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STUDY ON IN-VESSEL RETENTION (IVR) STRATEGY FOR CPR1000

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Abstract

The study on IVR (In-Vessel Retention) strategy for CPR1000 is introduced. For CPR1000, preliminary results showed that the RPV (Reactor Pressure Vessel) failure is the dominated by thermal failure mode and the IVR success probability is about 99%. The risk of steam explosion, which may happen with an extremely low probability due to corium-water interaction in the cavity if RPV fails, was however analyzed. Preliminary results showed that the CPR1000 containment will maintain integrity even though a steam explosion occurs. For detailed analysis, a test setup designed to gain the CHF (Critical Heat Flux) data for CPR1000 is under construction and planed to be completed at mid 2011. The characteristics of the test setup are introduced.

Introduction

The idea of IVR (in-vessel retention) by submerging the reactor vessel during the severe accident has been considered since mid 80s. With the vessel submerged before the corium reaches the lower plenum, the decay heat from the relocated corium will be removed by the water and the vessel will maintain its integrity.

The enhanced safety of the Westinghouse Advanced 600 MWe pressurized water reactor (PWR) (AP600) [1], which relied upon IVR, is approved by U.S. Nuclear Regulatory Commission (US NRC). After that, IVR is adopted by some operating nuclear power plants (for example, the Loviisa plant in Finland[2]) and proposed for some advanced PWRs, such as the Westinghouse AP1000[3], the Korean Next Generation Reactor (KNGR) [4] and the Korean Advanced Power Reactor APR1400 (APR1400).

The Chinese Pressurized-water Reactor 1000 MWe (CPR1000) is a major option for the construction of NPPs in the next decades in China with thermal power of 2895 MW. To improve the nuclear safety level in China, the IVR strategy is proposed for CPR1000. Before the IVR strategy is adopted by CPR1000, the following two key issues should be addressed: a) what is the success probability of IVR? In other word, what is the probability of RPV integrity with IVR strategy under severe accident? and b) if IVR didn't success, are there any negative effects threatening the containment integrity? These two issues are discussed in the present paper.

This paper consists of four main technical sections. Three sections (Sections 1-3) address the IVR success probability and Section 4 addresses the steam explosion as a negative effect of IVR. The paper comes to an end with the conclusions and prospects in Section 5.

1. Analysis of RPV failure modes

The IVR will success only if the RPV will not fail. There are three RPV failure models, the thermal failure, structural failure and penetration failure. In this section the bounding failure mode is determined.

1.1 Structural Failure

Great effort was expended in reference [1] to demonstrate that no structural failure was presented to the vessel as long as the thermal failure wasn't met (e.g., thermal load on the vessel wall less than CHF). Bounding analysis for dead weight loading, thermal stresses, ductile tearing and creep rupture were performed.

These arguments and analyses for AP600 were extended to the AP1000 as it is demonstrated that the structural margins for the AP1000 and AP600 vessels are on the same order of magnitude [3]. This subsection aims to demonstrate that the structural margins for the CPR1000 are also on the same order of magnitude as the margins in the AP600 analysis and to conclude that the argument for AP600 can also extended to the CPR1000. Therefore, the structural margin for CPR1000 is calculated as followed.

The analysis assumes that the RCS has been depressurized. For the CPR1000, the melt weight and the lower head weight is conservatively estimated to be 140 tons and 30 tons respectively, the buoyancy force for the vessel lower head displacing water up to the elevation of the nozzle gallery is approximately 87 tons (a effective hydrostatic head of 6.3 m on the lower head outer surface, which diameter is 4.411 m). Therefore, the dead loading is $8.2\text{x}10^5$ N (83 tons).

The yield strength of carbon steel at full strength (i.e., below 900 K) is 355 MPa (reference [1]). At the loading of $8.2\text{x}10^5$ N, the minimum area (A_m) that would be required to carry this load would be:

$$A_m = \frac{\text{load}}{\text{yield strength}} = \frac{8.2\times10^5 N}{355\times10^6 N/m^2} = 2.31\text{x}10^{-3}\text{m}^2 \quad (1)$$

The minimum area required to carry the dead load corresponds to a thickness of **0.017 cm** of the CPR1000 vessel wall at the outer diameter of 4.411 m.

