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Hydrogen and steam distribution following a small-break LOCA in large dry containment

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Abstract The hydrogen deflagration is one of the major risk contributors to threaten the integrity of the containment in a nuclear power plant, and hydrogen control in the case of severe accidents is required by nuclear regulations. Based on the large dry containment model developed with the integral severe-accident analysis tool, a small-break loss-of-coolant-accident (LOCA) without HPI, LPI, AFW and containment sprays, leading to the core degradation and large hydrogen generation, is calculated. Hydrogen and steam distribution in containment compartments is investigated. The analysis results show that significant hydrogen deflagration risk exits in the reactor coolant pump (RCP) compartment and the cavity during the early period, if no actions are taken to mitigate the effects of hydrogen accumulation.

Key words Severe accident, Small-break LOCA, Large dry containment, Hydrogen distribution

CLC number $TL364^{+}.4$

1 Introduction

In the Three Mile Island-2 (TMI-2) accident in 1979, a total of about 460 kg hydrogen was generated and eventually released into the containment building, causing hydrogen burning.[1,2] Since then the regulation requirement on prevention and mitigation of severe accidents has become a critical issue to ensure the ultimate safety of nuclear power plants (NPPs). In the severe accidents, substantial amounts of hydrogen can be generated as a result of the core degradation and oxidation (in-vessel origin) and the molten corium concrete interaction (ex-vessel origin). The potential hydrogen deflagration is probably one of major risk contributors to threaten the integrity of the containment.[3] Therefore, hydrogen control has to be included in nuclear regulations to mitigate the effects of severe accidents.[4]

In order to address this issue, detailed analysis of hydrogen risk should be carried out for the specific reactor and containment design, including hydrogen generation induced by typical severe accident sequences, hydrogen mixing and distribution in the containment compartments, potential hydrogen deflagration and its thermal and mechanical loads to the containment structure. Recently, some significant work has been done by researchers in China, and severe accidents, such as small-break loss-of-coolant- accident (LOCA) and station blackout (SBO) sequences, have been calculated to investigate hydrogen distribution in the containment, using MELCOR or CONTAIN code.[5-8] An analysis of hydrogen and steam distribution, which includes hydrogen source from both in-vessel and ex-vessel origins, was performed at SJU for the containment of a specific pressurized water reactor (PWR), with the MAAP code, a well-acknowledged analysis tool for severe accident. Major efforts were focused on evaluation of hydrogen or/and steam mixing in different compartments, based on the assumption of complete mixing in the containment volume.

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2 Analysis methodology

2.1 Selected accident sequence

The selected accident sequence consists of the small-break loss-of-coolant-accident (LOCA), leading to the core degradation and large amount of hydrogen generation.[9] The small-break LOCA accident is initiated by a 0.0127 m (0.5 inch) break in the cold leg. High pressure injection (HPI), low pressure injection (LPI), auxiliary feed water (AFW) and containment sprays are assumed unavailable at the beginning of the sequence. Moreover, hydrogen combustion is factitiously cut off in the calculation.

2.2 System modeling

For a 2-loop PWR nuclear power plant of 1,930 MW with a large dry containment, the MAAP severe-accident code is used to analyze the hydrogen risk. As an integral system analysis tool, the MAAP simulates the response to accident initiation events in a light water reactor. The reactor coolant system (RCS) is modeled with a reactor vessel, an active core region and two reactor coolant loops—the broken and unbroken loop. The broken loop models a single hot leg, steam generator, intermediate leg, reactor coolant pump, and cold leg. Additionally, the pressurizer is located on the hot leg of broken loop. The LOCA occurs in the broken loop. The unbroken loop models another hot leg, steam generator, intermediate leg, reactor coolant pump, and cold leg, without the pressurizer. The core region is modeled with 7 radial fuel channels, plus one bypass region, 13 axial active fuel nodes and two non-fuel nodes below the bottom of the active fuel and one non-fuel node above the top of the active fuel.

