Hydrogen behavior in a large-dry pressurized water reactor containment building during a severe accident

HSU Wen-Sheng[1], CHEN Hung-Pei[1], HUNG Zhen-Yu[1], and LIN Hui Chen[1]

1. Institute of Nuclear Engineering and Science, National Tsing Hua University, R.O.C 101 Section 2, Kuang Fu Rd., HsinChu, R.O.C (E-mail: saabsaab11@hotmail.com)

Abstract: Following severe accidents in nuclear power plants, large quantities of hydrogen may be generated after core degradation. If the hydrogen is transported from the reactor vessel into the containment building, an explosion might occur, which might threaten the integrity of the building; this can ultimately cause the release of radioactive materials. During the Fukushima Daiichi nuclear accident in 2011, the primary containment structures remained intact but contaminated fragments broke off the secondary containment structures, which disrupted mitigation activities and triggered subsequent explosions. Therefore, the ability to predict the behavior of hydrogen after severe accidents may facilitate the development of effective nuclear reactor accident management procedures. The present study investigated the behavior of hydrogen in a large-dry pressurized water reactor (PWR). The amount of hydrogen produced was calculated using the Modular Accident Analysis Program. The hydrogen transport behavior and the effect of the explosion on the PWR containment building were simulated using the Flame Acceleration Simulator. The simulation results showed that the average hydrogen volume fraction is approximately 7% in the containment building and that the average temperature is 330 K. The maximum predicted pressure load after ignition is 2.55 bar, which does not endanger the structural integrity of the containment building. The results of this investigation indicate that the hydrogen mitigation system should be arranged on both the upper and lower parts of the containment building to reduce the impact of an explosion.

Keyword: severe accident; hydrogen explosion; PWR; FLACS

1 Introduction

Following a severe accident in a nuclear power plant, large amounts of hydrogen could be generated owing to core degradation. Historically, the Three Mile Island accident in 1979 and the Fukushima Daiichi nuclear disaster in 2011 both experienced this phenomenon of hydrogen generation. Hydrogen can be produced from the following sources: zirconium-steam reaction, radiolysis of water, corrosion of metals, and degassing of the primary loop coolant water. Hydrogen and oxygen can form a flammable or explosive gas mixture, depending on the H_2-air-steam composition. The generated hydrogen is inevitably transported into the containment building and has the potential to explode. This poses a threat to the integrity of the containment building due to the overpressure following an explosion and can lead to the release of a large amount of radioactive material. The prediction of hydrogen behavior during the conditions following a severe accident will help in devising adequate accident management procedures (Royl, P., *et al.*, 2000). To develop improvement strategies, an accurate distribution of hydrogen and the pressure distribution of the hydrogen explosion are required.

Computational fluid dynamics (CFD) codes can be used to predict the hydrogen distribution in a containment building during the course of a hypothetical severe accident. The results can be used to obtain an estimate of the local hydrogen concentration in the various zones of the containment building. In this manner, the risk associated with hydrogen can be determined, and safety-related measurements and procedures can be assessed. The Modular Accident Analysis Program (MAAP) is a family of integrated computer models used for the analysis of severe accidents in nuclear power plants. The initial development of the code began in the 1980s and it has been developed according to the principle that all reactor systems and structures (including the engineered safety systems and natural heat sinks should be represented (MAAP, 1990). The Flame Acceleration Simulator (FLACS) tool is a CFD code that solves the compressible Navier–Stokes equations on a 3D Cartesian grid using a finite volume method

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(GexCon, 2013). FLACS is well validated and most commonly used to assess the explosion pressure (Hansen, 1999). It is a dedicated explosion simulator that provides hydrogen dispersion models that are very suitable for calculations of hydrogen explosion cloud sizes and for assessing hydrogen explosion risk (Prankul M., *et al*., 2009, 2010). In this study, the amount of hydrogen produced following an accident was first calculated using MAAP. The hydrogen transport behavior and the effect of the explosion on the PWR containment structure were then simulated using FLACS.

For typical severe accident sequences in large plants, flammable mixtures are generally predicted by the distribution analysis for specified time and space regions. To generate any potential risk to the containment building, an ignition event is necessary to start the combustion process. Ignition sources can be classified into random and deliberate (igniters). When igniters are included in the analysis, the location and time of the ignition event will be determined by the evolution and expansion of the H_2-air-steam cloud in the containment building. Without deliberate ignition, the location and time of the ignition event cannot be predicted in a deterministic manner. A number of potential ignition sources can exist in a severe accident environment such as electrical equipment, bursting pipes, and core-melt particles. The reliable prediction of the ignition event is important because it defines the end of the non-reactive phase of the accident and the beginning of the reactive phase, which can potentially damage the containment building.