The wall thickness that carries the loading is the portion of the wall with a temperature from the yield strength temperature (900 K) to the saturation temperature (373 K) at the peak CHF of the RPV outer wall of CPR1000. This peak CHF is conservatively estimated to be 2000 kW/m2 for this calculation. The thickness can be calculated from the thermal conductivity (32 W/m-K) through the vessel wall using the standard conduction rate equation and solving for the thickness:

$$x_v = \frac{K_v(T_{yield} - T_{sat})}{q_w} = \frac{32\times(900-373)}{2000\times10^3} = 0.843 \text{ cm} \quad (2)$$

The CPR1000 vessel wall, conducting heat at the peak critical heat flux, is 50 times thicker than the minimum thickness required carrying the dead load. This value for AP1000 and AP600 is 36 and 73 respectively. Therefore, the margin to structural failure is on the same order of magnitude as the AP1000 and AP600.

Now we can conclude that the structural analyses performed for the AP1000 and AP600 can be also extrapolated to the CPR1000. That is to say, no structural failure will be presented to the CPR1000 vessel as long as the thermal failure doesn't met.

1.2 Penetration Failure

There are 50 in-core instrumentation (ICI) nozzles penetrating the RPV lower head in CPR1000. The integrity of these penetrations is a necessary condition for the RPV integrity.

There are two major penetration failure modes: 1) The attack of the melted core material to the lower head penetrations of the reactor vessel may result in the melt entering a penetration channel and heating up the penetration tube, thus causing blockage of the penetrations and potentially a penetration rupture, and 2) The melted core material attack and sustained heating from accumulated core material may lead to ICI nozzle weld failure and subsequent ICI nozzle ejection to the cavity, which means reactor vessel failure.

Experimental and analytical studies on the penetration integrity of the RPV have been performed to investigate the potential for reactor vessel failure during a severe accident around the world. To the author's knowledge, all of the studies, including the Three Mile Island Unit 2 (TMI-2) Vessel Investigation Project (VIP) sponsored by eleven countries under the auspices of the Nuclear Energy Agency of the Organization for Economic Cooperation and Development [5], the cost-shared project ARVI (assessment of reactor vessel integrity) involves a total of nine organizations from Europe and USA [6], the penetration integrity study in APR1400 by Korea Atomic Energy Research Institute [7] and the penetration integrity calculations for a China 300MWe PWR [8], showed that external vessel cooling is very effective for reactor vessel penetration integrity, no penetration failure would expected under external vessel cooling, and the margin for penetration failure is large.

In fact, the EC-FOREVER-3B test [6] showed that, the vessel failure took place at the highest temperature location and not at the penetration location, in other words, the margin of the penetration failure is larger than the thermal failure. Therefore, no specific study on penetration failure is performed in the CPR1000 IVR project.

1.3 Thermal Failure

Considering the analysis mentioned above, we can now conclude that, for CPR1000, the success of IVR based solely on the thermal success criterion.

The thermal failure problem is whether the heat removal from the outer wall of the vessel is sufficient enough to maintain the steady state and the wall integrity. The issue is to define the thermal load inside the vessel for possible core melt scenario and to determine whether it is not exceeding the CHF limit at the outer wall. The calculation of the probability of thermal failure (in other word, the IVR success probability) is described in the next section.

2. Assessment of IVR success probability

The basic methodology for evaluating the IVR success probability for Loviisa plant [2], AP600 [1], AP1000 [3] and APR1400 was the Risk-Oriented Accident Analysis Methodology (ROAAM) which was developed by Theofanous [1]. In reference [9], the ROAAM is adopted to assess the success probability of the IVR-ERVC for CPR1000.

The thermal load is calculated using two layer model (metallic layer above the oxide layer, as shown in Fig. 1) which was proposed by Theofanous [1]. A correlation based on ACOPO tests have been used to determine the thermal load (see Appendix D of Theofanous et al. [1]). With the two layer model, the peak heat flux occurs at interface of the two layers.