The containment is modeled with 24 compartments (nodes), 58 flow junctions, and 90 distributed containment heat sinks in terms of the floors and walls, as illustrated in Fig.1. In addition, certain "lumped" heat sinks (metallic equipments) are modeled in a majority of the containment nodes. The reactor protection/control systems and the engineered safety related systems are also modeled, even if not considering HPI, LPI, AFW and containment sprays.

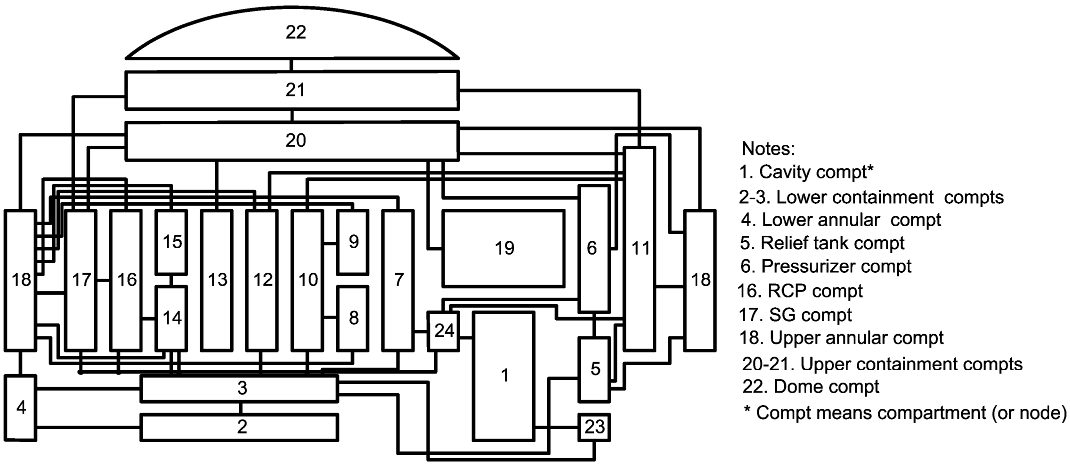

Fig.1 Nodes and flow junctions for the containment.

3 Analysis results

3.1 Accident progression and containment transient

This small-break LOCA scenario occurs with the absence of all active safety systems, including HPI, LPI, AFW and containment sprays. After the accident initiation, pressure of the reactor coolant system (RCS) decreases quickly because of the large amount of coolant loss from the cold leg break. When the RCS pressure falls below the pressurizer low-pressure setpoint, the reactor scrams at about 5 min. The decay heat is removed by the break flow and the secondary heat sinks. As the water disappears in the steam generators (SGs), the RCS pressure re-increases, while the power-operated relief valves (PORVs) of the pressurizer frequently open and close to maintain the pressure around 16.6 MPa, as shown in Fig.2. The core becomes uncovery, and heats up at 83 min, as illustrated in Fig.3. The coolant temperature increases due to the core heating up, and the coolant volume expands to make the water level increase and fluctuate. When the U-Zr-O eutectic temperature reaches 2500 K, the fuel rapidly heats up and melts, and relocates to the lower plenum at 217 min. The MAAP predicts a continuous pressure increasing while the molten fuel materials interact with the cooling water in the lower head. Because of high pressure and little accumulator injection, a certain amount of molten core materials interacts with the residual water in the lower head, where much steam is produced to pressurize the RCS quickly. At 254 min, the reactor pressure vessel (RPV) fails. The key accident events are shown in Table 1. The containment is pressurized because of a large amount of water and steam flowing from the break. There are two significant pressure increases when the core materials relocate to lower plenum and RPV fails, respectively (Fig.4). However, once the lower head fails, high temperature molten-core materials drain down and interact with water in the cavity and generate a great deal of steam to pressurize the containment rapidly, because most of the accumulator water (~56,000 kg) injects into the vessel and flows directly into the cavity. Thereafter, the pressure of containment decreases slowly, because containment floors and walls and large metallic equipments have absorbed lots of heat. During the late period of the accident, the containment is pressurized quite slowly by non-condensable gases generated by molten corium concrete interaction (MCCI).

