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Uncertainty Analysis of APR1400 Containment Conditions for Determining Sensor Operating Range

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1. Introduction

In order to improve the safety of operating nuclear power plants, it is necessary to minimize the environmental leakage of radionuclides in severe accident condition. A lot of efforts are being made to develop a radioactive material reduction facility in the containment building to remove fission products released into the environment from containment. Since the Fukushima accident in 2011, the need for strengthening hydrogen control and management has increased, and sampling-type hydrogen monitors are being installed. However, the sampling method measurement system contains many uncertainties due to delay time and limit of the number of samples. In addition, there is no instrument for monitoring or measuring carbon monoxide (CO), which is one of the combustible gas. Therefore, in order to overcome the limitations of the existing sampling methodologies, it is necessary to monitor and process the data of combustible gases obtained from sensors based on various measurement data with calculation results database obtained by severe accident analysis.

In this study, it was intended to conduct a severe accident analysis for APR1400, which is one of the representative types of operating nuclear power plants in Korea. Accident analysis was performed on the small break loss of coolant accident (SBLOCA), which is a more conservative accident process from the viewpoint of pressurization of the containment, and MELCOR 2.2_9541 was used as the analysis tool [1,2]. Since the amount of hydrogen and fission products in containment can be varied depending on major variables related to the core degradation, it is essential to present the range of results through uncertainty analysis. Therefore, in this study, the amount of hydrogen and fission products in the containment building, including the generation of combustible gases generated through MCCI period, was evaluated. The ranges of the amounts of combustible gases (hydrogen, carbon monoxide) and fission products in the containment derived from this study will be reflected in selecting the specifications of the instruments in the containment building in the future.

2. Base case calculation

2.1 Nodalization

Nodalization of APR1400 was presented in Figure 1. As shown in the Figure 1, the reactor pressure vessel consists of 5 nodes: downcomer, lower plenum, upper plenum, core, and bypass. Two loops are existed including hot leg, cold leg, and steam generator. There are four safety injection tanks, which are initiated at the pressure lower than 4.31 MPa. Containment consists of 4 nodes including IRWST, cavity region, middle and upper regions.

2.2 Accident sequence of base case

Accident sequence of base case is presented in Table 1. There were some assumptions for conservative results in the calculation, no operator action and no external water injection. At time of 0 s, SBLOCA occurred and the water level reached TAF at 250 s. Reactor trip and RCP trip followed at about 740 s. Fuel cladding degradation started at about 3200 s and water level reached BAF at 8600 s. Lower head penetration failure occurred at 14000 s though the SITs were initiated at 13000 s. Information on the thermal-hydraulic conditions of the core and reactor coolant system at major time point is presented in Figure 2.

3. Uncertainty analysis

Since the target of this study is to evaluate the amount of hydrogen and fission products in the containment building in the event of an accident, it is difficult to secure reliability with the base case calculation results of the representative accident. Therefore, it is essential to perform uncertainty analysis by selecting major variables that can affect the amount of hydrogen and fission products in the containment. In this study, uncertainty analysis results for major variables are presented using DAKOTA, an uncertainty analysis program built into the Symbolic Nuclear Analysis Package (SNAP, Version 3.1.1) developed by U.S.NRC [3, 4].

3.1 Analysis method

One of the biggest factors influencing the amount of hydrogen and fission products in a containment building is the degree of fuel degradation, which is related to several sensitivity coefficients (SC) related to core melting in MELCOR. In the COR package, which is a part of the MELCOR program related to core melting,