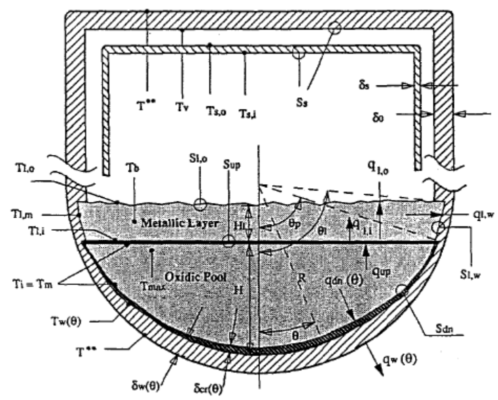

Figure 1 Two layer model of corium

In the process of thermal load calculating, the parameters are basically deterministic, except for the decay power, the quantity of zirconium oxidized (this affects the volumes and compositions in the metallic layer and oxide pools) and the quantity of steel in the metallic layer (this affects the depth). All three quantities are sensitive to the wall heat flux, therefore, their values and uncertainties should be considered very carefully. The approach proposed by Theofanous is to provide reasonably bounding distributions in the ROAAM sense using certain likelihood level (see Appendix A of Theofanous et al. [1]).

After the heat transfer model is defined, the heat flux from both the metallic and the oxide layers through the vessel wall can be calculated. Using Monte Carlo sampling method the uncertainty band of wall heat flux distribution can be acquired. The band of q_{wall} distribution is to compare with the heat transfer limit distribution of outer wall, i.e., CHF, to determine the success probability of IVR-ERVC.

The process of this assessment present in detail in reference [9]. Fig. 2 to Fig. 4 show the major probability input parameters in the assessment. Result showed that (Fig. 5), among the 30000 samples the number of exceeding CHF is 245. Therefore, the probability of the actual heat flux exceeding CHF is about 0.0082. In other words, the CPR1000's IVR success probability is about 99%.

Note that, in reference [9], the q_{CHF} of AP600 is used for the CPR1000 IVR preliminary assessment. If the specific CHF data for CPR1000 is higher than that of AP600, we can have a IVR success probability higher than 99% and vice versa. Therefore, for detailed analysis, specific CHF data for CPR1000 shall be gained. This is the intent of the CHF experiment described in the next section.

