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Analysis Method for Licensing Application of Passive Autocatalytic Recombiner System as a Hydrogen Mitigation System of OPR-1000

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1. Introduction

Importance of hydrogen safety in nuclear power plants has been emphasized especially after the Fukushima accident in Japan. A passive autocatalytic hydrogen recombiner (PAR) is considered as a viable option for the mitigation of hydrogen risk in case of station blackout because of its passive operation for the hydrogen removal. To enhance the capability of hydrogen control, passive autocatalytic hydrogen recombiners have been installed in all nuclear power plants in Korea. As a result, for some plants, dual hydrogen mitigation systems are prepared with a combination of PARs and igniters that each system has a 100% of full capacity for hydrogen control for postulated severe accident conditions. In the original design of OPR-1000, hydrogen mitigation systems consist of a thermal recombiner and twenty (20) glow-type igniters, which are used for design basis accident and severe accident, respectively. Additional hydrogen mitigation system with PAR is prepared to enhance the capability of hydrogen control for an extended station blackout such as Fukushima accident. To implement PAR as a hydrogen mitigation system, an extensive analysis should be required to demonstrate that the system is designed to meet the regulatory requirements for hydrogen control. This paper presents an analysis method for licensing application in Korea to determine the capacity and locations of PARs for the design of a hydrogen mitigation system with PAR.

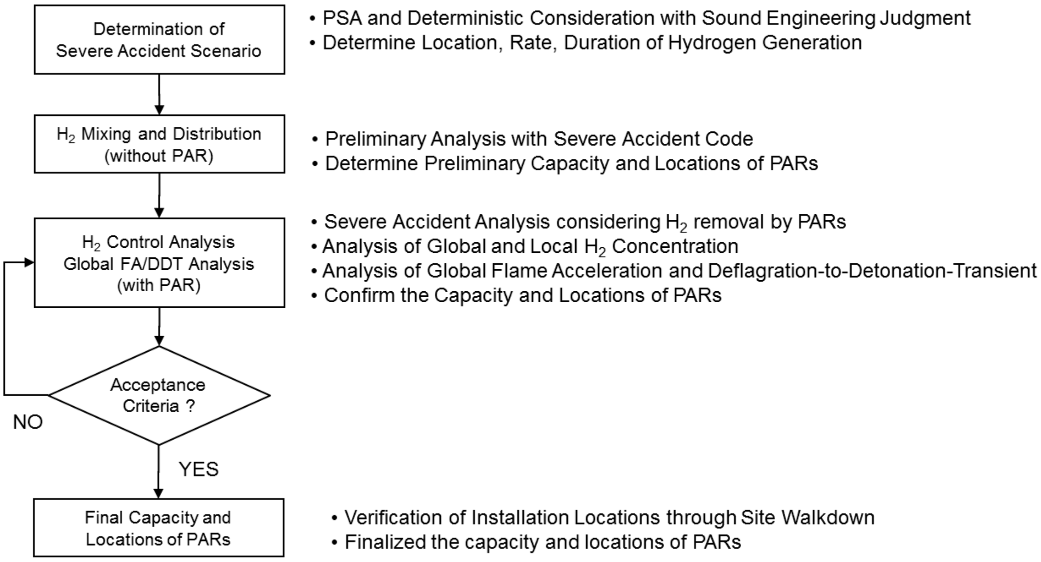


Fig. 1 General Design Procedure for the Implementation of PAR System

2. Analysis Method

1.1 General Design Procedure

In order to implement the PAR system as a hydrogen mitigation system, a series of analytical steps must be carried out to determine the capacity and locations of PARs. Figure 1 illustrates the general design procedure for the implementation of the PAR system. In the first step, the severe accident scenarios are selected through the probabilistic safety assessment and deterministic consideration with sound engineering judgments. The discharge locations, and rate, as well as duration of hydrogen generation are defined for each scenario. In the second step, the preliminary analyses for hydrogen mixing and distributions are performed without considering the hydrogen removal by PARs, and thus the required capacity and locations of PARs are determined in this step. In the third step, the detailed severe accident analyses for hydrogen distributions in the containment are performed considering the hydrogen removal by PARs. Sensitivity analyses are also performed for each scenario with and without operations of various safety systems such as containment heat removal systems, reactor coolant depressurization systems and safety injection systems (i.e., accumulator). The final capacity and locations of PARs are confirmed through the assessment of global FA and DDT. If the PAR system is concluded to meet the acceptance criteria, the capacity and locations are finalized through the site walkdown.

