Investigation of Local Hydrogen Risk in the RDT Compartment of OPR1000 under SBO Scenario

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1. Introduction

As TMI-2 and Fukushima accidents revealed, a high concentration of hydrogen in a nuclear power plant (NPP) could cause hydrogen combustion. In order to take follow-up measures, an average and local hydrogen concentration in the NPP containment are regulated below 0.1 using hydrogen mitigation system such as igniter and/or passive autocatalytic recombiner (PAR).

During a severe accident, some compartments of the NPP containment temporarily may show peaks of the local hydrogen concentration over 0.1 depending on the geometry of the containment structure and hydrogen transportation path. For example, the compartment of a reactor drain tank (RDT) is connected to the pressurizer nozzle and if the relieved pressure drives the significant amount of steam and hydrogen, then substantial peaks of the hydrogen concentration can occur. This is the postulated risk during a hypothetical severe accident initiated by a station black out (SBO) scenario.

Thus in this study the local hydrogen risk in the RDT compartment under SBO scenario was analyzed using MELCOR 1.8.6 code. The RDT compartment is known to include a major flow path of hydrogen release through the pressurizer in the current Optimized Power Reactor 1000 MWe (OPR1000) during the early phase of SBO scenario. This provides a rationale for the necessity of the hydrogen risk analysis in the RDT compartment to guarantee the improved safety of OPR1000.

2. Detailed modeling of the RDT compartment

The RDT is the destination volume for the pressurizer safety relief valve (PSRV). In the final safety analysis report (FSAR) for Shin Kori NPP units 1&2, it was specified that the RDT compartment is the main region for a hydrogen release under SBO scenario. The RDT rupture disk could be also ruptured if pressure difference between the RDT and the containment atmosphere exceeds 0.827 MPa [1].

The modeling of the OPR1000 nodalization was modified to calculate the local hydrogen distribution in the RDT compartment. This modeling contains the detailed packages related to RDT and the RDT compartment.

Table I shows the initial conditions of the RDT and the RDT compartment. They were used to model the control volume hydrodynamics (CVH) package.

Table I: The initial condition of the RDT and RDT room [1]

Control vol.	Pressure	Temperature	Water level
RDT	0.170 MPa	322 K	60 %
RDT room	0.101 MPa	301.1 K	-

Table II shows the flow path (FL) data of the RDT compartment. There are three flow paths related to the RDT compartment. They especially contain the RDT rupture path which opens over the design basis pressure of the RDT rupture disk.

Flow path	Area	Length
RDT rupture	0.29 m^2	0.306 m
Entrance	2.72 m^2	0.767 m
Exhaust opening	0.74 m^2	0.966 m

Table II: The area and length of flow paths in the RDT room [1]

Fig. 1 shows the detailed modeling of the OPR1000 containment used for MELCOR simulation. This modified modeling for the containment especially included the RDT compartment to capture the local hydrogen risk near the RDT. The RDT compartment is located at the floor of the annulus area. The volume of RDT and the RDT compartment is 20.84 m^3 and 114.68 m^3, respectively.

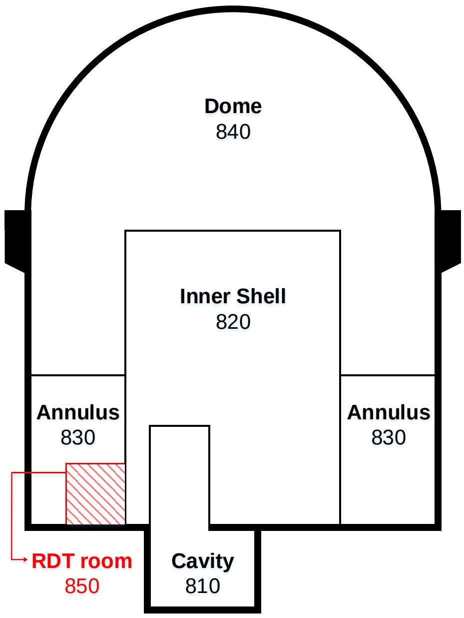

Fig. 1. The modified MELCOR nodalization of the OPR1000 containment including the RDT compartment [2]

3. SBO scenario analysis

SBO scenario is one of the most probable initiating events which can develop into severe accidents in the OPR1000. SBO event assumes that all of electronic power except 125 V power battery cannot be used to operate NPP.

