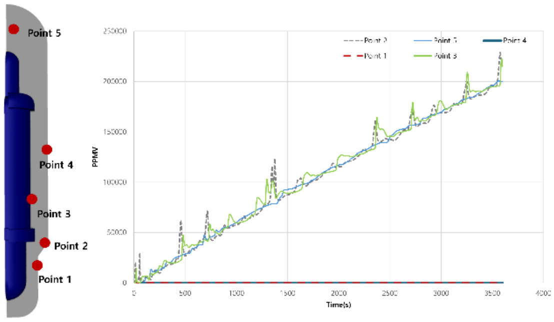


Fig. 3. Virtual sensor position and 0.05 gpm leak scenario PPMV time response

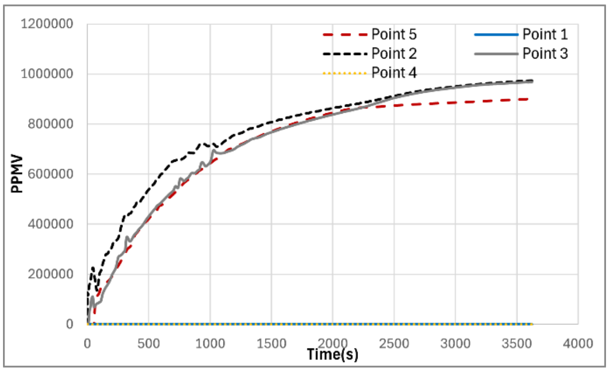


Fig. 4. 1gpm leak scenario PPMV time response

4. Conclusions

This preliminary analysis was conducted to establish the overall computational methodology. If potential failure locations can be identified through structural integrity assessments, the proposed approach is expected to be used to pre-evaluate leakage behavior at the predicted locations and to perform targeted simulations to demonstrate the detectability of leakage from those specific points.

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