1.2 Computational Model

The key plant parameters of OPR-1000 are summarized in Table 1. There were several options of the analysis methods for designing and implementing a PAR system in nuclear power plant containments [1]. This paper adopted a lumped parameter code of the MAPP 4.0.6+ [2] because various severe accident scenarios should be considered. The containment is divided into 26 sub-volumes, and has 58 flow paths and 70 heat sinks as shown in Fig. 2. The applicability of the multi-compartment model of MAAP has been verified through an extensive comparison with other multi-dimensional analysis codes such as GOTHIC [3] in the licensing process in Korea [4]. Generally, the exact location of a PAR in a compartment is not critical for its performance because the strong convection is expected to be created by a working PAR effectively mixes the atmosphere [5]. Therefore, the containment response and hydrogen behavior can be simulated effectively with this model for a variety of severe accident scenarios.

Table 1. Key Plant Parameters of OPR-1000

Parameters	Value
Core Thermal Power [MW]	2,815
RCS Average Temperature [K]	584.7
Pressurizer Pressure [MPa]	15.5
SG Pressure [MPa]	7.38
Mass of Zr Cladding in the Core Region [kg]	24,643
Containment Free Volume [m^3]	76,618

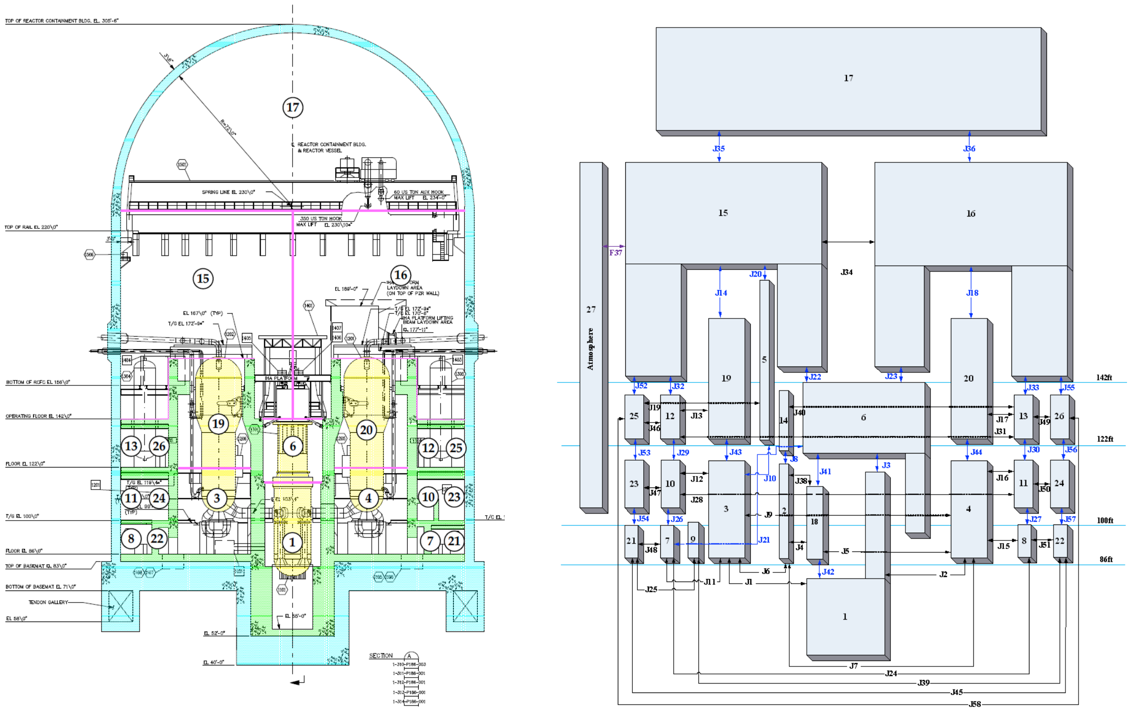


Fig.2 MAAP Multi-Compartment Model with 26 of Nodes

1.3 Hydrogen Removal Rate with PAR

In Korea, different types of PAR have been supplied by AREVA (France), CANDU Energy (Canada), KNT (Korea) and Ceracomb (Korea). The Fischer correlation is used in the current analysis because it is most conservative one among other supplier's correlations. The Fischer correlation for hydrogen removal rate is defined as [6]:

$$R_{H_2} = 13748 N \eta C_{H_2}^{1.307} \frac{P}{T} \qquad (1)$$

where R_{H2} is hydrogen removal rate (g/sec) and N, η, C_{H2}, P, T are the number of PARs, the efficiency of PARs, the molar fraction of hydrogen in H_2-H_2O-Air mixture (%), pressure (bar), and temperature (K), respectively.

