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Analysis of Hydrogen Concentration Distribution during an SBO Accident for Shin-Ulchin APR1400

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1. Introduction

Hydrogen safety is very important for the integrity of nuclear power plant (NPP) containment during a core melt accident such as the Fukushima accident. Many efforts are still being devoted to enhancing the hydrogen safety in NPPs by mitigating an accumulation of the hydrogen in a confined region and removing the possibility of a hydrogen explosion.

During a core melt accident, a large amount of hydrogen can be generated in a nuclear reactor and released into the reactor containment. Most of the hydrogen is from an oxidation of Zirconium used in fuel cladding. It is inevitable for hydrogen to be generated and released into the containment. To prohibit the accumulation of hydrogen, the containment volume is considered to reduce the hydrogen concentration, or hydrogen mitigation devices such as PARs or igniters are installed in the containment. In the case of the Fukushima NPPs, the applied strategy for the hydrogen safety is the use of a containment venting system (CVS). In this way, the hydrogen accumulated in the containment vessel is vented into the environment. One of the causes of the hydrogen explosions occurring in the containment buildings of the Fukushima NPPs is expected to be the failure of the venting system. The hydrogen was therefore easily accumulated in the containment building. It is uncertain what the ignition source for the hydrogen combustion was during the accident. However, it is not too conservative to assume that an ignition source exists at any time and any place in a containment during a core-melt accident.

Shin-Ulchin 1 & 2, which are construction plants of an APR 1400, are two of the newest NPPs in Korea. They have many features to enhance the safety margin during a design-based and beyond-design-based accident. One of them is the in-containment refueling water storage tank (IRWST) located inside the containment. It is used as a sink/source for feed-bleed operation. When the core is damaged along an accident progression, the hydrogen generated in the RPV can be released into the IRWST of the APR1400 with steam and water. From a previous study [1], it was found that a highly concentrated hydrogen/air mixture can be developed if the hydrogen is released into the IRWST. In the case of Shin-Ulchin 1 & 2, the hydrogen mitigation strategy during a high-pressure accident such as a station blackout (SBO) is changed by installing a 3-way valve. When a severe accident management (SAM) for the plant is initiated, the flow path from a pressurizer to the IRWST is changed into a steam-generator (S/G) compartment by turning the 3-wat valve actively (pilot operated). By doing so, it is expected that the hydrogen is not accumulated in the IRWST and released into the S/G compartment, which is relatively less confined.

Based on a common knowledge, it is easily expected that a hydrogen concentration near the release location could be high, and there is a possibility of a hydrogen accumulation in the dome of the containment. This study is focused on the characteristics of the hydrogen behaviors when the strategy described above is used for hydrogen mitigation during an SBO accident in the NPP of Shin-Ulchin 1 & 2.

2. Methods and Results

2.1 Analysis method and Conditions for Simulation

To study the characteristics of the hydrogen behaviors during an SBO accident, the GASFLOW [2] code is used. GASLOW is a finite-volume computer code that solves time-dependent compressible Navier-Stokes equations with multiple gas species in a three-dimensional computational domain.

To model the containment of the APR1400, a single block grid with 66,960 mesh cells is generated. A k-e turbulence mode with a wall function is used to simulate turbulent jet mixing and wall heat transfer. In addition, a radiation model based on the P1 method is chosen to consider a radiative heat transfer from the released hot steam to the containment wall.

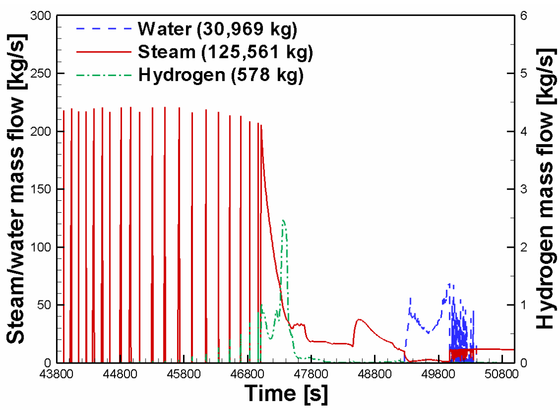

Fig. 1. Mass flow rates for hydrogen and steam-water released to S/G compartment under SAM

The hydrogen mass generated by fuel clad oxidation is dependent on the amount of Zirconium existing in the core. The mass ratio of Zirconium to hydrogen by a chemical reaction is 91:4. From the mass ratio, maximum hydrogen mass by Zirconium oxidation for the APR1400 core is 1203 kg. For this study, the hydrogen and steam/water mass rates released through the POSRV of APR1400 are obtained from the MAAP simulation. In the case of an SBO accident in Shin-Ulchin 1 & 2, the hydrogen is released in the S/G compartment by the 3-way valve under the SAM, which is initiated when the core exit temperature exceeds 650 ^{o}C. The mas flow rates for hydrogen and steam/water released in the S/G compartment are shown in Fig. 1.

