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Steam and Hydrogen Release Characteristics by SDS Depressurization Location During OPR1000 SBO

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1. Introduction

An unmitigated station blackout (SBO) event can lead to a prolonged loss of active core heat removal, resulting in core heatup, fuel degradation, reactor pressure vessel (RPV) failure, and ex-vessel molten core-concrete interaction (MCCI). Throughout this accident progression, combustible gases are generated and released into the containment. Specifically, hydrogen is produced by high-temperature cladding oxidation during the in-vessel phase, whereas both hydrogen and carbon monoxide can be generated during MCCI following vessel failure.

During an SBO of OPR1000 [1], the loss of residual heat removal causes the reactor coolant system (RCS) pressure to rise. When it reaches the set-point, the pressurizer safety relief valve (PSRV) automatically opens to control the pressure. The PSRV discharges into the Reactor Drain Tank (RDT) via piping, and the RDT is protected from overpressurization by a rupture disk.

If core temperatures continue to rise despite pressure control via the PSRV, operators manually actuate the safety depressurization system (SDS) by opening motor-operated valves to initiate rapid RCS depressurization. The SDS in OPR1000 consists of two trains, each equipped with a power-operated relief valve (PORV), flow regulation devices, and associated piping. One downstream line of the SDS is routed directly through a rupture disk mounted on the pressurizer compartment wall, while the other line connects to the RDT. The rupture disk on the pressurizer compartment wall is designed to burst at a differential pressure of approximately 96 bar, whereas the RDT rupture disk bursts at a tank internal pressure of about 5.7 bar. Bursting of the RDT rupture disk releases steam and hydrogen into the annular compartment via the RDT compartment, whereas a failure of the rupture disk on the pressurizer compartment wall results in a high-velocity steam jet directed into the upper containment region.

In this study, three-dimensional (3D) computational analyses were performed to investigate the effects of steam release locations during SDS depressurization on containment thermal-hydraulic behavior and the resulting hydrogen distribution during core degradation.

2. MELCOR Analysis of OPR1000 SBO Accident

In this study, the OPR1000 SBO sequence was simulated with the MELCOR [2] severe accident analysis code. The primary objective was to obtain the overall accident progression and transient source terms for subsequent detailed containment analyses. The quantities of interest include water vapor, H_2, CO, and CO_2 release rates and the associated discharge temperatures at major release locations. The MELCOR calculation was performed with a wet reactor cavity and operation of the SDS based on an assumed severe accident management guideline (SAMG) entry condition.

The SBO was initiated at 0 s with loss of offsite power and reactor trip. The main feedwater pumps and reactor coolant pumps were assumed to stop following the power loss. Containment spray operation was not credited, and the calculation was continued to 100,000 s. For the wet-cavity calculations, the cavity was continuously filled with approximately 5 m of water above the floor.

For the SDS case, the safety depressurization valve or PORV was opened when the maximum core exit temperature exceeded 923.15 K, which corresponds to the assumed entry condition for Severe Accident Management Guidelines (SAMG). Table 1 summarizes the sequence of major events for the SBO scenario.

Table I: MELCOR analysis results for SBO accident progression

Key event timings of SBO accident	
Event	Timing (s)
Loss of offsite power and reactor trip	0
pressurizer valve (PSRV) open	4,558
Start of core uncover	6,550
SAMG entry and SDS valve open	8,220
Fuel melting	9,380
Fuel relocation to the lower head	9,559
Reactor vessel failure	16,676
Initiation of MCCI	16,676

Figs. 1, 2, and 3 present the MELCOR simulation results, illustrating the transient mass flow rates and cumulative masses of steam and hydrogen released through the SDS, as well as the temperature of the released gases. Following the opening of the SDS valve, the steam release rate peaks at approximately 175 kg/s before undergoing a sharp decline. By 15,000 seconds,

the cumulative mass of the released steam amounts to approximately 50 tons.

Although the release trend of hydrogen closely mirrors that of steam, its release initiates about 5,000 seconds later. This delay is attributed to the sequential progression of events required for hydrogen generation, namely RCP depressurization, core uncovery, and subsequent cladding oxidation. According to the MELCOR calculations, the hydrogen release rate reaches a maximum of 0.53 kg/s, yielding a total cumulative hydrogen mass of about 370 kg at 15,000 seconds.

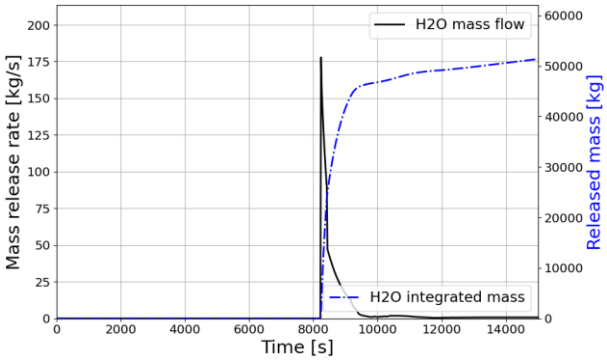


Fig. 1. Water vapor release rate and accumulated mass through SDS valve.

