Research on Hydrogen Risks in Large Advanced Passive Pressurized Water Reactor

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ABSTRACT

Severe accidents in nuclear power plants pose significant threats due to hydrogen generated by the zirconium-water reaction. This study focuses on the Large Advanced Passive Pressurized Water Reactor, evaluating hydrogen risks within various containment compartments under typical severe accident scenarios. The effectiveness and potential drawbacks of current hydrogen control strategies are also assessed. Simulation results indicate varying hydrogen risks across compartments. In confined spaces such as the In-Containment Refueling Water Storage Tank, hydrogen accumulation presents a heightened risk. Although the existing hydrogen control system effectively mitigates hydrogen-related risks, its failure necessitates alternative strategies, such as shutting down the Passive Containment Cooling System to promote steam accumulation and suppress hydrogen flammability. Nevertheless, this action may lead to elevated containment pressure and temperature, compromising containment integrity.

Keywords: Large Advanced Passive Pressurized Water Reactor, Severe accident, Hydrogen risk, Hydrogen control system, Containment pressure

I. Introduction

In the realm of nuclear power generation, ensuring the safety of nuclear power plants is of utmost importance. Among the various potential threats, hydrogen risk during severe accidents in nuclear power plants, especially in passive pressurized water reactor (PWR), has attracted significant attention in recent years.

Japan used the MAAP code to analyze hydrogen distribution in containment under severe accidents, showing that proper igniter placement minimizes pressure impacts from hydrogen combustion [1]. Dehjourian et al. simulated a LBLOCA at Beznau NPP and found combined use of spray systems and recombiners enhances hydrogen mitigation efficiency [2]. Joseph Amponsah employed ANSYS CFX to numerically investigate the substantial risks to containment and peripheral infrastructure integrity resulting from hydrogen release during severe accidents in light water reactors (LWRs) [3].However, most research focuses on Loss of Coolant Accidents (LOCA), with limited exploration of scenarios like Station Blackout (SBO) and Direct Vessel Injection (DVI) line breaks.

This paper establishes a passive PWR model and examines hydrogen risks under SBO and DVI accidents. The study also evaluates the implications of PCS shutdown as a mitigation measure.

II. Analysis method

Hydrogen risk analysis typically involves numerical simulations and experimental validation [4]. T Szabó coupled MELCOR with GASFLOW by developing an interface, enabling the function of receiving source terms from MELCOR during operation and feeding back the containment pressure to MELCOR [5]. The Energy Institute of the Netherlands Joint Research Centre evaluated the hydrogen mitigation measures in the VVER - 440/213 containment using GASFLOW, CFX, and Fluent programs respectively [6].

This study utilizes a severe accident simulation code to model a typical passive PWR, emphasizing hydrogen release points and their effects on containment compartments. The role of the hydrogen control system and the consequences of shutting down the PCS are also analyzed.

II.A. Nuclear Power Plant System Model

This study employs an integrated accident analysis code to establish a nuclear power plant model, including the Reactor Coolant System (RCS), engineered safety features, and the containment. The RCS consists of the pressure vessel, reactor core, steam generators, pressurizer, and main coolant piping. The engineered safety facilities primarily include: a four-stage Automatic Depressurization System (ADS), two Core Makeup Tanks (CMTs), an In-Containment Refueling Water Storage Tank (IRWST), a Passive Residual Heat Removal System (PRHRS), two Accumulators (ACCs), and associated piping.

The containment interior is divided into nine compartments (numbered 1 – 9), sequentially as follows: two SG compartment, CMT compartment, reactor cavity, IRWST compartment, upper space of the containment, A - train PXS compartment, B - train PXS compartment, and CVS (Chemical and Volume Control System) compartment. Three control volumes outside the containment, numbered 10 - 12, simulate the Passive Containment Cooling System (PCS), representing the PCS upper compartment, PCS rising section, and PCS descending section respectively. Moreover, thirty containment flow passages are set up to simulate air - water circulation within the containment.