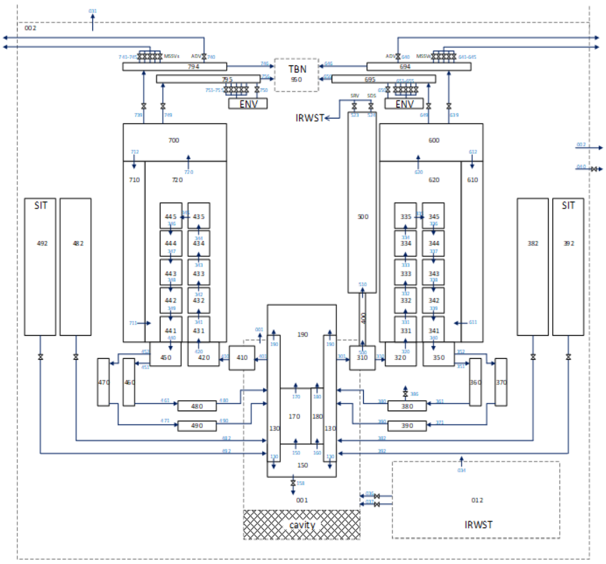

Fig. 1 Nodalization of APR1400 for MELCOR calculation

Table 1 Major event in base case calculation

Event	Time (s)
SBLOCA	0.0
Water level reached top of active fuel (TAF)	250.1
Reactor trip	745.8
RCP trip, MSIV close	746.4
CET=923 K	3200.1
Fuel gap release start	3253.4
First formation of particulate debris	3914.2
Water level reached bottom of active fuel (BAF)	8640.1
Safety injection tank (SIT) initiation	12840.0
Lower head failure	13963.8
Calculation end	72600.1

sensitivity coefficients are provided so that the user can adjust the sensitivity to the main phenomenon and reflect it in the calculation. Among them, major variables that can affect the core damage process are selected as shown in Table 2. The SC1001 was selected because it was directly related to the amount of hydrogen generated as a variable related to the oxidation of metal cladding. The variables (1001-5) and (1001-6) selected in this analysis which are values related to the reference temperature that determines the oxidation model applied to the calculation of the oxidation reaction of the cladding, and uncertainty analysis was performed on these values. SC1131 is a parameter related to a phenomenon in which the molten