3.2 In- and ex-vessel hydrogen generation

By the time of vessel failure, about 418.6 kg of hydrogen will have been generated in the core with 60.37% fuel cladding reaction. Little hydrogen is generated after the molten core relocation because the coolant is vaporized quickly and there is no water remaining in the lower head. Fig.5 shows the cumulative hydrogen production in the vessel. The maximum hydrogen generation rate from the in-vessel reaction is 1.0 kg·s^{-1}. The hydrogen generation is estimated to be 389.5 kg from the ex-vessel reactions at 50,000 seconds after the initiation of the accident. At the beginning, the molten core materials interact with the water in cavity and hydrogen is produced. However, the crust due to the quenching interaction is formed to prevent more hydrogen generated. After the water depletion in cavity, the molten corium concrete interaction becomes a significant hydrogen generating source. Fig.6 shows the cumulative hydrogen production outside the vessel, and the maximum hydrogen generation rate from the ex-vessel reactions is 0.021 kg·s^{-1}.

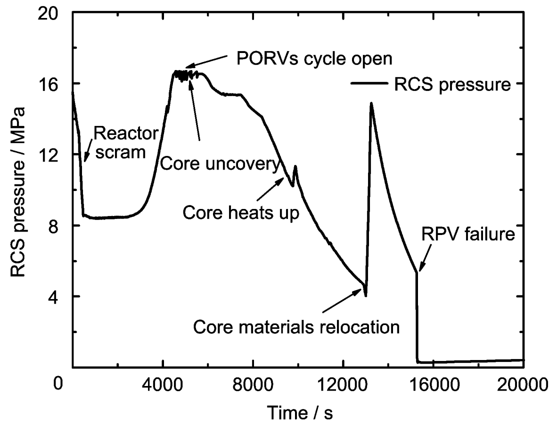

Fig.2 Reactor coolant system (RCS) pressure.

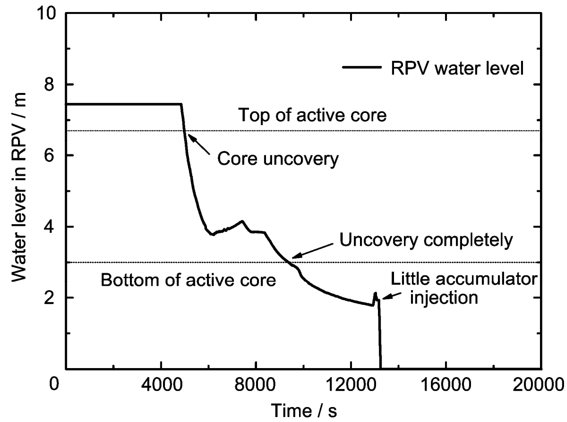

Fig.3 Water level in reactor pressure vessel (RPV).

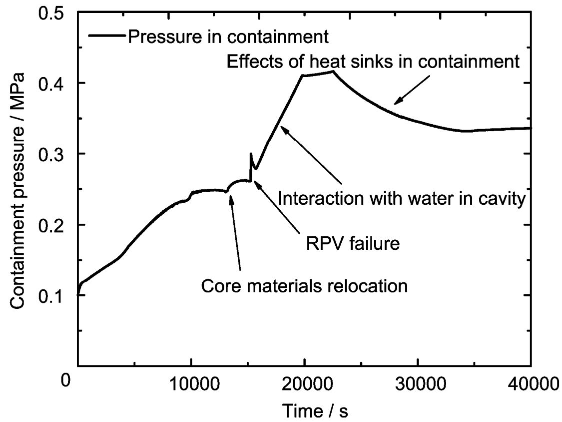

Fig.4 Containment pressure transient.