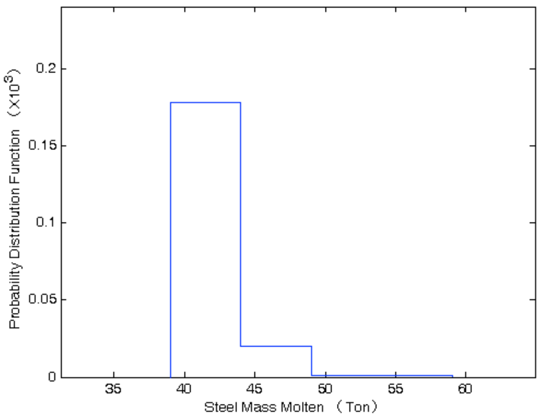

Figure 2 Steel Mass Molten Probability Distribution

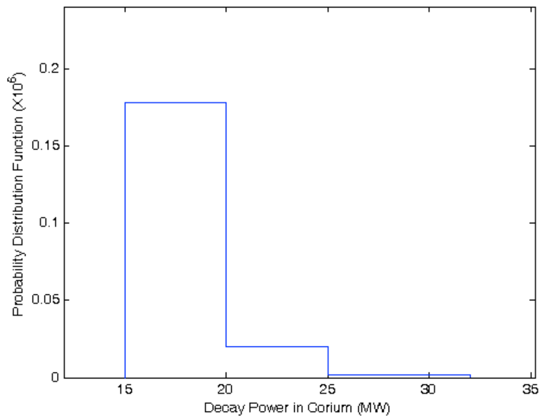

Figure 3 Decay Power in Corium Probability Distribution

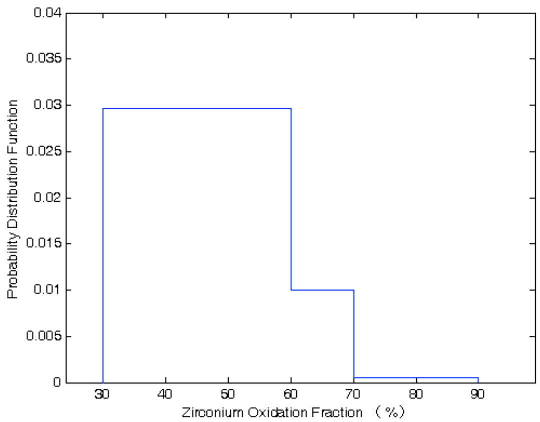

Figure 4 Zirconium Oxidation Fraction Probability Distribution

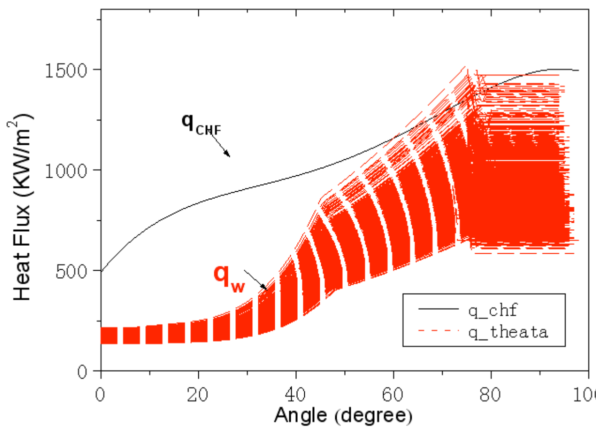

Figure 5 Wall Heat Fluxes and q_{CHF}

3. CHF experiment for CPR1000

It is known that the CHF value along the outer wall at the lower head of RPV is key factor that determines the success probability of IVR strategy. As for AP1000 of Westinghouse and APR1400 of South Korea, the CHF test for them had been conducted on the setup of ULPU2400 at California University at Santa Barbara and SBLB at the Pennsylvania State University. Due to the different geometry of RPV and reactor cavity, different design of the insulation near the lower head, different water ingress and steam venting, and so on, the CHF data is specific for different reactors. That is to say, it needs specific CHF test for different reactors.

On the basis of reserches on the IVR strategy for many years, CGNPC will adopt this strategy on its own new NPPs, such as the two units of CPR1000 at Yangjiang 3&4. For the same reason, the CHF test is necessary for evaluate the feasibility of the RPF (Reactor Pit Flooding) system and will be conducted in 2011.

3.1 Introduction to the RPF and insulation design for CPR1000

Fig. 6 shows the scheme of the concept design of insulation for CPR1000 which is similar to the insulation design of APR1400. As for AP1000, several designs of insulation had been studied experimentally to obtain the best design to improve the CHF value and finally the design with streamline style was used in AP1000. It was suggested that the mass flow of water and the gap between RPV and the inline part of the insulation. And it seemed that an optimal gap existed at the range of 150~200mm.

For CPR1000, the insulation design with taper style will be adopted which is a modification from cylinder insulation to improve the flow rate and CHF value. As shown in Fig.6, the cooling water from fire fighting system is injected form the bottom of the reactor cavity and flows into the gap by differential pressure passively. And then the cooling water is heated by the outer wall of RPV and flows upward derived by buoyancy with many steam bubble.

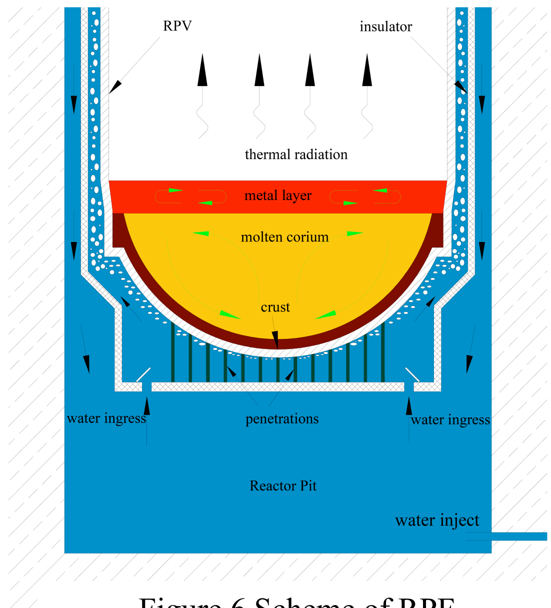

Figure 6 Scheme of RPF

The steam finally is released into containment and the water will then flow down between the gap between the insulation and reactor cavity. The natural circulation appears in and outside of insulation when the RPV are submerged by water.

3.2 The CHF test setup

To do the CHF test for CPR1000, a new test facility are established by CGNPC and the sketch and picture of the setup are shown in Fig. 7 and Fig. 8. The arrow in Fig. 7 means the typical water flow direction when the flow is natural circulation.

