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Investigation of hydrogen risk in the major containment compartments of OPR1000 using MELCOR code under SBO scenario

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1. Introduction

Through the TMI-2 and Fukushima accidents, it was revealed that hydrogen explosion accidents in Nuclear Power Plants (NPP) could occur. If hydrogen explosion goes through the flame acceleration (FA) or the transition from deflagration to detonation (DDT) during a hypothetical severe accident, this may add the significant dynamic pressure and temperature loads to the containment integrity [1].

In order to take follow-up measures, the enactments of regulations for the hydrogen risk are specified in the 10CFR and Korea nuclear safety act. They can be summarized as follows, providing a rationale for the necessity of an analysis related to the hydrogen risk.

- Limitation of the uniformly distributed hydrogen concentration in the containment below 10 vol.%.
- No FA and DDT in each compartment.
- Provision of containment-wide hydrogen control.

The characteristics of hydrogen explosion are mainly determined by hydrogen distribution in containment. Therefore, many studies for hydrogen distribution have been performed using numerical tools, which are specialized in simulating hydrogen distribution, e.g. GASFLOW, GOTHIC, and COCOSYS.

However, from a perspective on the regulations, the conservative and reliable analyses for thermal hydraulic phenomena including hydrogen distribution still need to be conducted particularly using the safety analysis codes developed for regulations. They can also contribute to the improvement of the reliability of their regulatory prediction regarding the hydrogen risk.

Thus, in this study, the postulated hydrogen risk in the current Optimized Power Reactor 1000 MWe (OPR1000) under SBO scenario was investigated using MELCOR 1.8.6 code, which has been used as the safety analysis code in the several nuclear regulatory bodies. Especially, the flammability and the flame propensity in the vulnerable locations in containment were evaluated by analyzing hydrogen distribution in the major compartments with criteria for ignition, FA, and DDT.

2. Analysis methodology

In this section, several analysis methodologies which were adopted for safety analysis of the hydrogen risk are introduced. First, the MELCOR input for the containment of OPR1000 is described. Second, the criteria for a random ignition are demonstrated. Third and fourth, criteria for FA and DDT are briefly explained.

2.1. MELCOR input for the containment of OPR1000

2.4.1. SBO scenario

SBO scenario was selected as the initiating event for SA in this study. It is one of the most probable events developing into SA in OPR1000. It also implies that all electronic power except 125 V power battery cannot be used to operate safety measures equipped in NPP.

2.4.2. Passive Autocatalytic Recombiner (PAR)

Despite the absence of electronic power under SBO scenario, the hydrogen risk can be mitigated with the operation of PAR.

OPR1000 was equipped with total 21 units of PAR, which were installed in the lower area of dome and the operating floor as the hydrogen mitigation system for Design Basis Accident (DBA) and SA. It is also noted that the current PARs have a similar performance regardless of the manufacturers.

Therefore, PARs in OPR1000 were modeled to deplete hydrogen with the default model of the NIS PAR in the MELCOR PAR package.

2.4.3. Nodalization for the containment

The local risk of hydrogen can take place in high hydrogen concentration of a certain compartment due to the dependence on the complicated geometry of containment structures and transportation paths. This is the reason why in this study the nodalization for the containment was divided into 20 compartments considering the geometric characteristics.

Figure 1 shows the control volumes in the MELCOR nodalization for the containment of OPR1000 in the cross-sectional drawing. Based on the Final Safety Analysis Report (FSAR) for Shin Kori NPP units 1&2, the nodalization was developed for investigating the local distribution of hydrogen in each compartment.

The Reactor Drain Tank (RDT) (CV850) and the reactor cavity (CV810) were subjects of the main compartments for the hydrogen release under SBO scenario. This was also specified in FSAR for Shin Kori NPP units.