In OPR-1000, honeycomb type recombiners (Ceracomb) are installed. The hydrogen removal rate of the Ceracombe PAR is defined as [7, 8]:

$$R_{H_2} = SNk(C_{H_2} - 0.15)^{1.16} P\left(\frac{273}{T}\right) \quad (2)$$

where S, k, C, P and T are the safety factor, the experimental coefficient (0.048), the volume fraction of hydrogen (%), pressure (bar) and temperaure (K), respectively. N is the size factor of PAR (N = 1, 2 or 3 if the the size of PAR is small, medium and large, respectively). In all applicable range of C, P and T, the hydrogen removal rate of the Ceracomb PAR is sufficiently higher than that of the Fischer correlation.

To consider the adverse effects on the PAR performance in severe accident conditions such as fission product poisons, aerosols, cable burn, etc, a performance degradation of 25% on the hydrogen removal rate is assumed in the current analysis. It is assumed that the PAR starts with a time delay of 15min to remove the hydrogen when the hydrogen concentration reaches to 3 vol.%. Generally the hydrogen removal rate increases with hydrogen concentration. In high concentration of hydrgen above 8%, however, it is possible to occur a local hydrogen combustion due to a high temperature of catalytst. Although a beneficial effect exists for hydrogen removal in high concentration, the hydrogen removal rate is assumed not to increase above 8% but to remain in a constant value.

To consider an oxigen starvation condition reported by OECD/NEA THAI experiment, the following PAR performance index (η_{O2}) is also considered [9]:

$\Phi \geqq 2.3$: $\eta_{O2} = 0.75 * 1.00 = 0.75$
$1.0 \leqq \Phi < 2.3$: $\eta_{O2} = 0.75 * 0.50 = 0.375$
$\Phi < 1.0$: $\eta_{O2} = 0.75 * 0.25 = 0.1875$

where Φ is oxygen surplus factor defined as 2×Oxygen/Hydrogen Concentration.

1.4 Evaluation of Global FA and DDT

After igniting the flammable gas mixture, the turbulent flame will slowly propagate along the hydrogen concentration gradient towards higher hydrogen concentration regions with intense turbulence. FA may result in a DDT. This condition may generate high-pressure loads, which could endanger the containment integrity. In the current analysis, the possibility of global FA and DDT is assessed using σ-criterion and 7λ-criterion [10].

For evaluation of the acceleration potential the following σ-index is defined as:

$$\sigma_{index} = \frac{\sigma(\bar{X}_{H_2}, \bar{X}_{H_2O}, \bar{X}_{O_2}, T)}{\sigma_{critical}(\bar{X}_{H_2}, \bar{X}_{O_2}, T)} \quad (3)$$

where the nominator is the expansion ratio of the average mixture in the specified compartment. The x_{H2}, x_{H2O} and x_{O2} are the average hydrogen, steam and oxygen concentrations in the specified compartment, respectively. The denominator is the critical expansion ratio of the average mixture. The idea in this approach is that when the $\sigma_{index} < 1$, FA is excluded, whereas there is potential for FA when $\sigma_{index} > 1$.

The potential of DDT is determined by the following 7λ-criterion:

$$\mathrm{DDT}_{\mathrm{index}} = \frac{\mathrm{L}}{7\lambda} \quad (4)$$

where L is characteristic dimension of the reaction cloud and λ is the average detonation cell size of the gas. When $\mathrm{DDT}_{\mathrm{index}} > 1$, there is a potential for deflagration-to-detonation transient.

3. Results and Discussion

2.1 Accident Scenarios and Hydrogen Generation

Since a lot of accident sequences could lead to core damage resulting in a large generation of hydrogen, it is not practical to consider all the postulated accident conditions. According to IAEA Standard Series NS-R-1, 5.31 the important sequences that may lead to a severe accident shall be identified by using a combination of probabilistic methods, deterministic methods and sound engineering judgment [11].