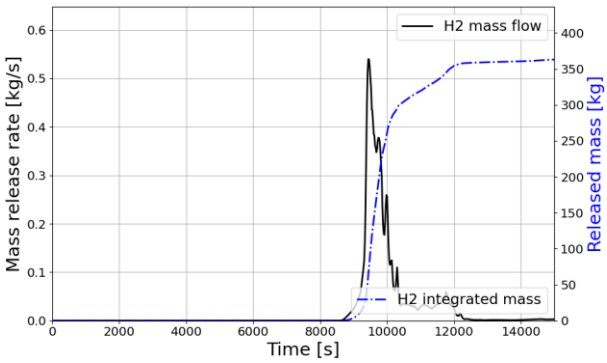


Fig. 2. Hydrogen release rate and accumulated mass through SDS valve.

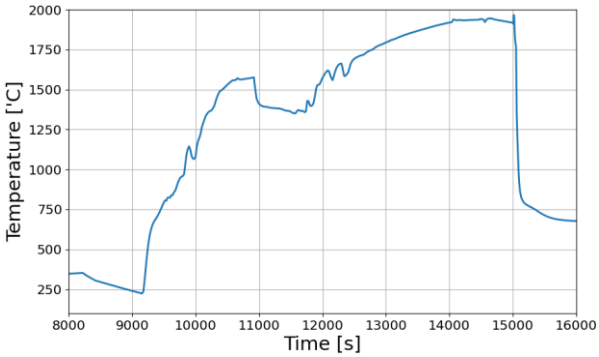


Fig. 3. Temperature of released gases through SDS valve.

3. 3-D Analysis of OPR1000 Containment

The turbulence-resolved computational fluid dynamics (CFD) code, HYCON3D [3], was recently developed based on CONTAIN3D [4] to analyze the thermal-hydraulic behaviors in pressurized water reactor (PWR) containments during both the early and late phases of severe accidents. In this study, HYCON3D was applied to analyze the release characteristics of steam and hydrogen depending on the depressurization location of the safety depressurization system (SDS) during a station blackout (SBO) accident in the OPR1000.

Fig. 4 shows the internal structure of the OPR1000 containment and the layout of major components, including the RCS and RDT. As shown in the figure, the RDT is installed within a small room located at the lower section of the annular compartment.

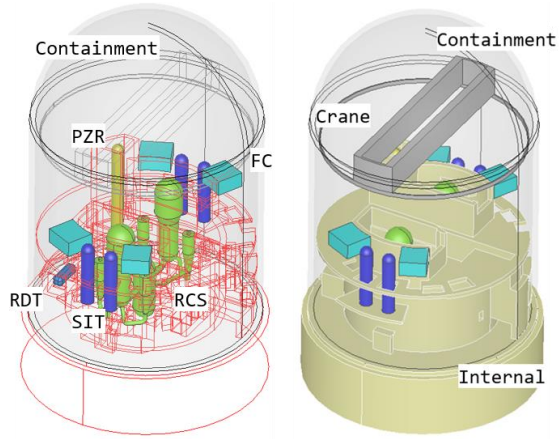


Fig. 4 Internal structure of the OPR1000 containment and major components installed in the containment.

The 3D analysis using HYCON3D was initiated at 8,220 seconds, corresponding to the point of entering the SAMG and opening the SDS valve (PORV) during the SBO accident progression. The containment conditions at 8,220 seconds were obtained from the MELCOR calculation results, and a 1D heat conduction model considering steam condensation was applied to the walls of the internal containment structures. In this study, both cases corresponding to different SDS depressurization locations were evaluated using the identical transient source terms derived from the same MELCOR calculation.

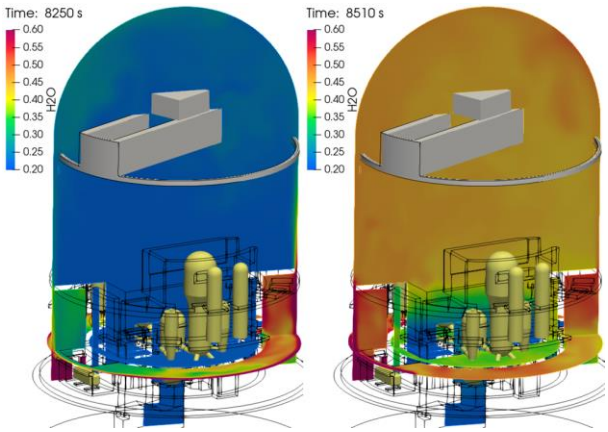


Fig. 5. Steam distributions in the containment released through the RDT.