Hydrogen generation is modeled as a function of fuel temperature, initiating when zirconium-steam reactions occur at temperatures above 1300 K. The oxide layer growth follows a parabolic law, and the reaction rate constant κ is defined as [7]:

$$K = A\exp\left(-\frac{B}{RT}\right) \tag{1}$$

Where: A is pre - exponential factor, B is activation energy, R is universal gas constant, and T is absolute temperature.

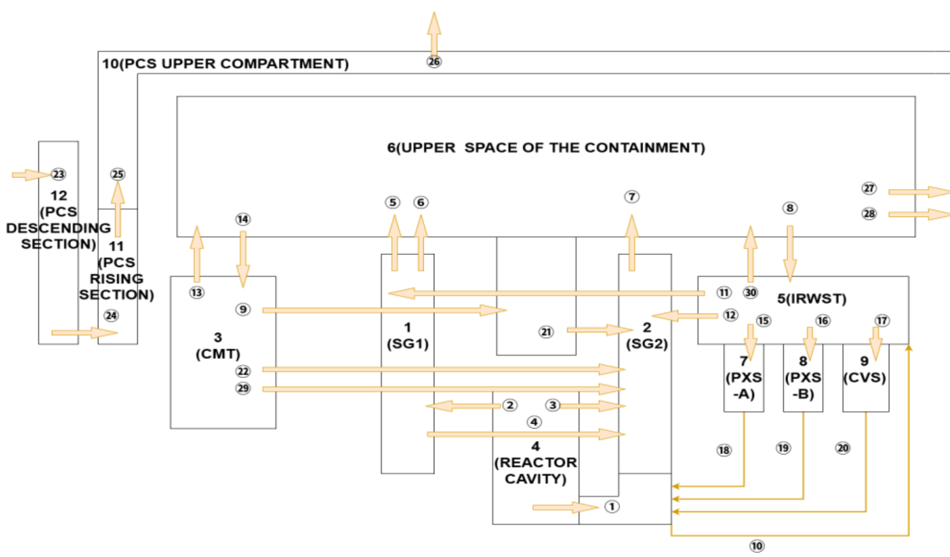

FIGURE 1 Containment Node Division

II.B. Hydrogen risk criteria

The Shapiro diagram is employed to evaluate hydrogen-air-steam mixture flammability [8]. Generally speaking, the formation conditions of a combustible gas mixture are as follows: when the water vapor content is less than 30%, the hydrogen concentration must exceed 4%; when the water vapor content is between 30% and 60%, the hydrogen concentration should be between 4% and 12%; and when the water vapor content exceeds 60%, the mixed gas is considered to be completely inert and cannot be ignited. The relationship is expressed as shown in Equation (2) and (3):

$$\mathrm{NF}_{\mathrm{H_2O}} < 60\% \tag{2}$$

$$\mathrm{NF}_{\mathrm{H_2}} \geqslant 4\% + \max\left[0, \frac{8}{30}\left(\mathrm{NF}_{\mathrm{H_2O}} - 30\%\right)\right] \tag{3}$$

Where: NF_{H20} is steam volume fraction, NF_{H2} is hydrogen volume fraction.

II.C. Severe accident sequences

This paper analyzes two typical severe accident scenarios in passive pressurized water reactors: Station Blackout Accident (SBO) and Direct Vessel Injection (DVI) Line Break Accident. To investigate the effects of different hydrogen release locations on combustion risks, comparative studies were conducted under SBO conditions with two configurations: failure of the fourth-stage ADS valves versus full opening of all ADS valves. The accident assumptions are as follows:

TABLE I. Severe Accident Sequences and Conditional Assumptions

Accident Sequence	SBO（ADS1-3）	SBO（ADS1-4）	DVI
Initiating Event	Loss of All Power Supplies	Loss of All Power Supplies	DVI Line Break
PRHR	N	N	N
ADS (1-3)	2/2	2/2	0/2
ADS4	0/4	4/4	0/4
CMT	2/2	2/2	1/2
ACC	2/2	2/2	1/2
Gravity Injection/Recirculation	0/2	0/2	0/2
PCS	Y	Y	Y
Hydrogen Control System	N	N	N

During SBO (ADS1-3) and DVI accidents, hydrogen is released into the IRWST compartment and the PXS compartment respectively. Since both compartments feature flow restrictions, they are ideal representatives for studying hydrogen - related risks in flow - restricted compartments during severe accidents.

