NUCL SCI TECH (2017) 28:131
DOI 10.1007/s41365-017-0287-7

Improvements to hydrogen depleting and monitoring system for Chinese Pressurized Reactor 1000

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Received: 6 July 2016 / Revised: 2 December 2016 / Accepted: 14 December 2016 / Published online: 9 August 2017

Abstract We evaluate the hydrogen depletion ability of the hydrogen depletion system for Chinese Pressurized Reactor 1000 (CPR1000), which has been applied in nuclear power plants with pressurized water reactors; moreover, we introduce a new device that can continuously monitor hydrogen concentration inside the CPR1000 containment building. Experimental studies show that a moveable hydrogen autocatalytic recombiner alone can sufficiently deplete hydrogen under the condition of a design-basis accident, and 33 passive autocatalytic recombiners placed in the areas of high hydrogen concentration satisfy the hydrogen depletion requirements under the condition of a beyond-design-basis accident. Meanwhile, the hydrogen concentration monitoring system is designed and installed based on the approach of detecting the temperature increase caused by the catalytic reaction of hydrogen. In conclusion, the hydrogen depletion capacity of the CPR1000 meets the requirements, and the system's safety can be enhanced by the improved hydrogen concentration monitoring system.

This work was supported by the Priority Academic Program Development of Jiangsu Higher Education Institution.

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Keywords Nuclear power plant · Hydrogen depleting system · Hydrogen monitoring · CPR1000

1 Introduction

If serious accidents occur in a nuclear power station, due to the decomposition and oxidation of the reactor fuel cladding at high temperature, a large amount of hydrogen will be generated by the reaction of zirconium and water, as well as by the reaction of melted core debris and concrete [1]. At a certain temperature and hydrogen concentration in the containment building, combustion or explosion may occur, posing a serious threat to the containment building [2].

On March 11, 2011, due to an earthquake and subsequent tsunami, a nuclear disaster rated level 7 on the International Nuclear Event Scale (INES) occurred in the Unit 3 reactor of the Fukushima Daiichi nuclear power plant [3, 4]. During this accident, a large amount of hydrogen accumulated at the upper part of the reactor building by the reaction of zirconium and water, causing explosions in the reactor building. As a result, radioactive substances were released into the atmosphere [5, 6]. This accident has forced the administrators of every nuclear power plant to pay more attention to the performance of hydrogen depletion equipment [7, 8]. According to the Code of Federal Regulation (10 CFR§50.44), all hydrogen depletion systems must be designed with the ability to limit the hydrogen concentration in containment during an accident, even if an equivalent amount of hydrogen is released by the reaction of 100% fuel-clad-coolant. The hydrogen concentration must be kept less than 10 vol% and distributed to maintain the containment's structural integrity and reduce the impact of an accident [9]. The International Atomic Energy Agency (IAEA) requires all new nuclear power plants to install a hydrogen control system [10]. A prevailing technique is installation of passive autocatalytic recombiners to dilute the hydrogen gas for large dry-type containments. The hydrogen igniter or hydrogen dilution equipment will be activated as auxiliary equipment when necessary [11–14]. Passive autocatalytic equipment, which operates when the accidents occur without an external energy supply or human intervention, has been adopted by many nuclear power stations. The main devices in this category include the FR90/1 series (Siemens, Germany), KATAREK (Sulzer, Switzerland), and AECL (AECL, Canada), among others [15].

In this paper, the operating principles of a hydrogen depletion system under the conditions of design-basis accidents and beyond-design-basis accidents are introduced. The performance of hydrogen depletion system for the Chinese Pressurized Reactor CPR1000, a pressurized water reactor (PWR) with independent intellectual property rights, is analyzed. Based on the analysis, a hydrogen monitoring system is designed, installed, and tested to ensure the effectiveness of the third safety barrier of the pressure boundary, namely the reactor containment.