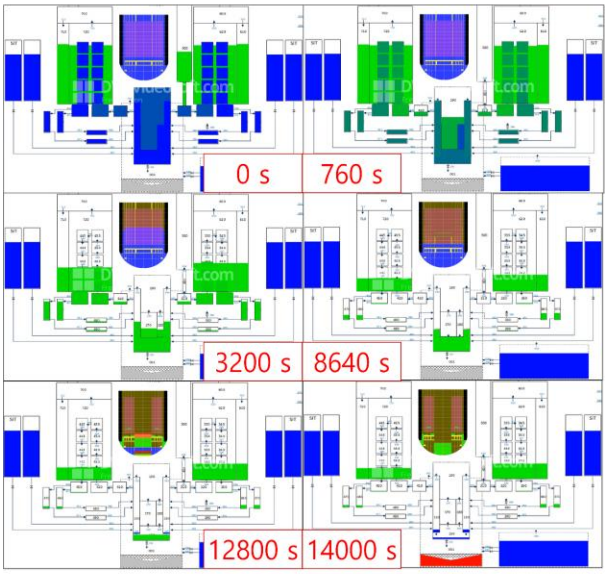

Fig. 2 Core and RCS thermal hydraulic status with accident progression

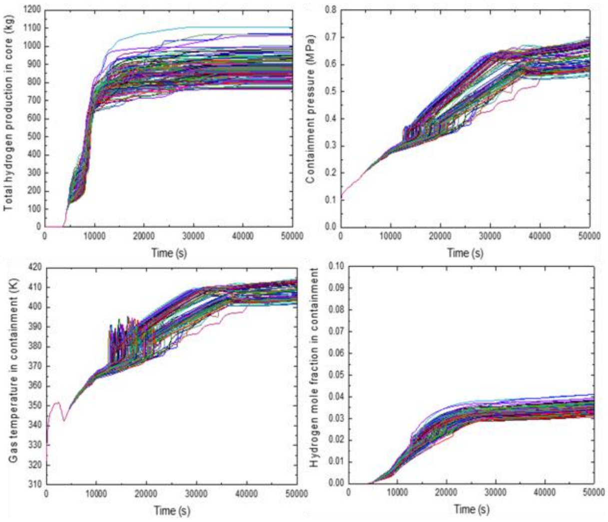

Fig. 3 Uncertainty calculation results with oxidation related variables

core material may be held in other oxidized structures. Among the variables selected in this analysis, SC1131(2) and 1131(4) are the variables that determine the maximum temperature at which ZrO_2 and SSOx can hold the molten material, respectively, and SC1131(6) is a variable that determines the maximum temperature at which the molten Zr contained in other structures can be captured. Since the variables selected in this analysis are directly related to the oxidation of the cladding and can directly affect the melting progress of the core, it is judged to be closely related to the amount of hydrogen and fission products in the containment building.

The main inputs for performing the uncertainty analysis are presented in Table 3. A non-parametric method was used and the number of sample counts was determined by applying the 1st order Wilks formula

Table 2 Uncertain variables

SC	variable	details	Default value
1001 (5,1)	Metallic cladding oxidation rate constant coefficients	Upper temperature boundary for low temperature range	1853.0 K
1001 (6,1)		Lower temperature boundary for low temperature range	1873.0 K
1131 (2)	Molten material holdup parameters	Maximum ZrO2 temperature permitted to hold up molten material in CL	2400.0 K
1131 (4)		Maximum steel oxide temperature permitted to hold up molten materials	1700.0 K
1131 (6)		Maximum ZrO2 temperature permitted to hold up molten Zr in CN, CB, SH, SS, FM, or NS components	2100.0 K
1132 (1)	Core component failure parameters	Temperature to which oxidized fuel rods can stand in the absence of unoxidized Zr in the cladding	2500.0 K
1132 (2)		Temperature at which fuel rods fail, regardless of the composition of the cladding	3100.0 K

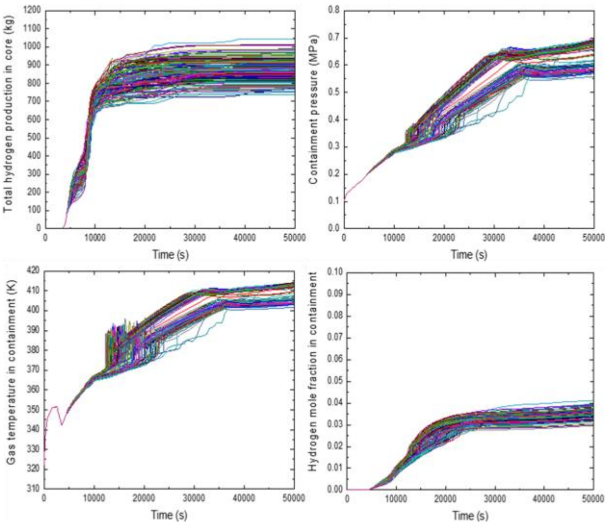

Fig. 4 Uncertainty calculation results with corium behavior related variables

method. In this calculation, 95% probability and 95% confidence were applied, and 4 Figure of Merits (FOMs) were selected and a total of 153 calculations in each case were performed. The FOM considered in this analysis is the amount of hydrogen generated in the core, the pressure of the containment, the gas temperature in the containment, and the concentration of hydrogen in the containment. The masses of radioactive aerosols and gases in the containment were also taken into account in the further calculations. Based on the base case calculation results, most accident events occurred before 50,000 seconds, so in this uncertainty calculation, the calculation time and the resulting value derivation time are set to 50,000 seconds. Table 4 presents the selection range of uncertainty variables considered in this analysis. Variable values were determined through Monte-Carlo sampling within the considered range and calculations were performed. A total of 2 cases were performed for uncertainty calculation.