III. Hydrogen risk analysis

III.A. Station Blackout Accident (SBO)

FIGURE 2 shows temporal hydrogen volume fraction changes in the IRWST and upper compartments. When only ADS1 - 3 valves are opened, core - generated hydrogen enters the IRWST. During the hydrogen release phase, a significant amount of hydrogen (82 %) initially accumulates in the IRWST compartment. Subsequently, the hydrogen diffuses into the containment atmosphere. Concurrently, the containment hydrogen concentration rises to 6.5 %, then gradually decreases and stabilizes at 5.3 % due to further diffusion to other compartments.

When ADS1 - 4 valves are opened, most hydrogen goes directly into the containment through the stage - 4 valve. The hydrogen volume fraction in the upper containment space peaks at 7.2% and ultimately stabilizes at 6.2%. Meanwhile, the IRWST peak concentration drops to 3.2%, much lower than the ADS1 - 3 scenario.

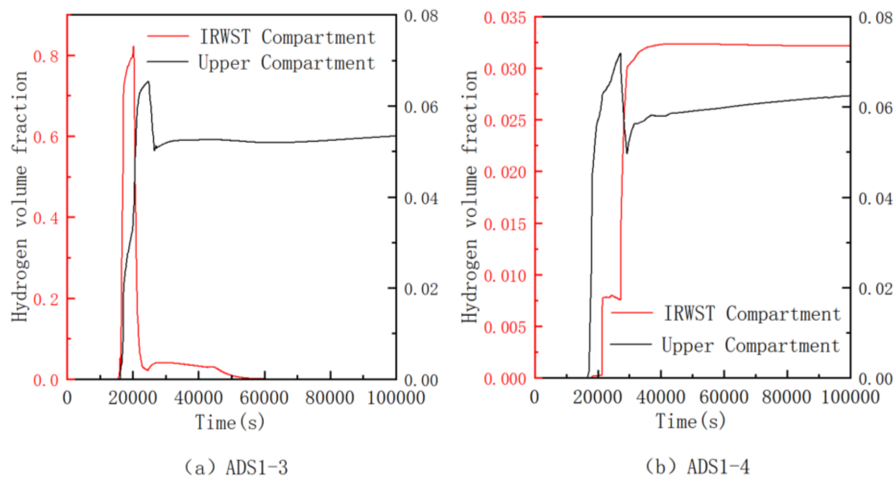

FIGURE 2. Hydrogen volume fraction in IRWST and Upper compartment under SBO scenarios

FIGURE 3 shows hydrogen combustion modes via the Shapiro diagram. The containment's upper space represents the well-mixed compartment, and the high - H_2 IRWST compartment represents the flow - restricted one.

For the 1 - 3 ADS valve scenario, the upper - containment H_2 concentration stabilizes at 5.3% later, slightly entering the combustion region. In the IRWST, H_2 stays in the combustion region for 700 s during the early rise and nears the deflagration region. In the 1 - 4 ADS valve case, the upper - containment H_2 stabilizes at 6.2%, also slightly entering the combustion region. As most H_2 releases directly into the containment, the IRWST H_2 concentration is low, keeping it out of the combustion region.

Comparative analysis reveals that during SBO accidents, the partial-opening configuration (ADS1-3) poses significantly higher hydrogen combustion risks in the IRWST compartment than the full-opening configuration (ADS1-4).