2 CPR1000 description

The CPR1000 is a large commercial PWR modified from the French M310 PWR, which was introduced by China Guangdong Nuclear Power Group in the Daya Bay and Ling'ao nuclear power stations. Each CPR1000 PWR contains a 1000-MW ratio and a three-loop nuclear steam supply system (NSSS). The core thermal capacity of each reactor is 2895 MWt, and the net heat output of the NSSS system is 2905 MWt. The reactor containment of a CPR1000 PWR has a cylindrical prestressed concrete structure with a volume of 49,400 m^3. A 4-mm-thick steel plate is bedded on its inner surface. The reactor containment is applied to isolate the reactor's pressure vessel and all related equipment from the environment [16]. Through August 2016, up to 28 sets of CPR1000 PWRs have been installed and operated in China.

3 Evaluation of hydrogen depletion performance

3.1 Design-basis accident conditions

When a loss-of-coolant accident (LOCA, a type of design-basis accident) occurs, the spray cooling system is activated to cool the air in the containment if the absolute pressure inside is over 0.24 MPa. A NaOH solution with a concentration of 0.6% by mass is used as the sprayed liquid in order to reduce the airborne radioactivity inside the containment. On this condition, hydrogen will be generated by the reaction of NaOH solution and the aluminum used in the cabling. If the hydrogen concentration increases to 4 vol%, combustion or explosion will occur between days 11 and 22 after the LOCA.

For the CPR1000 PWR, an interface is provided for the moveable hydrogen autocatalytic recombiner in the fuel plant hall at an elevation of +0.00 m for easy installation. The major components of the hydrogen autocatalytic recombiner are fixed on a moveable trolley for convenience, including the hydrogen depletion fan, cooling condenser, and demister. Meanwhile, to ensure the safety of a nuclear plant, the hydrogen autocatalytic recombiner should be activated in a timely manner with the approval of the plant's emergency command department after the occurrence of a LOCA. Under the suction of the hydrogen depletion fan, the air containing hydrogen is cooled after entering the cooler condenser and subsequently flows to the demister for gas–liquid separation. Next, the hydrogenous air without droplets will be forced into the catalytic reactor by the pressure of hydrogen depletion fan. Owing to the heating from the air heater at the bottom of the catalytic reactor, the air temperature increases to 120 °C. Thus, by chemical combination, the hydrogen and oxygen in the air will be converted to water with the catalysis of the hydrogen depletion catalyst XQ-IIIG, a precious-metal carrier composed mainly of Ti, Pt, and Pd. With the decrease in the hydrogen concentration, the mixed gas will return to the containment atmosphere to prevent radioactive air from being released into the external environment. The residence time of hydrogen in the recombiner is roughly 10 s. A schematic of a moveable hydrogen autocatalytic recombiner is presented as shown in Fig. 1.

If the inlet hydrogen concentration is below or equal to 4 vol%, the moveable hydrogen autocatalytic recombiner is activated. At the designed air flow rate of 119 m^3/h/STP, where STP denotes standard temperature and pressure, the hydrogen depletion efficiency of the moveable hydrogen autocatalytic recombiner is over 95%. The contents inside the recombiner are stabilized and the system is at steady state after running for 2 h. Under this condition, the hydrogen concentration at the outlet of the recombiner is reduced to less than 0.1 vol%. The definition of hydrogen depletion efficiency is expressed by

$$\eta = \frac{Q_1 - Q_2}{Q_1} \times 100\%, \tag{1}$$

where η is the hydrogen depletion efficiency, Q_1 the inlet concentration of the recombiner, and Q_2 the outlet