Table 1 Key event timing

Events	Time /s
Accident initiation	0
Reactor scram	281
Core uncovery	4,990
Initiation of core melting	9,490
Relocation into the lower head	13,012
RPV failure	15,260

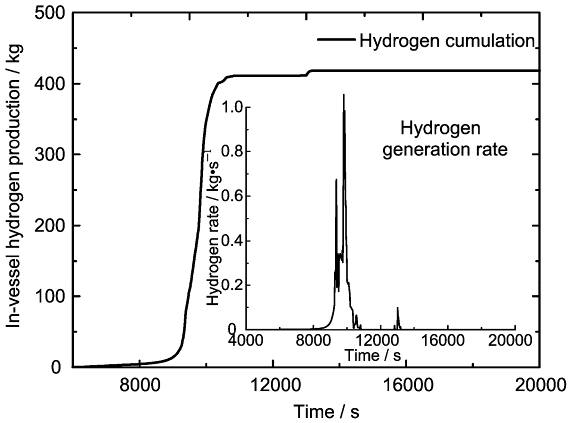

Fig.5 Hydrogen production in the vessel.

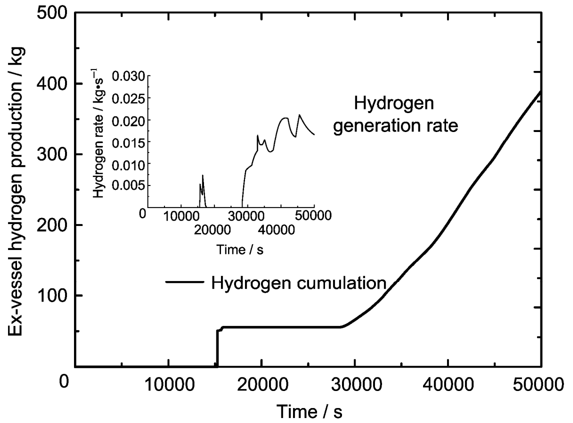

Fig.6 Hydrogen production outside the vessel.

3.3 Hydrogen and steam distribution in containment compartments

In order to analyze hydrogen and steam distribution in containment, four typical compartments, i.e. 1) the coolant pump (RCP) compartment where the cold leg break occurs, 2) the reactor cavity compartment, 3) the annular compartment and 4) the containment dome, are investigated. The hydrogen volumetric concentrations in different compartments are shown in Fig.7. Hydrogen concentration in the RCP compartment increases rapidly shortly after the core melting, and the peak value is up to 12.5%. The hydrogen diffuses to other compartments nearby through flow junctions. Hydrogen concentration in the cavity increases rapidly with the lower head failure, and the peak value can be 16.6%. Because of the diffusing effects, hydrogen becomes well-mixed during the late period of the small-break LOCA. Fig.8 shows the steam concentration in different containment compartments. The steam mass in the RCP compartment is reasonably different from other compartments during the beginning of the accident. After 20,000 seconds, the steam becomes well-mixed in the RCP compartment, the annular compartment and the containment dome. However, there is a large mass of steam generated after high temperature molten core drains into the cavity and interacts with water there.

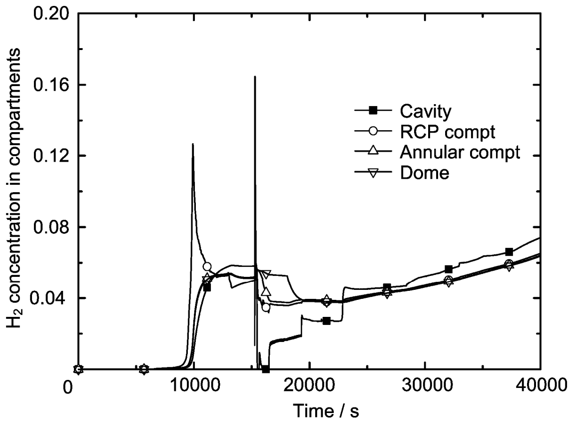

Fig.7 Hydrogen concentration in typical compartments.

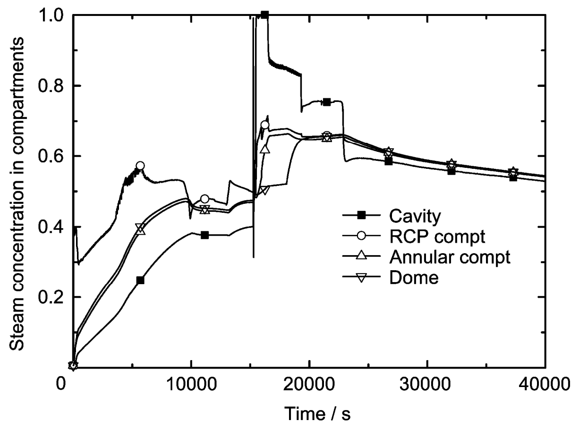

Fig.8 Steam concentration in typical compartments.

