Investigation of downward flow gas mixture in a PAR during SBO using the MELCOR code

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1. Introduction

Through the Fukushima accident, it was confirmed that hydrogen combustion can threaten the integrity of the containment during station blackout (SBO) scenario. Many countries have put tremendous efforts to reduce such potential risk from the hydrogen combustion. In case of Optimized Power Reactor 1000 MWe (OPR1000) constituting a majority of operating nuclear power plants (NPPs) in Korea, thirteen passive autocatalytic recombiners (PARs) were installed to mitigate the risk of hydrogen during SBO accident. The PAR is assembled with vertically installed catalytic plates forming vertical flow channels for the flammable gases. Hydrogen can be removed on the catalytic plates even at low temperature through exothermic reaction. The reaction heat generates buoyancy-driven force so that PARs can self-start and self-feed by forming chimney flow without any external power.

However, a large amount of steam released through pressurizer safety relief valve (PSRV) can hinder the hydrogen removal from PARs because the gas mixture released from the PSRV would rise to containment dome and flow downward along the containment wall. Thus a counter current flow may form, which may affect passive hydrogen removal and degrade PAR performance accordingly. These effects were confirmed in REKO test showing the delayed PAR operation by the counter flow [1]. Therefore it is worthwhile to investigate the possible formation of the counter current flow regarding its effect on PAR operation under SBO scenario. In this study, the possibility of downward flow formation was examined using the MELCOR code. The OPR1000 was selected as a reference NPP and detailed modeling in the MELCOR code was developed based on the Final Safety Analysis Report (FSAR) [6].

2. Methodology

2.1. MELCOR Input Model of OPR 1000

The MELCOR input model of the major primary system in the OPR1000 includes a core, a downcomer, a lower plenum, four cold legs, two hot legs, a pressurizer, two steam generators, four safety injection tanks (SITs) etc. The secondary system and containment structure were also modeled in this input.

Because MELCOR is a well-known lumped parameter (LP) code, checking out the existence of downward flow is a challenging task with the basic input. So a rather detailed modeling method was used in this study to capture the counter current flow in the dome area. Using the detailed modeling method, the containment was divided into 20 compartments as shown in **Fig.1**. The PARs were modeled in lower area of dome (CV841, CV846) and third floor of annulus (CV833, CV838). The PAR implemented in the input is NIS type.

Initial event was selected as SBO, which bears the highest transient probability to severe accident. All systems using electricity were assumed to fail during the accident. Major accident sequences in SBO are summarized in **Table 1.**

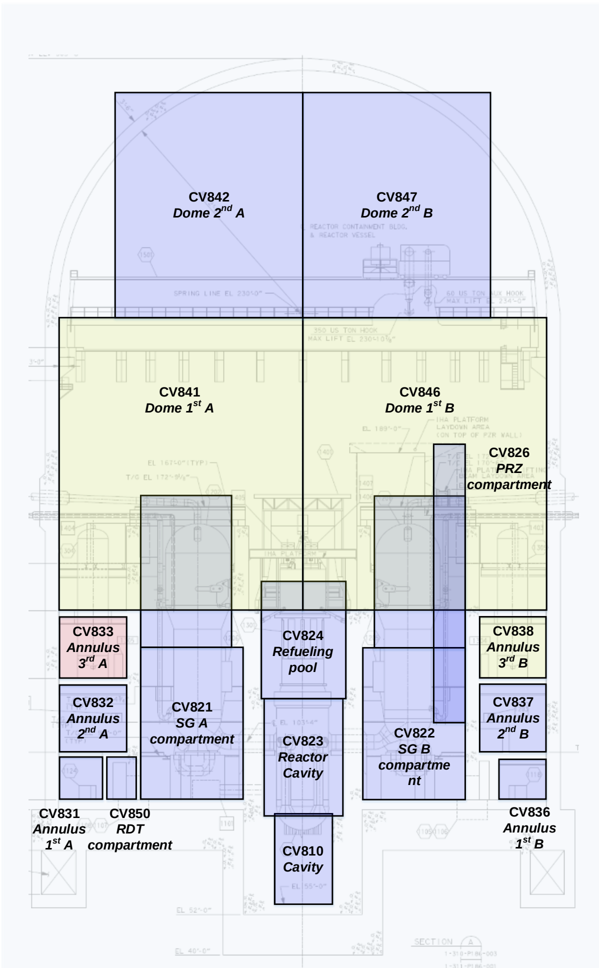

Fig. 1. Control volumes in the MELCOR nodalization using detailed modeling for the containment of OPR1000. [3]