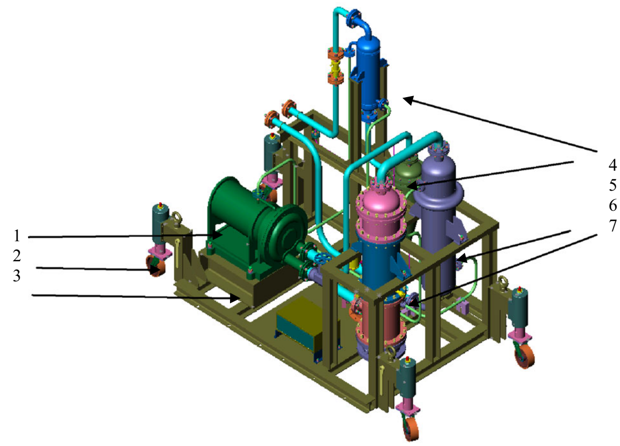


Fig. 1 (Color online) Schematic of moveable hydrogen autocatalytic recombiner. *1* Hydrogen depletion fan, *2* lift device, *3* connection box, *4* cooler condenser, *5* vapor liquid separator, *6* air cooler, *7* catalytic reactor

concentration of the recombiner. All parameters are expressed as percentages.

During the experiments, hydrogen with a volume concentration of 0.5 vol% was generated and pumped into the inlet of the air duct connected to the recombiner. Subsequently, the air flow rate in the duct was adjusted to 119 m^3/h and the temperature of the catalytic reactor was set between 100 and 115 °C. When a steady state was achieved, the outlet hydrogen concentrations of the recombiner were measured by a GC Agilent 490 gas chromatograph after 1, 3, and 5 min. The experiments on hydrogen with volume concentrations of 1.0, 2.0, and 3.5 vol% were conducted in the same way. The experimental process showed that the running time required to achieve a steady state in the recombiner is approximately 20–30 min, which is significantly less than 2 h, the design value.

The experimental results for the recombiner's hydrogen depletion performance under the conditions described above are presented in Table 1.

As shown in Table 1, the hydrogen depletion efficiency of the moveable hydrogen autocatalytic recombiner is 100% under the design conditions, which exceeds the value of 95% stated by the manufacturers. Therefore, according to the hydrogen depletion performance, the CPR1000 PWR moveable hydrogen autocatalytic recombiner meets the safety requirements under the condition of a LOCA design-basis-accident.

3.2 Beyond-design-basis accident conditions

Under the condition of a beyond-design-basis accident, multiple malfunctions may occur in the safety system that can potentially lead to a more severe risk of hydrogen

Table 1 Experimental results for moveable hydrogen autocatalytic recombiner hydrogen depletion performance (July 16, 2012)

Hydrogen source concentration (vol%)	Temperature (°C)			Air flow rate (m^3/h)	Hydrogen concentration (vol%)	
	Control point	Catalytic bed	Cooling water		Inlet	Outlet
0.5	105.1	111.2	36	117.9	0.60	0
	154.6	120.8	36	117.1	0.60	0
	142.2	116.4	35	117.2	0.54	0
1.0	118.8	118.0	36	115.0	1.3	0
	137.9	147.1	37	115.0	0.91	0
	151.4	139.2	36	114.2	1.03	0
2.0	115.2	156.9	37	111.8	2.10	0
	107.4	177.5	38	114.6	2.17	0
	147.2	169.1	38	111.0	2.10	0
3.5	115.0	181.5	37	110.2	3.71	0
	103.1	193.7	37	110.7	3.44	0
	142.7	192.5	38	110.7	3.40	0

combustion or explosion that the moveable hydrogen autocatalytic recombiner cannot handle. Here, 33 groups of passive autocatalytic recombiners (PARs) are included in the CRP1000 as a containment hydrogen depletion system to ensure that the hydrogen concentration in the containment is kept below a level of 10 vol%. The PARs are composed of 11 XQ-FN/30 and 22 XQ-FN/50 units. Table 2 lists the performance parameters obtained at 50 °C air temperature and 0.15 MPa air pressure.