For OPR-1000, six (6) representative severe accident sequences are selected based on core damage frequencies (CDF) and plant damage state (PDS) from level 1 and 2 probabilistic safety assessment (PSA). The selected initial events for hydrogen control analysis are large break loss of coolant accident (LBLOCA), medium break loss of coolant accident (MBLOCA), small break loss of coolant accident (SBLOCA), total loss of feedwater (TLOFW), station blackout (SBO) and steam generator tube rupture (SGTR). Table 2 shows the summary of key event and hydrogen information of the selected accident scenarios.

Figure 3 shows the total hydrogen masses generated from both in-vessel and ex-vessel. The integrated hydrogen mass equivalent to a total of 150% of MWR (1,253kg) is considered with conservative modeling. To this end, the values of MAAP code variables related to the hydrogen generation such as FAOX, FGBYPA, FCHF, WH2MIN, etc. were selected to obtain the conservative results of hydrogen generation.

Table 2, Accident Event Summary for Selected

	LBLOCA	MBLOCA	SBLOCA	TLOFW	SBO	SGTR
Core Uncovery [s]	1,450	441	2,987	3,389	31,861	11,078
CRLP[1] [s]	5,457	3,334	7,583	7,163	43,595	18,066
Vessel Failure [s]	10,051	7,653	11,691	10,437	44,695	19,507
H2 Generation [kg]						
Total	1,253 (150%)	1,252 (150%)	1,251 (150%)	1,251 (150%)	1,250 (150%)	1,249 (150%)
In-Vessel	402 (48%)	363 (44%)	625 (75%)	625 (75%)	658 (79%)	643 (77%)
Ex-Vessel (MCCI)	851 (102%)	889 (106%)	626 (75%)	626 (75%)	592 (71%)	606 (73%)

[1] CRLP : Core Relocation to the Lower Plenum

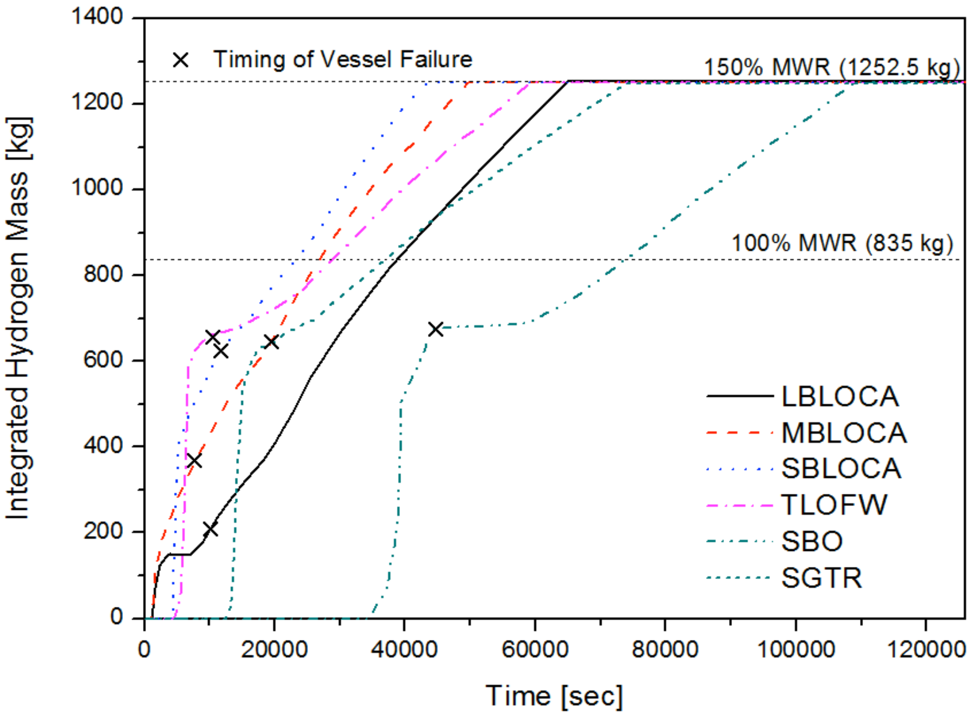


Fig. 3 Total Hydrogen Mass Generated in the Selected Accident Scenarios

2.2 Capacity and Locations of PAR

Hydrogen distribution analysis is performed for the selected severe accident scenarios. Through the analysis without the hydrogen removal by PARs, the required capacity and locations of PARs are determined. Based this analysis, a total of twenty-four (24) PARs are installed in the various locations inside the containment. There are eight (8) PARs in the containment dome, six (6) PARs in the steam generator rooms, eight (8) PARs around the annulus area and two (2) PARs in other area connecting room from in-core instrument chamber to adjacent annulus area. The final capacity and locations of PAR is confirmed through the detailed analysis stage. As the existing igniter system is not considered in current analysis, there is no hydrogen mitigation countermeasure in the analysis.