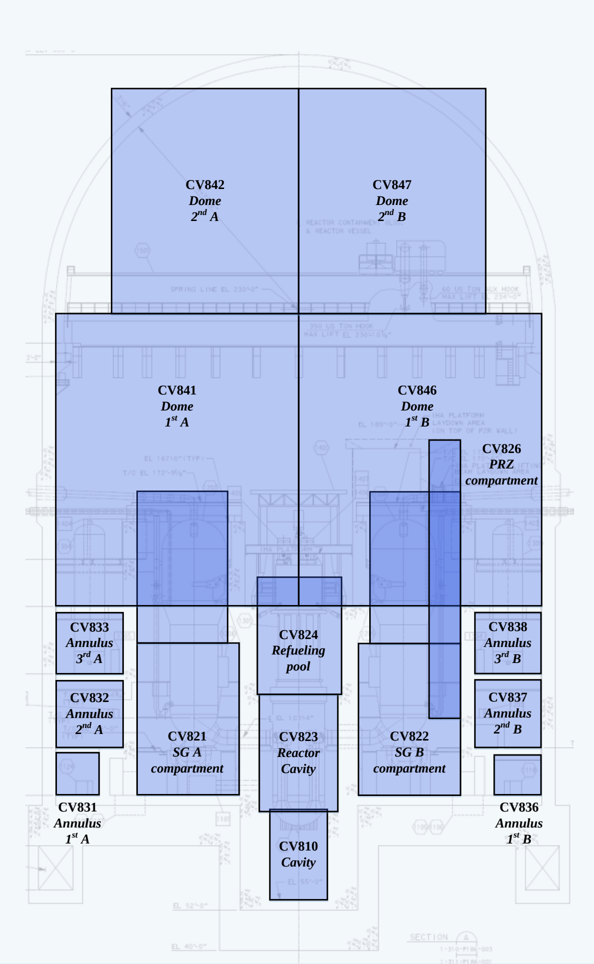

Fig. 1. Control volumes in the MELCOR nodalization for the containment of OPR1000.

2.2. Ignition criteria

Combustion of gas mixture was judged to be triggered with the criteria for a random ignition event, which is used in the MELCOR BUR package [2]. The ignition criteria for the presence of sufficient hydrogen, oxygen, and diluent gases are described from Eq. (1) to Eq. (3) as follows:

$$X_{H2} \geq 0.10 \tag{1}$$

$$X_{O2} \geq 0.05 \tag{2}$$

$$1 - X_{H2O} \geq 0.45 \tag{3}$$

where X_{H2}, X_{O2}, and X_{H2O} are the mole fraction of hydrogen, oxygen, water vapor, and carbon dioxide in the control volume, respectively.

2.3. σ-criterion for FA

The σ-criterion was implemented to evaluate the possibility of FA. The FA index σ_{index} was adopted with the derived σ and the estimated $\sigma_{critical}$-table in Eq. (5). If σ_{index} is over 1, FA can be judged to occur [3].

$$\sigma_{index} = \frac{\sigma(\bar{x}_{H2}, \bar{x}_{O2}, \bar{x}_{H2O}, T)}{\sigma_{critical}(\bar{x}_{H2}, \bar{x}_{O2}, T)} > 1 \tag{5}$$

where $\bar{x}$ means the mole fraction of constituents of mixtures and *T* is the initial temperature of mixtures.

The expansion ratio σ is defined as the ratio of the volume of the burned mixture to the volume of the unburned mixture at constant pressure [1]. It can be derived from the law of the conservation of energy in the reaction equation of hydrogen combustion. Properties of the reactants and the products were interpolated from the thermochemical table by NIST-JANAF [4].

The critical expansion ratio $\sigma_{critical}$ can be summarized as function of temperature in Table I. It was estimated by interpolation from various experimental data with different mixtures in obstructed tubes of different scales, e.g. RUT facility tests and FZK experiments [5].

Table I: the critical σ used as function of temperature for lean and rich H_2-air-steam mixtures [3]

Temperature [K]	$\sigma_{critical}$	
	$x_{H2} < 2\ x_{O2}$	$x_{H2} > 2\ x_{O2}$
300	3.75	3.75
400	2.80	3.75
500	2.25	3.75
650	2.10	3.75

2.4. L/7λ-criterion for DDT

The potential of DDT was predicted using the *L/7λ*-criterion, where *L* is the characteristic geometrical size and *λ* is the detonation cell size. The idea of this approach is that *L/7λ* over 1 can indicate the onset of the detonation.

The characteristic geometrical size L of each compartment was determined using the aggregation rules developed for a 900 MWe French Pressurized Water Reactor (PWR) [3]. Based on the above rules, compartments can be classified into 4 different shapes: the cubic, flat, long, and tall. Most of compartments in the MELCOR input can be regarded as the cubic rooms.

The detonation cell size *λ* of the average mixture composition can be calculated by an analytical function in Eq. (6) [6], which is used for interpolation of the previous experimental data by McGill Univ., SNL, and BNL [3].

$$\begin{aligned}\log(\lambda) = {} & m+(D-c)\cdot(1/(0.1-c)+n(D-0.1))\cdot \\ & \cdot(a-m+(b/(A-k/B)^{f}+h(A-gB))(1+dC+eBC^{2})j/B)\end{aligned} \tag{6}$$

where A is the dry hydrogen concentration in vol.%, B is the initial temperature in K, C is the steam concentration vol.%, and D is the initial pressure in MPa. There are 11 coefficients from *a* to *n*.