Table 1. Major accident sequences in SBO

Events	Time (hr)
Accident start	0
Reactor trip	0
PSRV open	1.36
SG dryout	1.04
Oxidation start	2.29
Core dryout	2.62
Cladding melt	2.65
UO2 melt	2.67
Relocation to lower head	2.83
SIT injection	3.80
SIT exhaust	3.94
RPV failure	3.78

2.2. Definition of downward flow

Because MELCOR code is classified as LP code, the analysis with fine grids can be difficult compared to computational fluid dynamics (CFD) codes. It is challenging to directly identify the existence of downward flow through the catalyst zone of PAR by MELCOR code. Therefore, the formation of the downward flow in the catalyst zone is assumed when the vapor flows downward in every vertical flow path as shown in **Fig.2**. The flow paths are connected to the control volume where PARs are included. Its magnitude is defined as area-averaged velocity of every flow path using **Equation (1)**. When considering downward flow and its magnitude, velocity from horizontal flow path was neglected.

$$\bar{v} = \frac{\sum v_i A_i}{\sum A_i} \qquad (1)$$

The downward flow occurred in only one control volume of 3rd Annulus (CV833) out of four control volumes where PARs are installed. So the CV833 was analyzed in this study. CV833 includes flow paths connected to annulus 2nd floor, namely FL1, 2, and another connected to dome 1st floor, FL3, and 4.

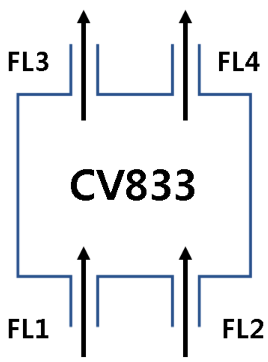

Fig. 2. A schematic of flow paths connected to control volume 833

2.3. Hydrogen removal model in MELCOR

Hydrogen reaction rate per a unit of NIS PAR is calculated in MELCOR using Equation (2).

$$R_H = \eta\, \rho_H\, Q\, f(t) \qquad (2)$$

η is hydrogen reaction efficiency with default value of 0.85. ρ_H is density of entering hydrogen. Q is total volumetric flow rate of gas mixture through the PAR unit. $f(t)$ is relaxation time factor, which considers transient effect during the initial PAR heat-up.

As seen in **Equation (2)**, as the total volumetric flow decreases, the removal rate also decreases. The volumetric flow rate through a NIS PAR unit, Q is given by **Equation (3)**.

$$Q = a_2 {C_H}^{a_1} \qquad (3)$$

C_H is hydrogen mole fraction. a_1 and a_2 are design parameters of constant values. As shown above, terms related to the flow rate in **Equations (2-3)** only include hydrogen concentration. In other words, the effect of counter flow on the hydrogen removal cannot be explicitly estimated through the MELCOR code.

3. Results and Discussion

3.1. The magnitude of the downward flow

The downward flow occurred only in CV833 because a strong counter-clockwise circulation of the large amount of gas mixture was formed throughout the dome area. As far as the current simulation is concerned, this was confirmed by checking out the average velocity calculated with **Equation (1)**. As a result, **Fig. 3** shows the averaged velocity passing through the control volume and mostly the results are in the negative region.

The shaded region indicates the time, during which PARs normally operate. **Fig. 4** shows vapor velocity of four flow paths connected to CV833. Duration of downward flow was estimated as approximately 16,000 seconds as shown in **Fig. 4.** The maximum downward flow velocity was evaluated as 0.54 m/sec at 13,600 seconds due to RPV failure.