2 PWR containment model

The simulation case is based on the Maanshan nuclear power plant located on the south coast of Taiwan. The plant is a large-dry pressurized water reactor (PWR) and has a power capacity of 951 MWe. The plant has a spherical containment structure with a height and diameter of approximately 60 and 40 m, respectively. The free gas volume is approximately 100,000 m^3.

A simplified 3D model was developed for FLACS v10.0. The cross section of the FLACS model is shown in Fig. 1. The containment structure was discretized using a 3D Cartesian mesh with 154,468 cells (46 *x*, 46 *y*, and 73 *z* mesh). The average cell volume was 1 m^3. No ventilation is provided.

In order to calculate the hydrogen production, the MAAP computer code was used. MAAP gives the production of hydrogen as a function of time. The investigated scenario was a station blackout accident (SBO) with safety injection and spray failure due to a stuck-open power-operated relief valve (PORV). This hypothetical scenario was designed to cause rapid core melting and used to calculate the amount of hydrogen generation. Hydrogen generation and release begins at approximately 41,500 s. During the next 13,000 s, approximately 325 kg of hydrogen is released into the containment structure (Fig. 2). The variation of the mass flow rate with time is shown in Fig. 3.

Hydrogen gas is highly flammable and will burn in air at a wide range of concentrations between 4% and 75% by volume (Lewis B., *et al*., 1987). In this study, three different ignition times and four ignition locations were simulated to predict the pressure load on the containment building.

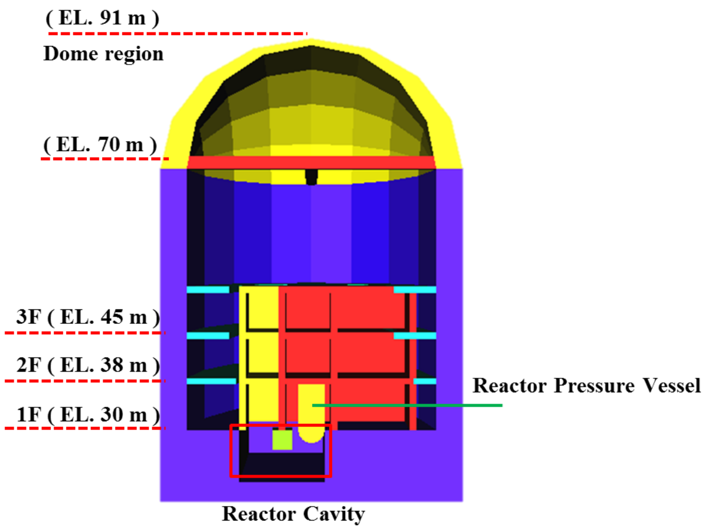

Fig. 1 Cross section of 3D reactor and containment model used in FLACS.

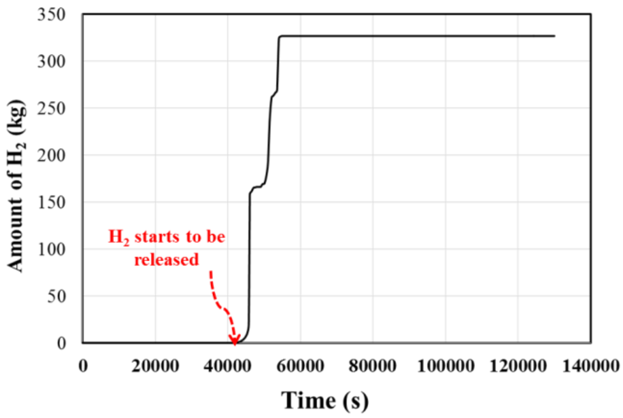

Fig. 2 The variation in the amount of hydrogen generated with time.

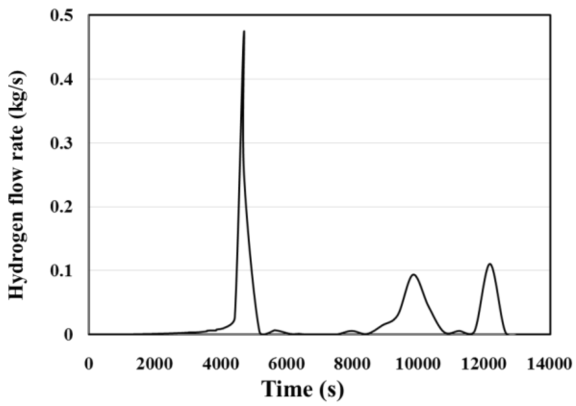

Fig. 3 The variation of the mass flow rate with time.