The total mass of hydrogen released until 50,800s is 578 kg, which is half of the mass from full Zirconium oxidation. The mass of steam after the flow path change is 125 tons. In this study, a basic case with the mass release rates from the MAAP analysis is simulated. In addition, two test cases are proposed to check the safety margin. Case 1 considers a 3,000s delayed flow path change, which affects the mass of steam release into the S/G compartment. And in case 2, a dependency on the mass of the released hydrogen is considered by increasing 50% of the mass because the rate of Zirconium oxidation and hydrogen generation is dependent on the core degradation model.

2.2 Results

For the base case, the simulation results are shown in Fig. 2. The mixture cloud with a hydrogen concentration of more than 10 vol% is developed vertically in the S/G compartment at 47,400s. However, it is quickly collapsed after 50s by continuously released steam.

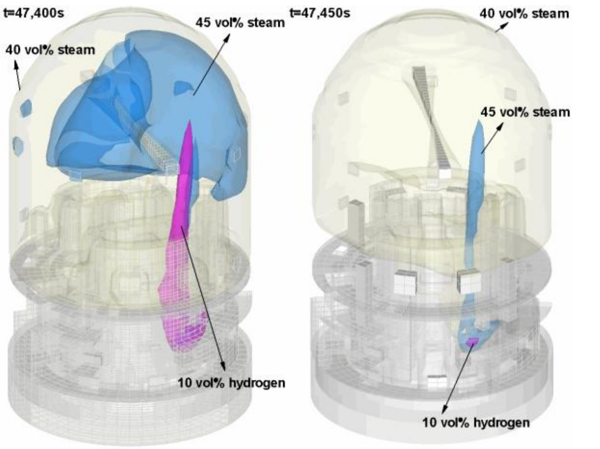

Fig. 2. Steam-hydrogen distributions for SBO accident: left, at 47,400s; right, at 47,450s

Fig. 3 shows the mass rates for case 1 where the flow path change is delayed 3,000s. It was found from the calculated results that a highly concentrated hydrogen cloud is not greatly affected by the reduced mass of the steam. To determine the flame acceleration characteristic of the hydrogen mixture, a sigma cloud is used, as shown in Fig. 4. In case 1, the possibility of flame acceleration is negligible. For case 2, it is seen that the sigma cloud is very enlarged by the increased hydrogen mass. However, because of the dense steam located above the operating deck in the containment, DDT is not likely to occur.

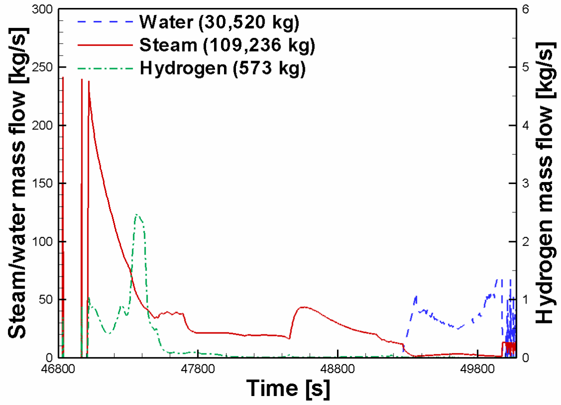

Fig. 3. Mass flow rates for hydrogen and steam-water released to S/G compartment for test case 1.

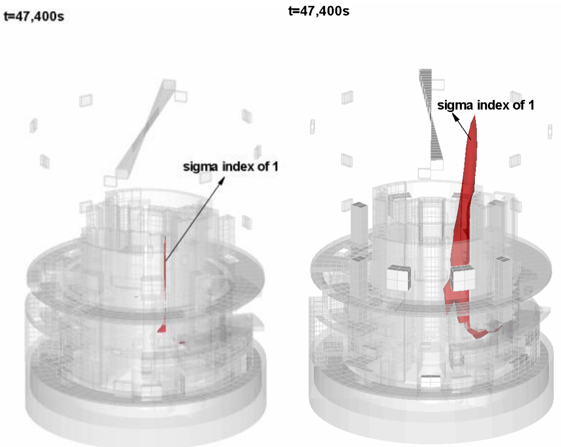

Fig. 4. Mixture cloud with sigma index larger than 1: left, case 1; right, case 2.

3. Summary

In this study, a hydrogen mitigation strategy implemented in the Shin-Ulchin 1 & 2 NPPs during an SBO accident was evaluated using a 3-D analysis code. It was found that a highly concentrated hydrogen mixture can be developed in the S/G compartment. However, it is quickly diluted by the continuous release of steam. DDT is not likely to occur because it contains a high volume fraction of steam.

REFERENCES

[1] J. Kim, et al., "Hydrogen Mitigation Strategy of the APR1400 NPP for a Hypothetical SBO accident," Nucl. Tech. vol.150, pp.263-282, 2005

[2] J. R. Travis, et al., GASFLOW: A Computational Fluid Dynamics Code for Gases, Aerosols, and Combustion, LA-13357-M, FZKA- 5994, 1998.