The facility is made up of electric system, power control system, cooling water system, water purifiers, test section, water tank, condenser, mixer and data acquirement system.

The power capacity is 2.0MW and the cooling power is 200 ton. The power control system is based on silicon controlled thyristor and the accuracy of output power is within3% and twenty four thyristors are used to control the 24 test zones which can mostly simulate the heat flux distribution along the lower head. The flow rates are measured by electromagnetic flow meter which can reduce the influence on the flow and its accuracy within scan is 0.2%.

Similar to UPLU-2400, the test section is one cooper block with many holes drilled precisely form side. 499 cartridge heaters are inserted into the tolerance of the holes and heaters are both controlled strictly during manufacturing processes. The test section is divided into 24 test zone and 5 thermocouples are located in every zone. Two thermal couples are used to monitor the temperature and it's change with time, 1 used to monitor the inner temperature of the heater, and other 2 thermal couples are used to measure the actual temperature. It is evaluated by numerical simulation that the temperature difference between these two couples is about 130℃ when the heat flux is 2.0 MW/m^2. The heat flux designed is 2.4 MW/m^2 which is equivalent to ULPU-2400 and can satisfy the needs for the CHF test of CPR1000.

The flow path within the test section can be adjusted by different baffle configurations and the gap between RPV and the inline part of the baffle ranges from 100-400mm which covering the possible optimal value for the gap.

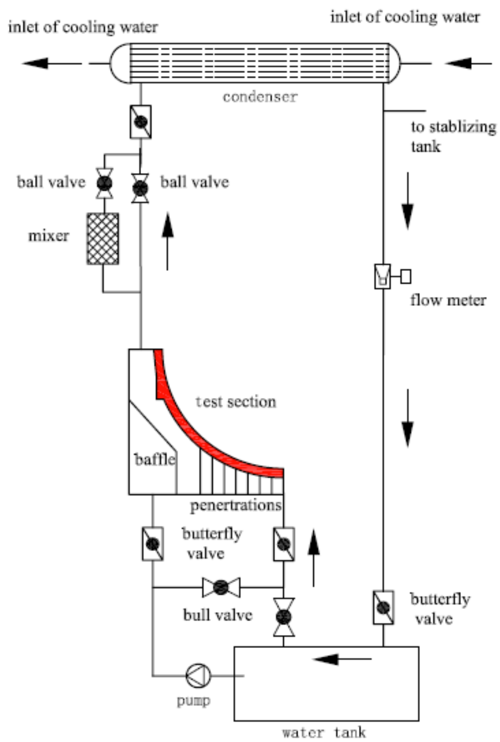

Figure 7 Sketch of test setup


Figure 8 Photograph of the setup

During the design of the test setup, not only the natural circulation which has been shown in Fig. 7 by arrows is considered, but the forced circulation working conditions also is taken in account. Because the existence of many penetrations (used to detect the neutron flux) and horizontal convex plate at the lower head, so the water flow may be affected, resulting in reducing the local CHF value and the success probability of IVR strategy, so the forced circulation are designed.

To improve the compatibility of the setup, the working conditions for different location of water ingress are considered because the water ingress on the insulation may be at the center or at the side. The case that the water ingress locates at the side is shown in Fig. 7.

During forced circulation, the water is pumped into the test section from central ingress or side ingress after the flow rate is adjusted by valves with bypass.

3.3 Test Schedule

Up to now, the test setup had been debugged and the preparations for form experiments are being made. And the test will be done from April 2011 to July 2011.

- April 2011-May 2011 Test with different baffle configurations to obtain the optimal design which correspond to maximum flow rate.
- June 2011-July 2011 Test for CHF data with the optimal design and actual design used in CPR1000.

Additionally, the detailed information and the results will be published in near future and one can pay attention to the future conference paper or articles.

4. Risk of steam explosion

When IVR strategy fails, the lower head will break. The molten corium falls into the reactor cavity which is full of cold water from RPF. The steam generated in extremely short time yield steam pulse, may result in steam explosion. The steam explosion, if enough violent, may affect the structure reactor cavity and threaten the integrity of containment. Because the explosion takes place outside the RPV, it is named as Ex-vessel Steam Explosion (EX-SE).