3 Results and discussion

The containment building initially contains dry air at 1 bar and 313 K. The vertical H_2 jet enters from the first floor (EL. 30 m), at a temperature of 393 K. The H_2 distribution in the containment area was calculated using FLACS. It was observed that the hydrogen concentration increased rapidly at approximately 4,200 s. At about 4,800 s, the hydrogen volume fraction in the first to third floors of the containment reaches 4%, which is above the ignitable limits (Fig. 4). The hydrogen flows upward to the dome region owing to momentum and buoyancy. The hydrogen volume fraction therefore drops below the lower explosive limit at 5,000 s. With the increase in the amount of hydrogen release, the volume fraction once again reaches the LEL after 8,000 s. The concentration reached a peak value of approximately 7.5% and slowly reduced to approximately 7% at around 13,000 s, at which point the simulations were stopped. Fig. 5 is a 2D cross section of the hydrogen distribution. The density of hydrogen is much lower than air and it therefore rises up to the dome region owing to buoyancy. As a result, there is a lower hydrogen concentration at the first floor after the release is stopped.

In the simulation of hydrogen explosion, three different ignition times and four ignition locations were simulated to predict the pressure load of the containment building. The first ignition time occurred at 4,800 s, at which time the hydrogen inventory was 157 kg in the building. The initial temperature was 321.25 K, and the hydrogen volume fraction was approximately 4%. The details are summarized in Table 1. Four ignition points were prescribed in the containment building (Fig. 6). Fig. 7 shows the predicted pressure loads at different ignition times and points. The predicted pressure loads range from 0.16–2.59 bar and increase with the total H_2 mass in the containment. The predicted pressure loads following ignition located in first floor are higher than other floors as a result of shock wave reflections and structural response. When the ignition occurred at 16,000 s on the first floor, the maximum predicted pressure load was 2.55 bar. The containment building in the Maanshan nuclear power plant is made of prestressed concrete with a 1.2 m wall thickness. The tensile strength of the containment wall is 8.5 bar. Based on the simulation results, the maximum predicted pressure load after ignition is 2.55 bar, which does not endanger the integrity of the containment building.

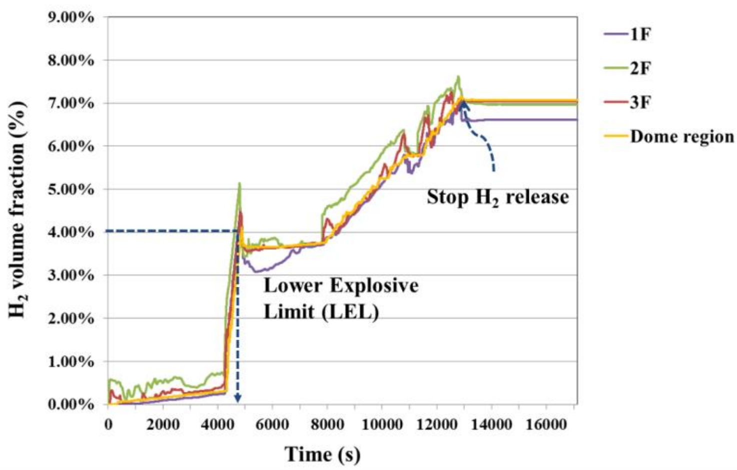

Fig. 4 Change in hydrogen volume fraction over time in containment building. Concentration sensors are located on the ground of the 1st floor (1F), 2nd floor (2F), 3rd floor (3F), and the center of the dome region (Dome region).