2.3 Hydrogen Distribution

Figure 4 shows the hydrogen concentrations in four representative locations: the reactor cavity (node 1 in Fig.2), the steam generator room (node 3 in Fig.2), containment dome (node 15 in Fig.2), and annulus area (node 25 in Fig.2) for SBLOCA, TLOFW and SBO. The hydrogen concentrations of other scenarios are bound to the present analysis results of current SBLOCA and TLOFW, i.e. SBLOCA is a bounding scenario for LOCAs and TLOFW is for the other transient scenarios. For TLOFW scenario, there are two hydrogen release paths: one is to the reactor drain tank (RDT) through the pressurizer safety valve (PSV) and the other is to containment atmosphere through the manual operation of a rupture disk (RD) in safety depressurization system (SDS). The hydrogen distribution for SBO scenario is also presented because of its importance after Fukushima accident. As shown in Figs. 3 and 4, SBO scenario shows less severe hydrogen concentrations compared to the other accident scenarios because of its slow hydrogen generation. In all cases although the hydrogen concentration increases rapidly, the maximum value remains sufficiently below 10%. The hydrogen distribution in each area shows a similar trend because hydrogen and air are mixed well in the containment.

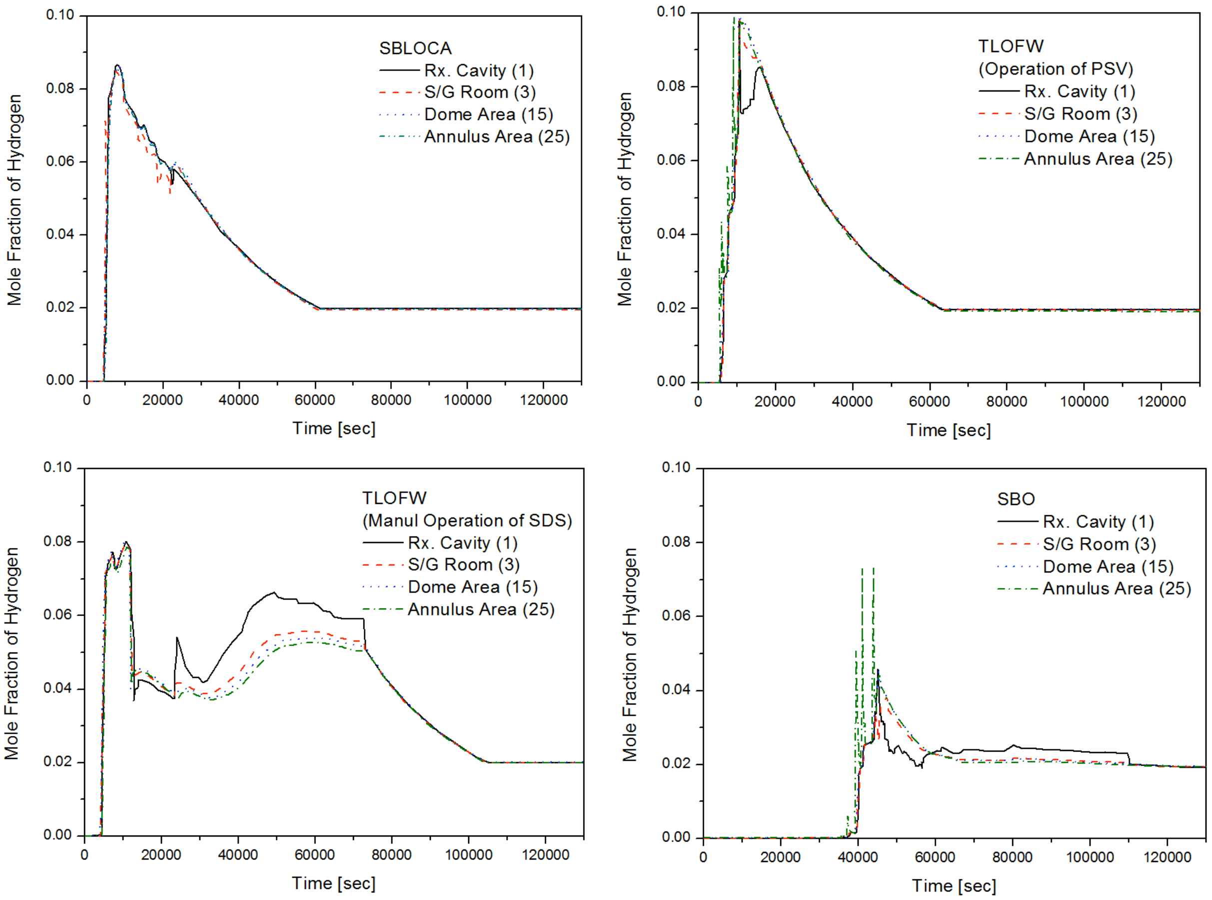
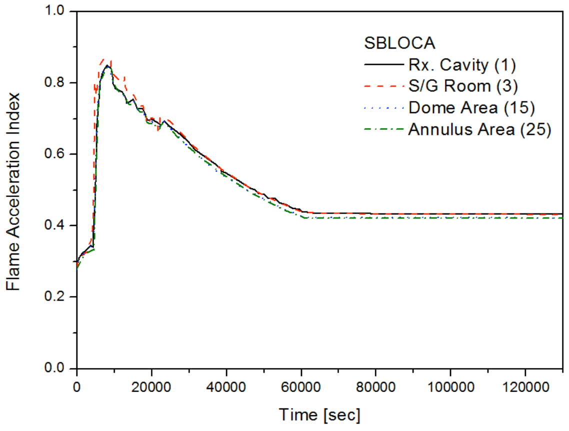