The local hydrogen risk in the RDT compartment during SBO was numerically calculated using MELCOR 1.8.6 code simulation. The calculation time continued for 3 days (259,200 sec).

Table III shows the result of MELCOR simulation for a severe accident under SBO scenario. The accident was initiated by receiving a reactor trip signal from the loss of power signal at 0 hour.

Before the failure of a reactor pressure vessel (RPV), openings and closures of PSRV was repeated to relieve high pressure of the reactor coolant system (RCS). After the PSRV opened at 1.36 hour, the pressure of the RDT increased sharply over the design basis pressure to break the RDT rupture disk at 1.40 hour. Since the flow path was generated by this break, the RDT compartment had been the main region of the hydrogen release before the RPV failure.

Table III: Major accident sequence under SBO scenario

Accident sequence	Time [hr]
Accident start	0
Reactor trip	0
Steam generator dry out	1.02
PSRV open	1.36
RDT rupture	1.40
Oxidation start	2.27
Cladding melting	2.66
UO_2 melting	2.68
UO_2 relocation to lower head	2.86
RPV failure	3.59
SIT injection	3.68
Containment leak	37.12
Containment failure	N/A

4. Results and Discussion

In this section, the mass flow rate through the RDT break and the hydrogen volume concentration are described to explain the local hydrogen risk in the RDT compartment. The Shapiro diagram, which is the indicator map of the gas mixture flammability, is also described for the RDT compartment.

4.1. Mass flow rate of water, steam, and hydrogen through the RDT break

Fig. 2 shows the mass flow rate of water, steam, and hydrogen through the RDT break. The mass flow rate is peaked several times because they are affected directly by the PSRV openings and closures.

Some of the water and steam in the RDT was released into the RDT compartment as soon as the rupture disk was broken. The water level in the core decreased to uncovery level of the fuel assembly. Zirconium, which is the main constituent of the fuel cladding, started to interact with steam in the core and to produce hydrogen at 2.27 hour. The hydrogen generated in the core was then released in the RDT compartment.

Total mass of water, steam, and hydrogen released into the RDT compartment was 56,955 kg, 133,729 kg, and 264 kg, respectively.

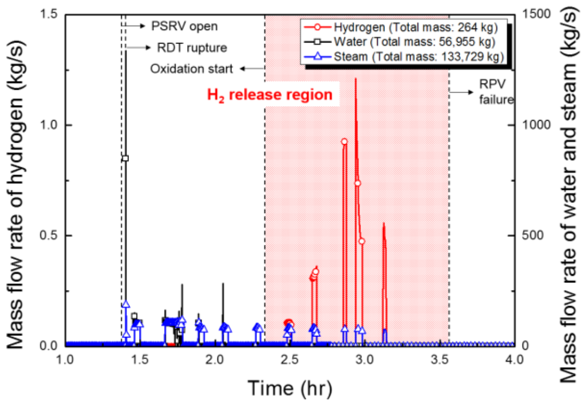

Fig. 2. The mass flow rate of water, steam, and hydrogen through the RDT break [3]

4.2. Hydrogen volume fraction

Fig. 3 shows the hydrogen volume fraction in the RDT compartment. The hydrogen in the RDT compartment kept its volume fraction below 0.1 which is the limit value for random ignition. After the RDT rupture and hydrogen production, however, the RDT compartment exhibited high hydrogen fraction exceeding 0.1. The maximum value of hydrogen fraction was calculated surprisingly about 0.17 at 2.94 hour.

Thus, the hydrogen combustion is expected to occur in the RDT compartment when the local hydrogen fraction exceeded 0.1.