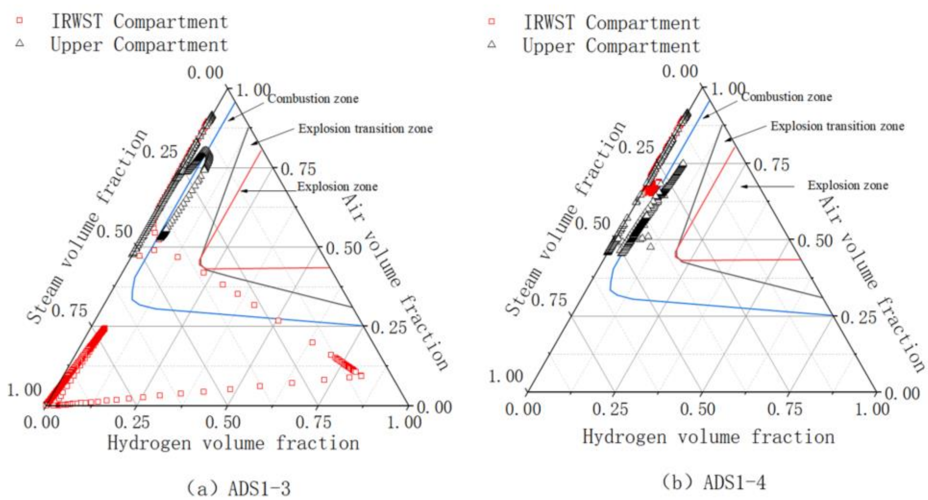

FIGURE 3. Hydrogen Combustion Modes under SBO scenarios

III.B. Direct Vessel Injection (DVI) Line Break Accident

FIGURE 4 (a) shows temporal hydrogen volume fraction changes in the IRWST and upper compartments. During this accident sequence, a DVI pipeline break and closed ADS1 - 4 valves force hydrogen release into the PXS compartment. Given its small size and flow restrictions, the PXS compartment sees a 92% concentration peak. As hydrogen diffuses into the containment, PXS concentration drops while the upper - containment concentration rises, stabilizing at 8.2%.

FIGURE 4 (b) shows hydrogen combustion modes via the Shapiro diagram. The upper - containment space represents the well - mixed compartment, and the PXS compartment represents the flow - restricted one. During the later accident stage, upper - containment H_2 stabilizes at 8.2%, entering the combustion region and nearing the deflagration - transition zone. In the PXS compartment, its small size, flow restrictions, and high initial water - vapor level prevent combustion at first. As H_2 concentration surges, there's insufficient air for combustion. Only later, as H_2 and water-vapor levels drop, does it enter the combustion region.