As shown in Table 2, the activation threshold value of the PARs is 8 vol%, less than the hydrogen explosion concentration of 10 vol%, because the activation should be applied before the hydrogen concentration reaches the explosion point. Based on the catalytic principle, the PARs deplete the hydrogen with the newly developed full metal catalysts, which can act passively by using the temperature gradient force caused by exothermal reactions [15]. The PARs are distributed at several locations including the locations of the pressurizer stabilizer compartment, pressurizer compartment, reactor coolant pump compartment, steam generator compartment, and the steel platform of the reactor building. There are three reasons for applying this distribution method: (1) The air circulation speed is accelerated in the compartment; (2) the mixed gas is evenly distributed in the entire containment environment; and (3) the peak regional concentration of hydrogen is reduced.

When hydrogen concentration in the containment approaches a specific value under the condition of a beyond-design-basis accident, the mixed gas containing hydrogen will flow upwards through the PARs. The mixed gas enters the bottom of the PARs and discharges from the top. Supplementary heat- and corrosion-resistant plates with an active catalyst coating inside the PARs cause the mixing of hydrogen, oxygen, and catalyst, forming only steam after contact. The PAR, shown in Fig. 2, also controls the hydrogen concentration in the containment within a safety range.

In order to evaluate the capability of the CPR1000, the accident process calculation and the hydrogen source term analysis are carried out for large-break LOCA (LB-LOCA), middle-break LOCA (MB-LOCA), small-break LOCA (SB-LOCA), station blackout (SBO), steam generator tube rupture (SGTR), and main steam line rupture (MSLB) conditions. Taking LB-LOCA as an example, under the most serious condition, 2119 kg of hydrogen was generated in the reactor pressure vessel (RPV) and 2400.3 kg of hydrogen entered the containment atmosphere. The generating rate of the hydrogen is shown in Fig. 3.

Fig. 2 (Color online) Passive autocatalytic recombiner

A model was established using TONUS(TOkamaks and NUmerical Simulations) software. The objective of the TONUS project is to deal with complex mathematical and

Table 2 Performance parameters of passive autocatalytic recombiner under design conditions

Model	XQ-FN/30	XQ-FN/50
Catalysis element number	80	160
Fluid flow rate (0.15 MPa, 50 °C) (m^3/h)	833	1667
System tolerance temperature (°C)	600	
System tolerance pressure (MPa)	0.7	
System tolerance moisture (vol%)	100	
Hydrogen depletion capacity (0.15 MPa, 4 vol% H_2) (kg/h)	2.4	5.4
Initial H_2 threshold value (vol%)	1.0–2.0	
Stop threshold value (vol%)	0.5	
Ignition threshold value (vol%)	8	

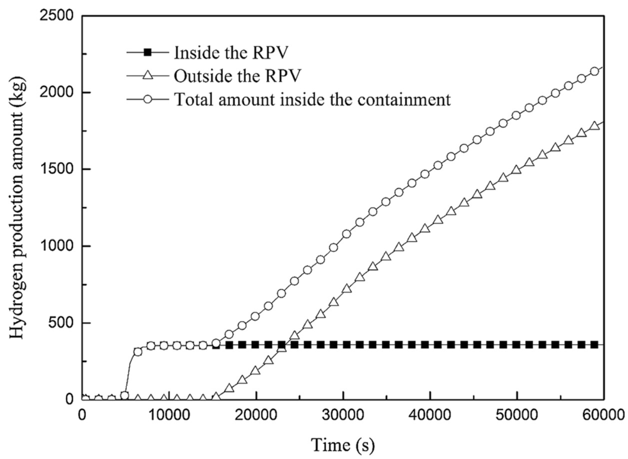


Fig. 3 Variation of hydrogen amount with time inside the containment (LB-LOCA)

computing issues. The simulations were carried out under the operating conditions with and without the XQ-FN recombiner. The variations in hydrogen percentage by volume are shown in Fig. 4.

As shown in Fig. 4, without the recombiner, the amount of generated hydrogen soon approaches the value of 100%, which equals the value produced by the reaction of zirconium and water. Under the same conditions, when 33 groups of PARs are erected inside the reactor containment, the highest hydrogen concentration remains below the maximum safe value of 10 vol%.