3.2. Amount of hydrogen recombined under the downward flow

One unrealistic result is the fact that hydrogen in CV833 was being removed normally by PAR operation although the downward flow existed. This is because the MELCOR code is unable to take into account the counter flow effect. Experimentally, this is one important issue to be identified and Z. Liang et al. experimentally investigated the effect of ambient flow conditions generated by fan on performance of AECL PAR [4]. The measured flow speed by fan was ranged 1.5 to 5 m/s. The experiment results showed that overall hydrogen removal rate can be reduced by nearly 50% under counter flow with AECL PAR. In other words, under the vertical downward flow at the PAR outlet, the hydrogen removal rate may decrease up to 50% compared to a case under quiescent atmosphere.

Although the exact thermal-hydraulic or thermodynamic conditions and PAR type are different, it was assumed that the factor reported by Z. Liang et al can be applicable [4]. The assumption seems reasonable because OECD THAI project has shown that behaviors of commercial PARs (AECL, AREVA, and NIS) are very similar [5].

The total amount of hydrogen recombined under downward flow for 16,000 seconds in MELCOR was about 19.98 kg. If simply applying the factor of 0.5, 9.99 kg of hydrogen could be overestimated in MELCOR simulation. Considering the overestimated amount of removed hydrogen, more detailed researches on counter flow that may affect PAR performance seem to be required.

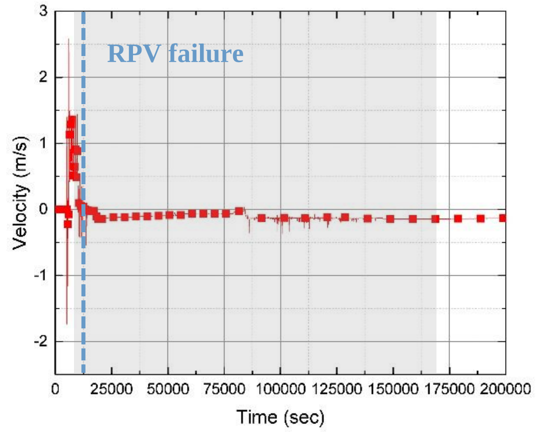

Fig. 3. Average velocity passing through CV833

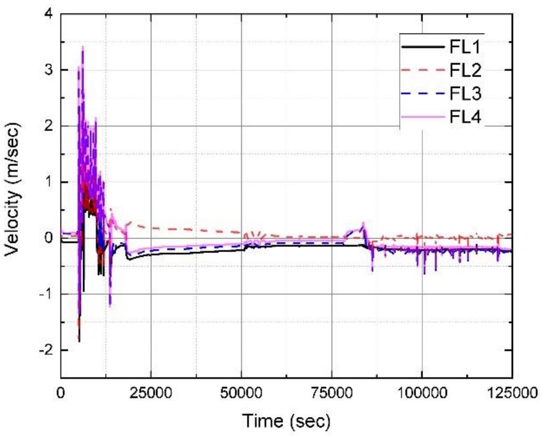

Fig. 4. Vapor velocity in each flow paths of CV833

4. Conclusions

In this research, the existence of downward flow that may create counter flow was identified using MELCOR. In addition, the overestimated amount of removed hydrogen by PAR was simply calculated. As a result, about 10 kg hydrogen was overestimated under SBO scenario.

For more reliable results, more detailed thermal-hydraulic and thermodynamic conditions are required to implement in the MELCOR input. Major findings and future works are summarized as below.

(1) The detailed input considering the PAR installation was used in the MELCOR simulation.
(2) The existence of downward flow that might create counter flow against chimney flow of PAR was confirmed with MELCOR 1.8.6. The maximum magnitude of the downward flow was about 0.54 m/s.
(3) Simply considering Liang et al.'s result, about 10 kg of hydrogen was overestimated under the downward flow during SBO in MELCOR simulation.
(4) The existence of counter flow needs to be confirmed through more detailed modeling and simulation.

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