3. Results and discussion

3.1. Ignition

The most flammable locations exceeding the ignition criteria were the compartments of the annulus 1st A (CV831) and B (CV836) and the regenerative heat exchanger (RHX) (CV825). They are the areas surrounding the RDT compartment and the reactor cavity. Although the RDT compartment and the reactor cavity were modeled as the main regions for hydrogen release under SBO scenario, they were not determined as the flammable compartments because of the large release of steam over 55 vol.%.

Fig. 2 shows the mole fraction of hydrogen, steam, and oxygen in the annulus 1st A indicating the duration of flammability with the ignition criteria. The analysis regarding the annulus 1st B was skipped because its gas composition had a similar tendency with that in the annulus 1st A. Hydrogen combustion in the annulus 1st A could occur within 50 sec (about 0.02 hrs). When pressurizer safety relief valve (PSRV) was open thirdly at 2.91 hrs after the start of the zircaloy oxidation process, some hydrogen and steam were released into the annulus 1st A and B through the RDT compartment. By the effect of the complicated structures on hydrogen behavior, the mixtures in their compartments consisted of sufficient amount of hydrogen and oxygen and adequate steam to the random ignition in the short term.

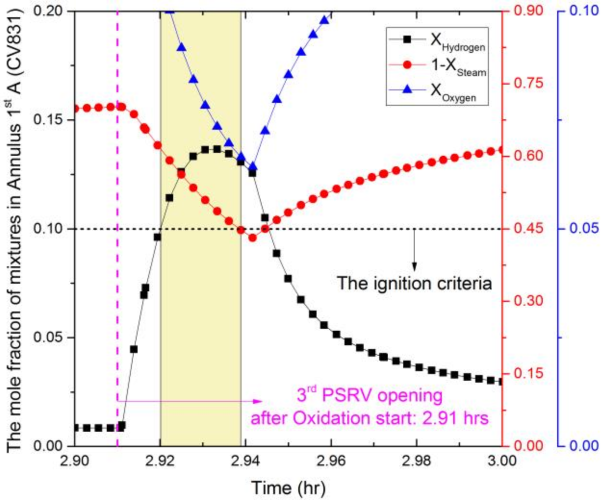

Fig. 2. The mole fraction of hydrogen, steam, and oxygen in the annulus 1st A (CV831).

Fig. 3 demonstrates the mole fraction of mixture in the RHX compartment. Hydrogen combustion in the RHX compartment was expected to take place within 150 sec (about 0.05 hrs). After the lower head of the reactor pressurized vessel (RPV) exhausted at 5.26 hrs, a huge amount of hydrogen and steam were released into the RHX compartment via the reactor cavity and the cavity door (CV812). Consequently, the hydrogen-steam-air mixture met the ignition criteria temporarily under the influence of the transportation path of hydrogen.

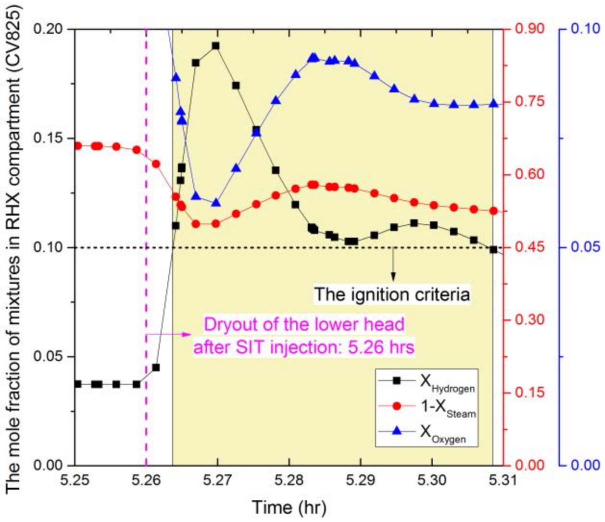

Fig. 3. The mole fraction of hydrogen, steam, and oxygen in the RHX compartment (CV825).

3.2. Possibility of FA

Both the annulus 1st A and the RHX compartment showed the possibility of FA because of the σ-index over 1 in the flammable duration, which started at 2.92 hrs and 5.26 hrs.

Fig. 4 describes the σ-index of those compartments according to the initial temperature of mixtures. For the most of the flammable duration, the mixtures in those compartments can be regarded as the H_2-lean ($x_{H2} < 2\ x_{O2}$) mixtures. The σ-index was relatively high valued in those mixtures. It was because the $\sigma_{critical}$ in those mixtures is inversely proportional to the initial temperature due to the influence of a local behavior of a flame element [3].