In addition, other compartments near the break position, such as the RCP compartment, the pressurizer compartment, the relief tank compartment and the steam generator (SG) compartment, are selected and analyzed. Hydrogen and steam distribution in these compartments are shown in Fig.9 and Fig.10, respectively. The hydrogen concentration profile in pressurizer compartment is similar to the profile in SG compartment. Hydrogen concentration in relief tank compartment is a little higher than that in the pressurizer and SG compartments, because a portion of hydrogen is released from the pressurizer cycled-open PORVs into the relief tank compartment.

During the early period, significant hydrogen deflagration risk exits in the RCP compartment and the cavity because of the high hydrogen concentration, even if steam may make hydrogen inert to a certain extent. During the late period, hydrogen deflagration becomes possible in many containment compartments, if no measures are taken to mitigate the hydrogen accumulation.

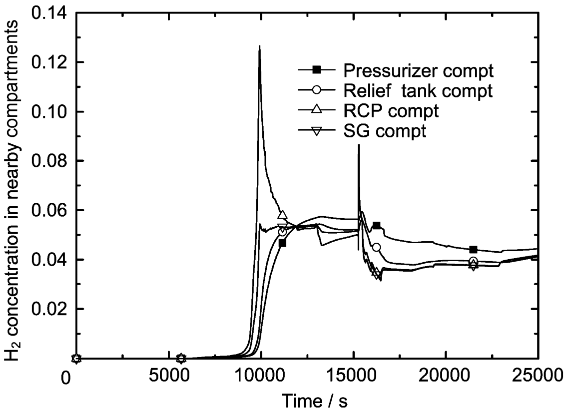

Fig.9 Hydrogen concentration in nearby compartments.

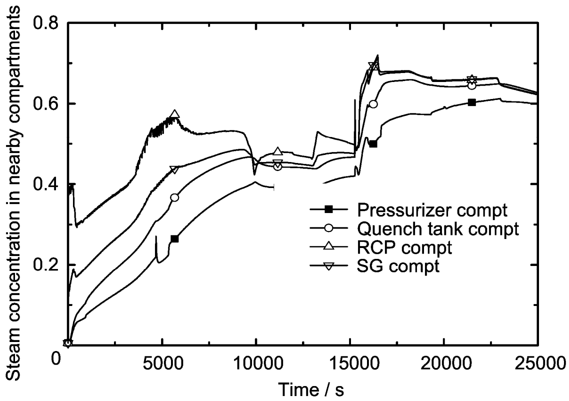

Fig.10 Steam concentration in nearby compartments.

4 Conclusions

In order to analyze the hydrogen risk in a severe accident, the reactor coolant system and large dry containment model is developed with the MAAP severe-accident code. A small-break LOCA leading to core degradation and large hydrogen generation is calculated, assuming that HPI, LPI, AFW and containment sprays are unavailable. Accident progression, in- and ex-vessel hydrogen generation, containment pressure transient, hydrogen and steam distribution in different containment compartments are analyzed in this paper.

The results show that ~418.6 kg hydrogen is generated in core with 60.37% fuel cladding reaction, and the maximum hydrogen generation rate from the in-vessel reaction is 1.0 $kg \cdot s^{-1}$, while 389.5 kg is estimated from the ex-vessel reactions until 50,000 seconds after the initiation of the accident, and the maximum hydrogen generation rate is 0.021 $kg \cdot s^{-1}$. Additionally, during the early period of the accident, significant hydrogen deflagration risk exits in the RCP compartment and the cavity because of the high hydrogen concentration, and during the late period, hydrogen deflagration becomes possible in many containment compartments, if no measures are taken to mitigate the hydrogen accumulation.

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