3.2 Analysis results

3.2.1. Zr oxidation related variables

In this calculation, uncertainty variables SC1001(5) and SC1001(6) were selected, uncertainty calculations were performed for a total of 153 cases, and the results were obtained for the FOMs. However, 4 calculations out of 153 calculations did not proceed until 50,000 seconds and the results were evaluated based on a total of 149 calculations. Figures 3 presents the uncertainty evaluation results for the amount of hydrogen generated in the core. The maximum amount of hydrogen generated in the core for 50,000 seconds was estimated to be about 1105.6 kg. In the Figures 3, the pressures and gas temperatures in the containment building are presented, respectively. The maximum pressure and temperature of the containment were evaluated to 0.694 MPa and 414.2 K, respectively. The mole fraction of hydrogen in the containment upper region is also shown in the Figures 3. The containment building was largely consists of three nodes with IRWST. The maximum

Table 3 Pearson coefficient analysis

Pearson coefficient	COR-DMH2-TOT	CVH-P_9	CVH-TVAP_9	CVH-X.6_9
1001(5,1)	-0.11206	-0.02498	-0.02337	-0.06854
1001(6,1)	-0.05395	-0.08746	-0.08341	-0.03362
1131(2)	0.240757	-0.1127	-0.1185	0.311488
1131(4)	0.103396	0.125834	0.12287	0.096692
1131(6)	-0.08082	-0.07943	-0.07151	-0.0876
1132(1)	0.051386	-0.05318	-0.05181	0.038955
1132(2)	0.037022	-0.00188	0.003978	-0.01436

hydrogen concentration at the top of the containment was calculated to be about 4.12%.

3.2.2. Molten material behavior related variables

In this calculation, uncertainty variables SC1131(2, 4, 6) and SC1132(1, 2) were selected, uncertainty calculations were performed for a total of 153 cases, however, 5 calculations out of 153 calculations did not proceed until 50,000 seconds and the results were evaluated based on a total of 148 calculations. Figures 4 presents the uncertainty evaluation results for the amount of hydrogen generated in the core. The maximum amount of hydrogen generated in the core for 50,000 seconds was estimated to be about 1045.2 kg. In the Figures 4, the pressures and gas temperatures in the containment building are presented, respectively. The maximum pressure and temperature of the containment were evaluated to 0.558 MPa and 401.6 K, respectively. Figures 4 show the mole fraction of hydrogen in the containment upper region. The maximum hydrogen concentration at the top of the containment was calculated to be about 4.11%

3.3 Pearson coefficient

Pearson coefficients between the uncertainty variable and FOMs were considered in the calculation, and the values are presented in Table 3. Overall, it was analyzed that there was a negative correlation between the selected uncertainty variable and the FOM values, and the correlation was not large. Among them, the SC1001(5) had a correlation coefficient of about -0.112 with the total amount of hydrogen generated from the core, which was higher than other cases. Uncertainty variable most closely related to the hydrogen generation amount in the core and the mole fraction of hydrogen in the containment is the SC1131(2), the maximum temperature of ZrO_2 that can hold the molten material in the cladding material. In addition, although the coefficient was not as high as that of SC1131(2), it was confirmed that SC1131(4) (the maximum temperature of SSOx that could hold the molten material) had a significant correlation with the amount of hydrogen generated and the mole fraction of hydrogen in the containment building.

4. Conclusions

APR1400 severe accident calculation results are presented to evaluate the operating condition of the instruments in the containment building. For this purpose, MELCOR input was prepared for APR14000, and reliability of input was secured through steady-state calculation. Base case calculation were made for SBLOCA based on reasonable assumptions. In addition, major variables that can affect the amount of hydrogen generated and the release of core melting and fission products were selected, and the range of target variables in the containment building was derived by performing uncertainty calculations on the major variables. This study needs to be supplemented for considering other important uncertain parameters in other packages in the future with considering references [5, 6].

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