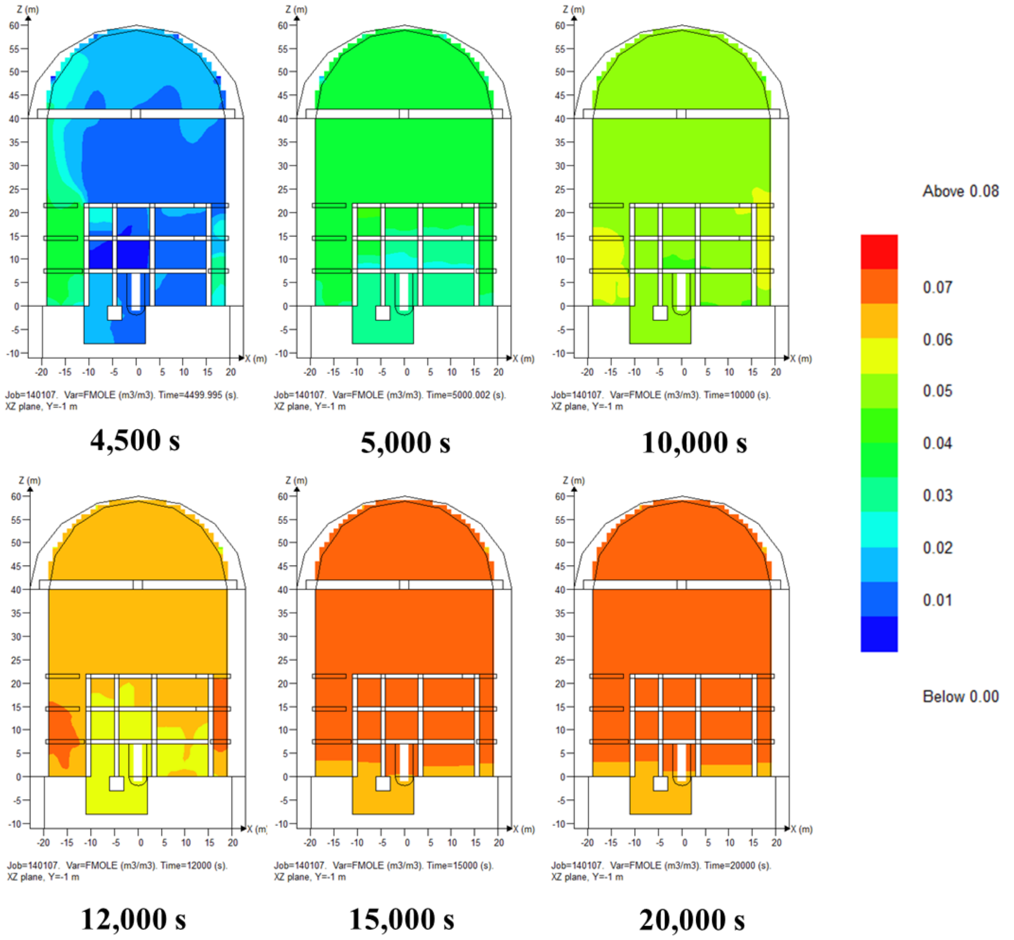

Fig. 5 2D cross section of hydrogen distribution.

Table 1 The ignition times and initial conditions

Ignition Time (s)	H_2 Inventory (kg)	Temperature (K)	H_2 volume Fraction (%)
4800	157	321.25	1F：4.35%
			2F：5.14%
			3F：4.38%
			Dome Region：3.67%
10000	236	325.38	1F：5.37%
			2F：5.84%
			3F：5.13%
			Dome Region：5.25%
16000	325	329.85	1F：6.64%
			2F：6.95%
			3F：7.02%
			Dome Region：7.07%

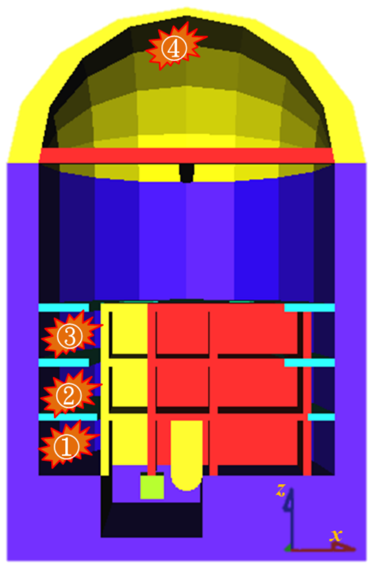

Fig. 6 The ignition points in the containment building. Points 1–3 are located on floors 1–3, respectively, and point 4 is located in the dome region.

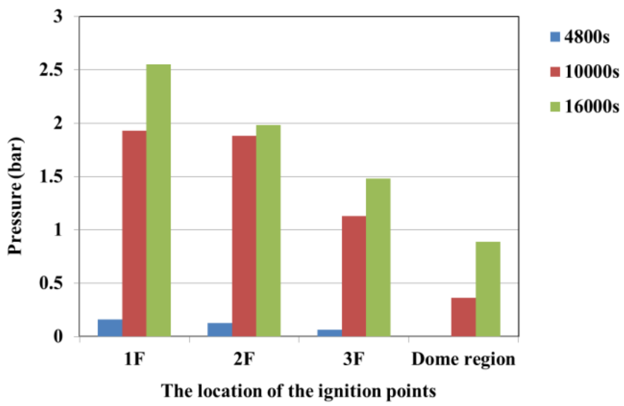

Fig. 7 Predicted pressure loads at different ignition time and points.

4 Conclusion

The containment analyses were divided into two parts: the hydrogen distribution and the pressure loads after hydrogen explosion in severe accidents. FLACS simulations of a hypothetical station blackout accident at the Maanshan nuclear power plant have shown that the maximum hydrogen concentration peaks at 7.5% during the hydrogen release process. The hydrogen concentration of the dome region was higher due to buoyancy. The maximum pressure in 12 analyzed cases was compared with the failure pressure of the containment building. In this study, 325 kg hydrogen was burned. When the ignition point was located on the first floor, it caused a large pressure load in the containment. The maximum predicted pressure load after ignition was 2.55 bar, which occurred at an ignition time of 16,000 s. This does not endanger the structural integrity of the containment building. It should be noted that the highest pressure load was caused by the ignition on the first floor because of shock reflections and the structural response. Based on this investigation, it is recommended that the hydrogen mitigation system should be arranged at both the upper and lower parts of the containment building to reduce the explosion impact.

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