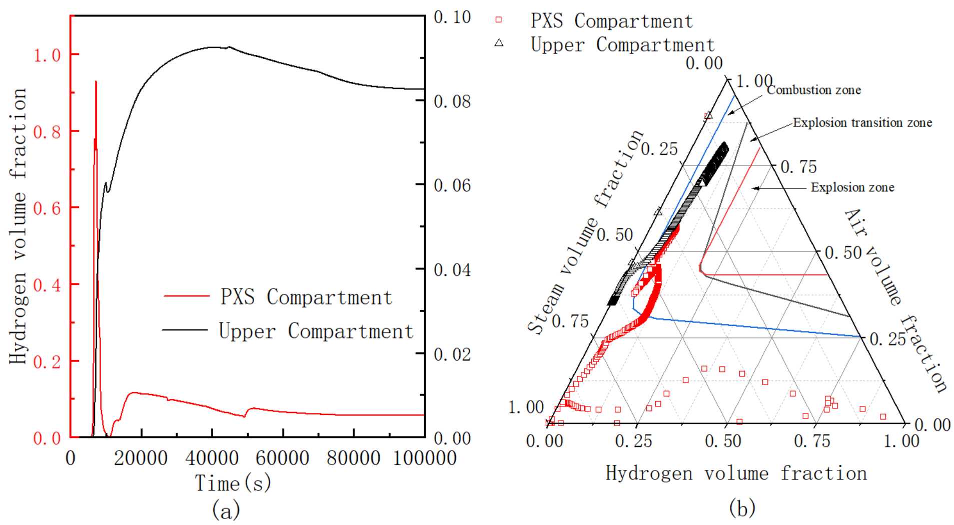

FIGURE 4. Hydrogen volume fraction and Combustion Modes under DVI scenarios

IV. Risk mitigation measures

Typical passive pressurized water reactors use a hydrogen control system to mitigate hydrogen risks. Each compartment is equipped with two hydrogen igniter subsystems, each consisting of 33 units and powered independently. Only one set runs during operation; the other serves as backup. The configuration of igniters is presented in TABLE II. To verify the system's effectiveness, we put it into operation. Below are the hydrogen concentrations in compartments and combustion modes under the aforementioned scenarios.

TABLE II. Igniter placement configuration

Compartment Name	Number of igniters
SG ROOM 1	4
SG ROOM 2	5
CMT Compartment	5
CAVITY	0
IRWST Compartment	4
UPPER Compartment	12
PXS-A Compartment	1
PXS-B Compartment	1
CVS Compartment	1
PCS upper compartment	0
PCS rising section	0
PCS descending section	0

IV.A. Research on the Effectiveness of Hydrogen Control System

Figures 5 and 6 illustrate that activation of the hydrogen igniter system reduces hydrogen concentrations in both SBO (ADS1-3) and DVI scenarios.

In the SBO (ADS1-3) accident, the peak hydrogen concentration in the IRWST compartment drops to 74%, and the hydrogen concentration in the upper space of the containment drops to 4.1%. The hydrogen combustion modes in both compartments are basically out of the combustion zone, and the hydrogen risk is mitigated.

In the DVI pipeline break accident, due to the action of the hydrogen igniters, the hydrogen concentration in the upper space of the containment decreases to 4.1%, and the risk is mitigated. However, as the number of igniters in the PXS compartment is small, there are no significant changes in the peak hydrogen concentration and combustion mode in the PXS compartment, which still remains in the combustion zone.

Therefore, the existing hydrogen control system of typical passive pressurized water reactors can basically mitigate the hydrogen risk under severe accidents, but the mitigation effect in the PXS compartment is not obvious due to limited ignition capacity and poor ventilation in the PXS compartment, increasing the number of igniters may enhance hydrogen removal efficiency.

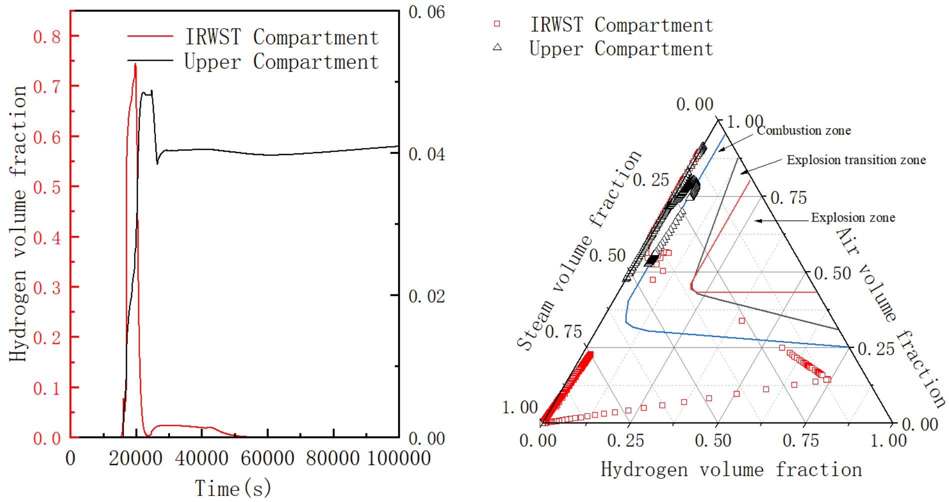

FIGURE 5. Hydrogen volume fraction and Combustion Modes under SBO(ADS1-3) scenarios (Hydrogen Control System)