The accident processes of LB-LOCA and MB-LOCA are similar in that the hydrogen is generated earlier and more rapidly than in other accident conditions. Under other accident conditions, hydrogen is generated later and more slowly. The increasing rate of hydrogen concentration can be restrained effectively by the PARs, and the amount of hydrogen can thereby be controlled below the edge of the

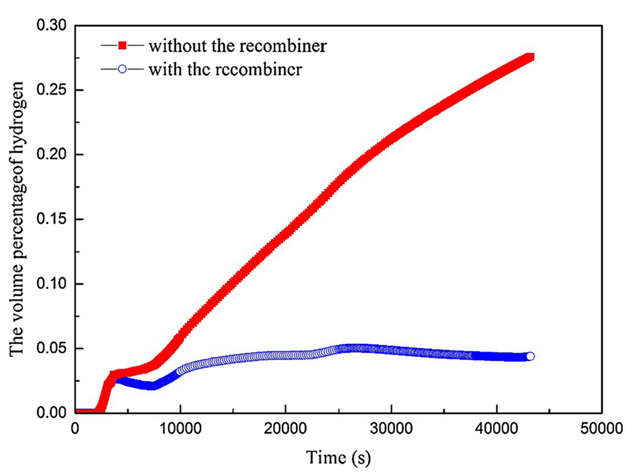


Fig. 4 (Color online) Percentage by volume of hydrogen inside the containment atmosphere with and without the recombiner

combustion zone, which means conflagration cannot occur in the reactor containment [17].

Moreover, the experiment demonstrated that PARs normally operate at lower depletion efficiency owing to the existence of fission products such as iodine, selenium, tellurium, and stibium, while PARs normally operate at higher depletion efficiency due to the existence of CO. In an aerosol environment, when the concentration is no less than 10 g/m^3, PARs can satisfy the requirements of hydrogen depletion. Therefore, the hydrogen depletion system of the CPR1000, composed of 33 PARs, can easily meet the safety requirements under the condition of a beyond-design-basis accident.

4 Improvement of hydrogen monitoring equipment

Under accident conditions, the key factor in the prevention of future potential nuclear accidents is to measure the hydrogen concentration inside the reactor containment accurately and effectively. The US regulation 10 CFR§50.44 mandates that “Equipment must be provided for monitoring hydrogen in the containment. Equipment for monitoring hydrogen must be functional, reliable, and capable of continuously measuring the concentration of hydrogen in the containment atmosphere following a significant beyond-design-basis accident for accident management, including emergency planning” [9]. The Regulatory Guide 1.7-2007 requires that “the hydrogen monitors should be able to assess the degree of core damage during a beyond-design-basis accident and confirm that random or deliberate ignition has taken place” [18]. Since complicated conditions always exist in a serious accident, it is difficult to develop the equipment for monitoring hydrogen deployed in nuclear facilities throughout the world.

There are two measurement methods for hydrogen concentration inside the containment: sampling of extracted air and sampling of air within the containment. The hydrogen detectors using the former method are installed outside the containment, and all the processes of pretreatment and analysis are performed outside. An example of such a system is the HERMETIS (AREVA, Germany) [19]. The hydrogen detectors that employ the latter method are distributed inside the containment, while the transfer signals are received outside the containment for further processing to obtain the hydrogen concentration. The direct measurement can be divided into three methods according to the operating principle. Method 1 is to detect the resistance variation with heat catalytic electrodes, method 2 is to detect the temperature variation of the chemical reaction of hydrogen and oxygen, and method 3 is to detect the resistance variation of a hydrogen absorption material [20]. For example, the AREVA WS-85 hydrogen concentration sensor is designed based on method 1, while the hydrogen concentration sensor JMU 10 from Russia for beyond-design-basis accidents is designed based on method 3 [21].