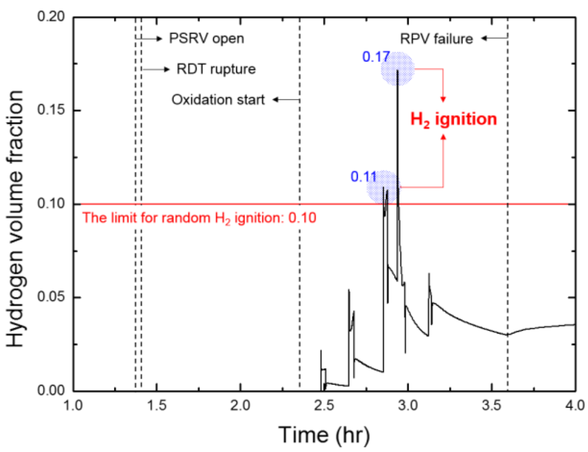

Fig. 3. The hydrogen volume fraction in the RDT compartment of the OPR1000

4.3. Gas mixture flammability on the Shapiro diagram

The Shapiro diagram describing detonation and burn limits for hydrogen-air-steam mixture was used to visualize the local hydrogen risk [4].

Fig. 4 shows the gas mixture flammability in the RDT compartment on the Shapiro diagram. Spots on the diagram demonstrate the gas composition from the RDT rupture to the RPV failure. When the hydrogen volume fraction was over 0.1, the spots were often entered in the burn limit region.

As a result, several spots of indicating sustainable hydrogen combustion in the RDT compartment could occur in the short term. For an example of those spots, the proportion of hydrogen, steam, and air was 10 %, 40 %, and 50 %, respectively at 2.94 hour.

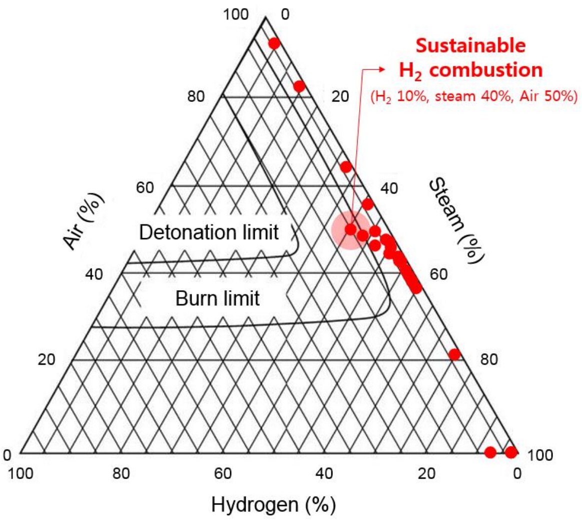

Fig. 4. The gas mixture flammability in the RDT compartment on the Shapiro diagram [4]

5. Conclusion

Before the RPV failure under SBO scenario, the RDT compartment was the main region for hydrogen release due to the RDT break. Therefore, confirming the local hydrogen risk in the RDT compartment is very important to verify the integrity of the NPP containment.

In this study, the local hydrogen risk in the RDT compartment of OPR1000 under SBO scenario was evaluated using MELCOR 1.8.6 code in terms of the hydrogen volume fraction and the Shapiro diagram.

(1) The RDT compartment showed the peaks of the hydrogen volume fraction over 0.1. This postulates that random ignition events are possible in the RDT compartment.

(2) The RDT compartment exceeded the burn limit on the Shapiro diagram in the short term. In other words, the possibility of sustainable hydrogen combustion existed temporarily.

Consequently, this study suggests that the additional hydrogen mitigation system let alone the passive autocatalytic recombiner needs to be installed in the RDT compartment to guarantee the improved safety against the hydrogen risk.

As a future work, the local hydrogen risk of the compartment of a steam generator (SG) needs to be analyzed under SBLOCA scenario. Because the SG compartment is also a main region of hydrogen release under SBLOCA scenario. In the long run, the analysis for the detailed hydrogen distribution, based on detailed modeling of the whole OPR1000 containment, needs to be performed.

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