Fig. 4 Hydrogen Concentration in Representative Nodes for SBLOCA, TLOFW and SBO

2.4 Assessment of Global FA and DDT

The possibility of the global FA and DDT is evaluated by by σ-criterion and 7λ-criterion [10]. For all selected severe accident scenarios, FA and DDT indices in all the computational nodes are maintained below the limit (< 1). Figure 5 shows FA indices for SBLOCA and TLOFW in representative nodes (operation of PSV) that are bounding scenarios with respect to hydrogen concentration among six accident sequences. The DDT indices are not presented in this paper because FA indices are maintained sufficiently below the limit. There is no need of further consideration on the possibility of DDT because FA indices in all compartments are maintained sufficiently below the limit. Through the present analysis, it is concluded that new PAR system with twenty-four (24) recombiners can remove hydrogen effectively in the containment atmosphere, to prevent from global FA and DDT.



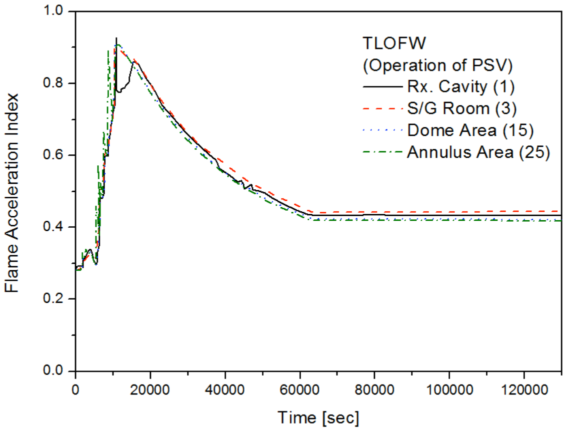


Fig.5 Flame Acceleration Index in Representative Nodes for SBLOCA and TLOFW

4. Conclusions and Recommendation

A licensed analysis method of OPR-1000 has been presented to determine the capacity and locations of PAR for the design of a hydrogen mitigation system with PAR. A lumped parameter code of MAAP 4.0.6+ has been adopted to simulate various severe accident scenarios with a 26 multi-compartment containment model. Hydrogen generations were analysed and required capacity and locations of PAR were determined for six accident scenarios selected from a combination of probabilistic and deterministic considerations. A total of twenty-four (24) PARs in the containment dome, steam generator rooms, annulus and adjacent areas was designed and the adequacy of this system has been confirmed through detailed analyses including sensitivity analyses with/without operations of safety systems such as containment heat removal systems, reactor coolant depressurization system and safety injection by accumulator, etc. Through the assessment on the possibility of global FA and DDT, it has been concluded that new PAR system with twenty-four (24) recombiners can remove hydrogen effectively in the containment atmosphere and prevent from global FA and DDT.

Further works are required in the future to develop a well-balanced analysis methodology with a combination of lumped and CFD tools focusing on the optimum locations of recombiners and local hydrogen behaviour in containment compartments.

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