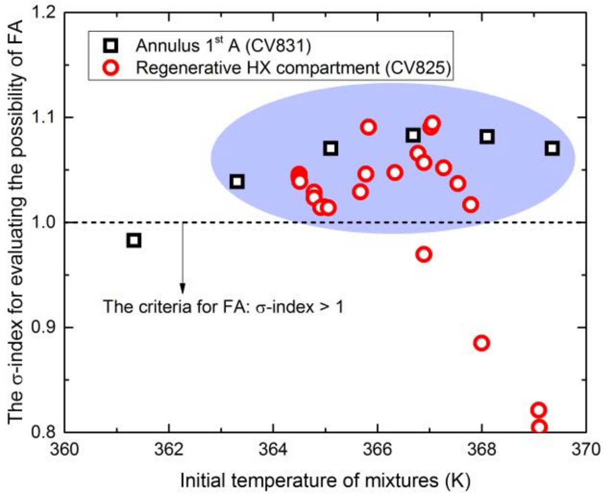

Fig. 4. The σ_{index} for evaluating the possibility of FA in the annulus 1st A (CV831) and the RHX compartment (CV825) during the flammable duration.

Table II shows the averaged flame temperature and σ-index in those compartments calculated by the gas composition and the initial temperature of the mixtures. Assuming complete combustion at constant pressure, the flame temperature and σ-index in those compartments were estimated by the difference between the total enthalpies of the reactant and the product.

Table II: The averaged flame temperature and σ-index in the annulus 1st A and the RHX compartment.

Control volume	Flame temperature	σ-index
Annulus 1st A	1289 K	1.05
RHX compartment	1275 K	1.02

3.4. Possibility of DDT

In both the annulus 1st A and the RHX compartment, the onset of the detonation could not occur because the *L/7λ* did not exceed 1 for all time of simulation.

Fig. 5 demonstrates the *L/7λ*-criterion of those compartments according to the mole fraction of dry hydrogen. Although the *L/7λ* increased exponentially with dry hydrogen, the maximum value was 0.04 in the annulus 1st A and 0.20 in the RHX compartment because of the large size of the detonation cell. The large *λ* resulted from that mixtures in those compartments were not reactive by the large mole fraction steam [1]. This was also indicated by the previous experimental data on DDT [3].

In addition, with the aggregation rules introduced in Section 2.4, the room shape and the characteristic geometrical size *L* was evaluated as shown in Table III.

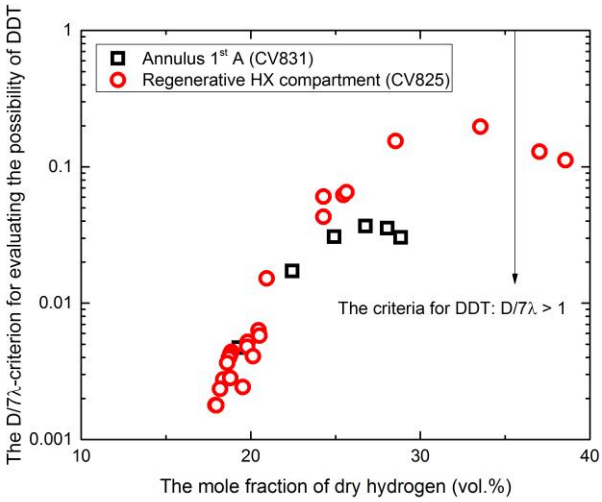

Fig. 5. The L/7λ-criterion for evaluating the possibility of DDT in the annulus 1st A (CV831) and the RHX compartment (CV825) during the flammable duration.

Table III: The room shape and the characteristic size of the annulus 1st A and the RHX compartment

Control volume	Room shape	Char. size, L
Annulus 1st A	Long	5.11 m
RHX compart.	Tall	8.39 m

4. Conclusions

As a result of the MELCOR simulation, the annulus 1st A and B and the RHX compartment were temporarily considered as the most vulnerable locations for hydrogen risk under SBO scenario. Thus, the flame regimes in those compartments were investigated and evaluated in terms of the criteria for the ignition, FA, and DDT.

The hydrogen-steam-air mixture in the annulus 1st A showed the gas composition exceeding the ignition criteria within 50 sec after the 3rd opening of PSRV at 2.91 hrs. The mixture in the RHX compartment also satisfied the ignition criteria within 150 secs after the dry-out of the lower head at 5.26 hrs. This postulates that hydrogen combustion in those compartments could be initiated by random ignition events. The σ-index of the mixtures was also evaluated over 1. Therefore, not the detonation but the fast deflagration in those compartments was expected to occur due to FA.

Consequently, this study suggests the practical assessment methodology of hydrogen risk for the safety analysis code including MELCOR. Besides, this study can provide the database for the improvement of reliability of numerical prediction regarding hydrogen risk.

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