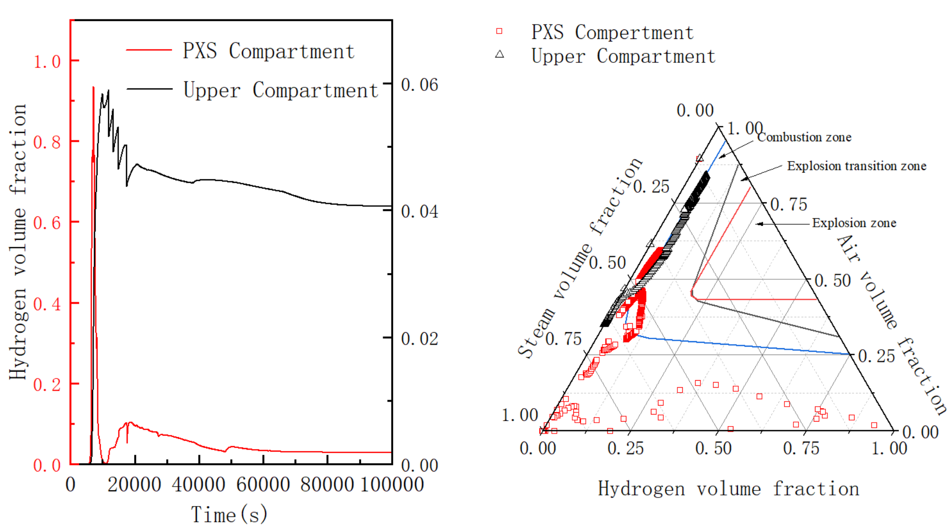

FIGURE 6. Hydrogen volume fraction and Combustion Modes under DVI scenarios (Hydrogen Control System)

IV.B. The Influence of PCS on Hydrogen Risk

When the igniters fail, steam volume fraction can be increased by closing the PCS to mitigate the hydrogen risk. This section conducts research on the aforementioned SBO (ADS1-3) condition. In this condition, hydrogen generation occurs mainly between 16,000 s and 17,000 s, and the igniters have already failed. After shutting off the PCS, the hydrogen volume fraction and combustion modes in both the IRWST compartment and the upper space of the containment are as follows:

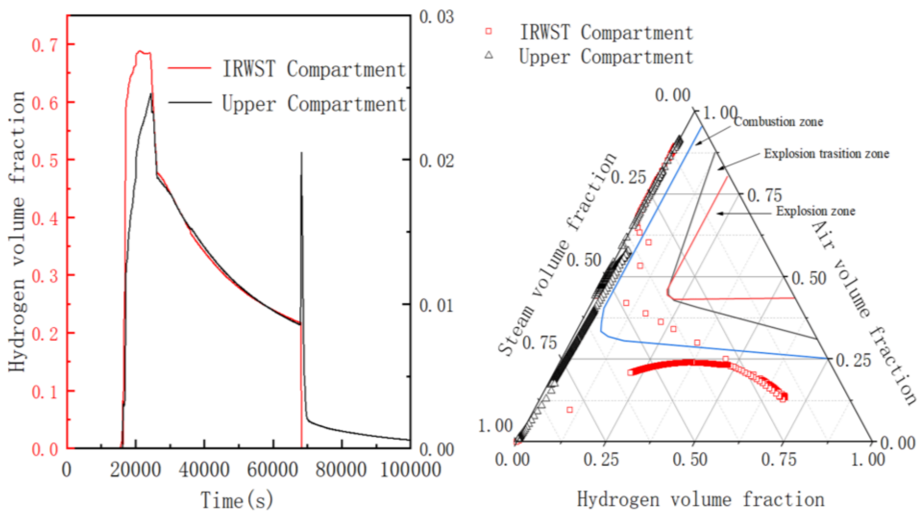

FIGURE 7. Hydrogen volume fraction and Combustion Modes under SBO(ADS1-3) scenarios (PCS Shut Down)

As can be observed, with the PCS shut down, water vapor entering the containment isn't condensed, leading to a large accumulation. This significantly reduces the hydrogen concentration, moving the combustion mode far from the combustion zone and easing the risk. High containment pressure slows hydrogen diffusion from the IRWST, causing its hydrogen concentration to drop slowly and remain in the combustion zone for a while.