Fig. 5 presents the steam behavior when the PORV of the SDS is opened, releasing steam into the RDT. The high-temperature steam, discharged as a high-velocity vertical jet through the rupture disk of the RDT, impinges on the ceiling of the RDT compartment. Upon exiting through the compartment outlet, the flow transitions into a horizontal direction and propagates along the annular compartment. Subsequently, driven by strong buoyancy, the high-temperature steam escapes the annular compartment and ascends toward the upper dome region of the containment.

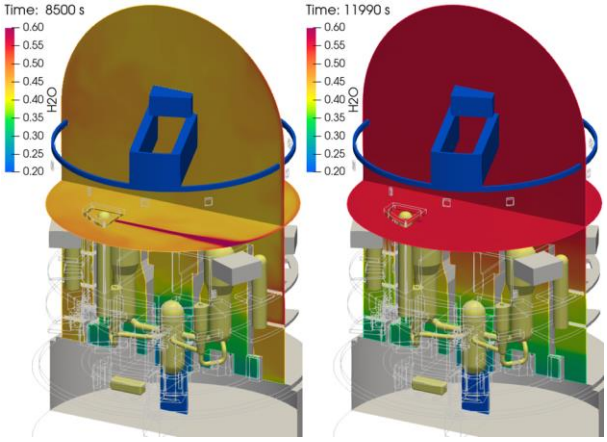


Fig. 6. Steam distributions in the containment released through the rupture disk on the pressurizer compartment wall.

Alternatively, if the rupture disk on the pressurizer compartment wall bursts simultaneously with the opening of the SDS PORV, the steam is discharged as a horizontal jet from the upper section of the pressurizer, as depicted in Fig. 6. Notably, due to the exceedingly high initial mass flow rate of the released steam, the high-velocity steam jet impinges directly on the containment wall. Following this impingement, the flow bifurcates, with a portion migrating upward to the dome region and the remainder directed downward into the lower annular compartment.

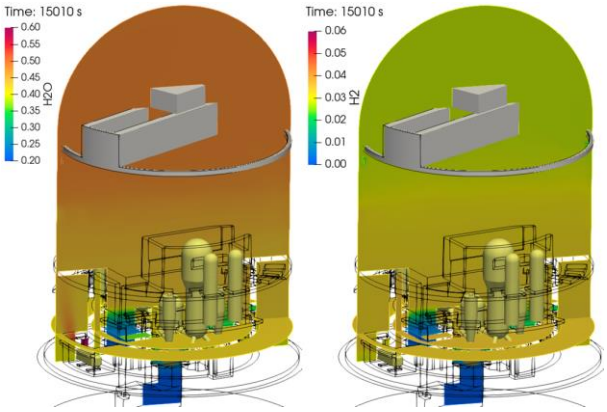


Fig. 7. Steam and hydrogen distributions in the containment released through the RDT before the RPV failure.

Fig. 7 illustrates the spatial distributions of steam and hydrogen within the containment immediately prior to the RPV failure, assuming the releases occur through the RDT. In this scenario, a mild yet discernible concentration stratification is observed. While steam accumulates at elevated concentrations in the upper region of the containment, hydrogen exhibits a concentration inversion phenomenon, whereby its concentration is noticeably higher in the lower region than in the upper region.

Conversely, when the RCS is depressurized through the rupture disk on the pressurizer compartment wall, a distinct distribution profile emerges. As depicted in Fig. 8, a dense mixed-gas cloud characterized by exceedingly high concentrations of steam and hydrogen forms in the region above the discharge nozzle.

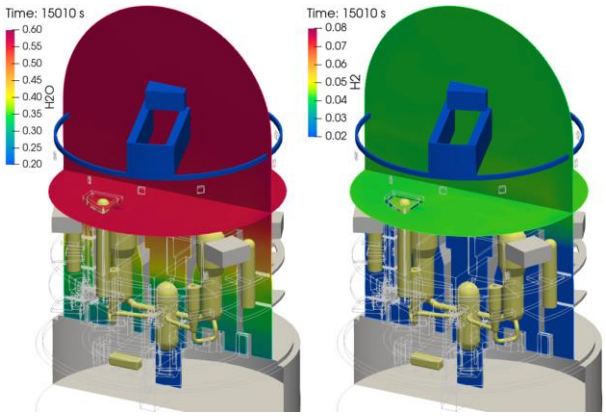


Fig. 8. Steam and hydrogen distributions in the containment released through the rupture disk on the pressurizer compartment wall before the RPV failure.

4. Summary and Future Work

To evaluate the applicability of the HYCON3D code, we investigated the release characteristics of steam and hydrogen depending on the safety depressurization system (SDS) depressurization location during a station blackout (SBO) accident in the OPR1000 containment. The results of this analysis successfully demonstrated the distinct stratification behaviors of steam and hydrogen governed by the specific SDS depressurization locations.

As a follow-up to this study, detailed computational analyses are currently underway to investigate the behaviors and spatial distributions of combustible gases, specifically hydrogen and carbon monoxide, generated during the molten core-concrete interaction (MCCI) phase.

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