Owing to the low density of hydrogen, the hydrogen from different compartments will be mixed in the top area of the containment [22]. The large 20-m-high space inside the reactor containment can be selected as the monitoring zone for hydrogen concentration. The steam generator compartment is close to the reactor containment core, near the pressurizer compartment and reactor coolant pump compartment. Therefore, it is convenient to monitor post-accident hydrogen concentration in different zones. In addition, it is convenient to install hydrogen monitoring equipment on the top platform of the steam generator compartment. CH-15 equipment, installed in the CPR1000 PWR for hydrogen concentration monitoring after an accident, has a measuring range of 0–10 vol%; thus, an alarm will be triggered when the hydrogen concentration in the vicinity of the sensor exceeds 10 vol%.

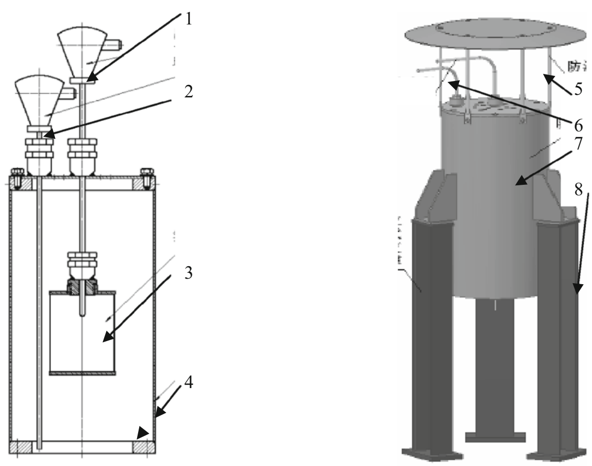


Fig. 5 Two- and three-dimensional diagrams of catalytic hydrogen sensor. *1* Thermoelement for measuring catalytic reaction, *2* thermoelement for measuring circumstance temperature, *3* hydrogen response element, *4* protecting barrel, *5* spray prevention cap, *6* thermocouple, *7* protecting barrel, *8* vertical poling

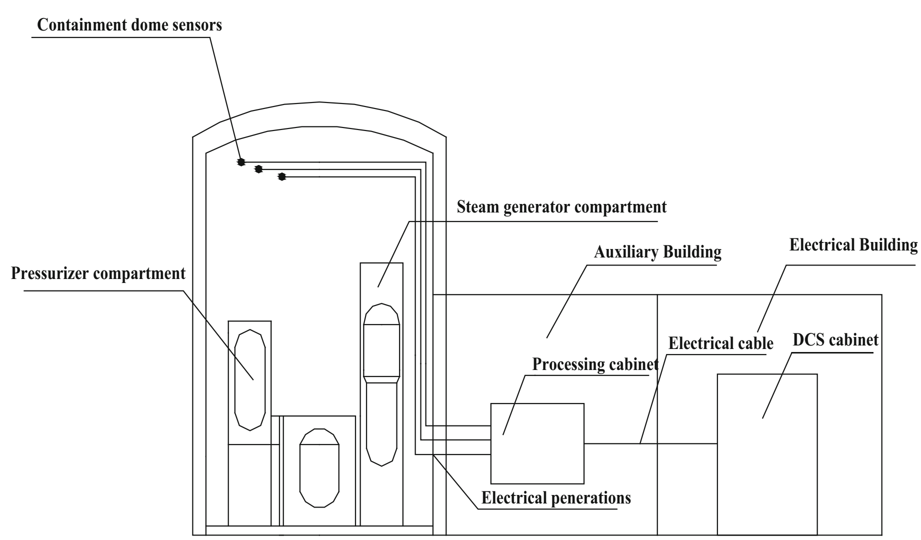
The CH-15 detects the temperature increase caused by the exothermic reaction of hydrogen and oxygen. A catalyst is used as the hydrogen response element, and, in addition, the released heat accelerates the action of oxygen and hydrogen. The exothermal reaction equation is [23]

$$H_2(g) + 0.5O_2(g) \xrightarrow{\text{Ti,Pt, and Pd}} H_2O(g) + 241.2\ \text{kJ}. \tag{2}$$

The higher the hydrogen concentration, the higher the detected reaction temperature. Hence, the temperature signals received by the detector can be directly used to detect the hydrogen concentration. The construction of the detector is shown in Fig. 5.