While shutting down the PCS mitigates hydrogen risks in the containment, restricted compartments (e.g., IRWST) show limited improvement due to high pressure suppressing hydrogen diffusion, causing sustained high concentrations in the combustion zone. Additionally, this approach can cause overpressure in the containment, the containment pressure is as follows:

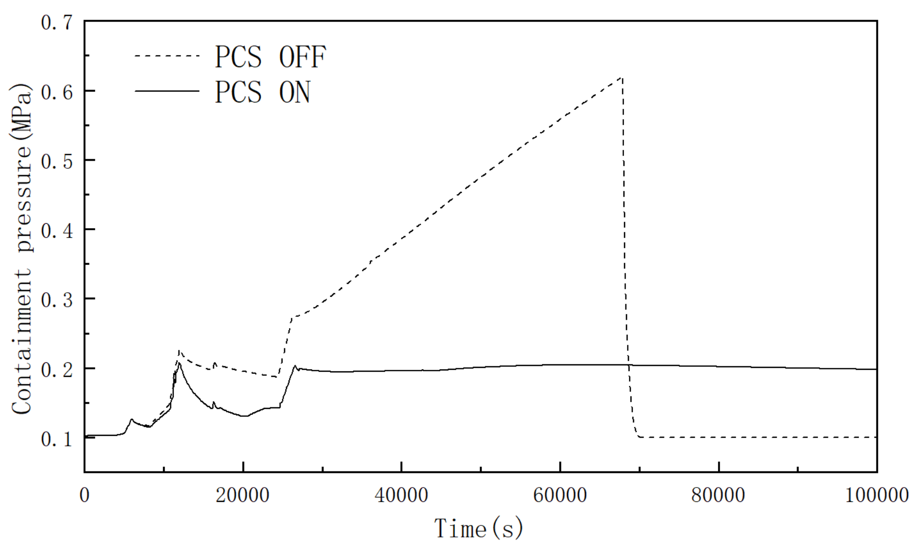

FIGURE 8. Containment Pressure under SBO(ADS1-3) scenarios

As can be seen, with the PCS closed, uncondensed water vapor accumulates in the containment, causing the pressure to rise. At around 68,000 s, the containment pressure hits 0.6 MPa, exceeding the design pressure, and then the pressure relief device activates, leading to a rapid pressure drop.

V. CONCLUSIONS

During severe accidents in large - scale advanced passive pressurized water reactors, hydrogen poses significant risks in flow - restricted compartments like the IRWST compartment and PXS compartment. Conversely, within the large - volume containment, good fluidity helps disperse hydrogen, resulting in relatively lower hydrogen - related risks.

During station blackout incidents, opening merely the ADS1-3 valves leads hydrogen to discharge into the IRWST compartment. This influx drives the IRWST compartment into the combustion regime. In contrast, when all four - stage ADS valves are opened, a substantial portion of hydrogen vents into the containment space via the fourth - stage valve. This effectively mitigates the hydrogen - related hazards in the IRWST compartment. During a DVI pipeline break accident, hydrogen is released into the PXS compartment, propelling it into the combustion region.

The hydrogen control system can effectively reduce hydrogen risks. However, due to the small number of igniters in the PXS compartment, its effect is not remarkable. When the igniters fail, closing the PCS to increase the steam volume fraction can reduce the hydrogen risk in the containment. Nevertheless, this measure has little effect on restricted compartments and meanwhile, it will pose a risk of over - pressurizing the containment.

In future research, more realistic boundary conditions and three-dimensional computational fluid dynamics (CFD) models will be incorporated to improve the accuracy of hydrogen risk assessment in confined compartments. Additionally, experimental validation of hydrogen distribution and mitigation strategies will be pursued, with particular focus on the optimization of hydrogen mitigation strategies under various accident scenarios.

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