When the temperature signal is transmitted outside the containment, the hydrogen concentration inside the containment can be calculated by a signal processing unit, and the concentration will be displayed in the main control room in real time. Monitoring points are positioned on the top platform of each steam generator, at a height of 34 m. The CH-15 hydrogen concentration monitoring equipment is composed of three hydrogen concentration detectors installed inside the containment and a signal processing cabinet outside the containment. The signals from each detector can be either displayed on the screen directly or transmitted to the external system after calculating and compensating. The distribution of the equipment is shown in Fig. 6. The hydrogen concentration sensors are distributed inside the containment, enhancing the reliability of the acquired data.

Fig. 6 Distribution of hydrogen concentration measurement system inside the containment



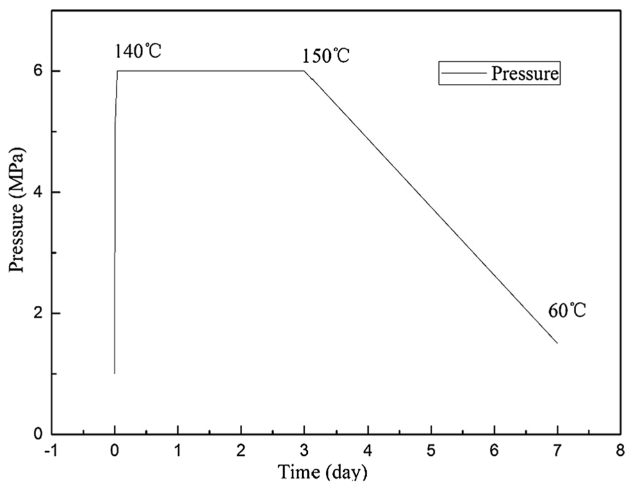


Fig. 7 Variation of pressure inside the containment with time under a beyond-design-basis accident condition

Table 3 Performance test results for CH-15 hydrogen concentration monitoring equipment (vol%)

Test results	Hydrogen source concentration		
	3 vol% (after 25 min)	6 vol% (after 3 min)	10 vol% (after 2 min)
Sensor 1	2.6	5.5	9.5
Sensor 2	2.9	6.2	10.6
Sensor 3	2.7	6.0	10.2

The performance of the CH-15 hydrogen concentration monitoring equipment was examined under the conditions listed in Fig. 7.

The test results are listed in Table 3, which shows that the response time of the CH-15 hydrogen concentration monitoring equipment is only 2 min when the hydrogen concentration is 10 vol%, under the condition of a beyond-design-basis accident. The maximum deviation of the measurement accuracy is only 0.6 vol%, and the response time decreases rapidly with increasing hydrogen concentration. Therefore, CH-15 equipment satisfies the requirements of monitoring hydrogen concentration under the condition of a beyond-design-basis accident.

5 Conclusion

The hydrogen depletion capability and hydrogen concentration monitoring system of the CPR1000 PWR inside the containment under the conditions of a design-basis accident and a beyond-design-basis accident were evaluated in this paper. The conclusions are as follows:

(1) Under the condition of a design-basis accident, the moveable hydrogen autocatalytic recombiner can satisfy the hydrogen depletion requirements.

(2) Under the condition of a beyond-design-basis accident, the groups of passive autocatalytic recombiners can satisfy the hydrogen depletion requirements.

(3) Based on the experience obtained from Fukushima Daiichi nuclear disaster, a CH-15 hydrogen concentration monitoring system has been manufactured and installed in a CPR1000 unit in order to directly monitor the hydrogen concentration inside the containment in real time. The hydrogen concentration is assessed in line with the principle of temperature variation due to catalytic combination of hydrogen and oxygen. The deployment of this sensing equipment improves the hydrogen monitoring capability under the condition of a beyond-design-basis accident, enhancing the system safety of CPR1000 units.

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