In the other hand, if the safety injection initiates, the steam explosion may take place inside the RPV and similarly it is named as In-vessel Steam Explosion (IN-SE). But in present section, only the EX-SE is discussed.

Several experiments of steam explosion had been done but because the condition of steam explosion was so strict that only one (FARO L-33 test by CEA, NRC, IRSN, et al) succeeded. In the test, the trigger time is 1.124s after the corium falls into the test section. Now, no particular parameter can be thought as the criteria to predict the steam explosion. In present section, the MC3D code was used to analyze the EX-SE, which is usually used to study the Fuel-Coolant Interaction and had been verified by FAROL-33 test and so on.

In the process of steam explosion analysis, there are two phases: Premixing and Explosion. In premixing phase, the pressure of steam, the explosion time, the volume of corium fragments and other parameters can be calculated and as the input data for explosion phase. In the whole calculation process of explosion including two phases, the corium consists of three states, melt jet, melt droplet and fragment. The flow field also consists of three states, liquid, vapor and non-condensable gas. In the premixing phase, the time of interreaction between corium and cold water is longer relatively. The fragments and liquid can be as thermal balance and have the same flowrate and temperature, so they can be treated as one field. But in the explosion phase, the fragment and liquid is different field. However, the steam and no-condensable gas are supposed to be thermal balance, not only in premixing, but also explosion.

For the steam explosion analysis, the first step is to built the 2-D axial symmetry model of the reactor cavity (including RPV) seen in Fig. 9, according to the structure sketch of CPR1000+'s reactor cavity. In the model, the inner diameter of reactor cavity wall is 5.2m. The bottom is -3.4m elevation, and the cylinder thickness of RPV is 0.2m. The second step is to prepare input data seen in Table 1.

Table 1 Input data of steam explosion

Case	Mass of Corium (t)	Temperature of Corium (K)	Temperature of Water in Cavity (K)	Pressuren in Cavity (MPa)
1	155	2900	303.15	0.3
2	211	2900	303.15	0.3
3	155	2900	373.15	0.3
4	211	2900	373.15	0.3

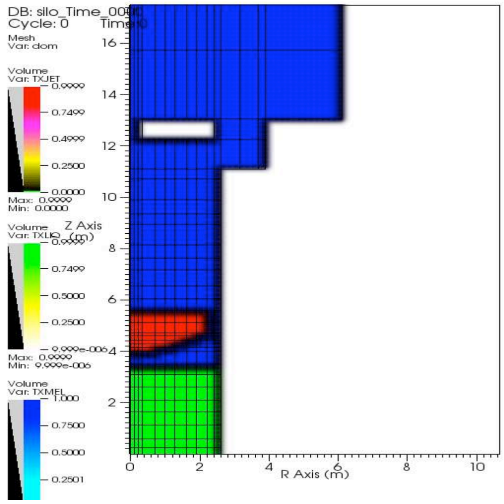

Figure 9 Analysis Model of Steam Explosion

4.1 Premixing phase

Fig. 10 shows the explosion process and Fig. 11 shows the maximum pressure at different locations. Both figures are based on the calculated results of Case 1. There is a pressure pulse in cavity, which the maximum value is 3.0 MP. But the pressure of cavity wall almost remains unchanged. From Fig. 11, the maximum pressure of the upper space of containment is only about 0.3 MPa. So it can be concluded that in the premixing phase, the steam explosion have litter risk for cavity, cavity wall and containment.

4.2 Explosion phase

Fig. 12 shows the results the result for case 1 during explosion phase. The explosion time is 1.3s and the pressure pulse of cavity is violent. The maximum value of pressure in cavity is up to 386 MPa, but falls to 0.3 MPa within 0.003s. The maximum pressure on cavity wall is only 100MPa and also falls quickly. From Fig. 13, it is showed that the violent impulse occurs at 0.25 elevations and the impulse load pressure rises to 371 kPa.s. The pressure variation of upper space in containment is not obvious. The results including case 2-4 are summarized in Table 2.

To summary, when the steam explosion occurs, the pressure impulse on cavity are stronger than the containment, and the impulse load ranges from 310 kPa.s to 440 kPa.s, which is much less than 700 kPa.s (the capacity of AP600). So we can preliminarily conclude that there is no risk of threatening the integrity of containment if the capacity of CPR1000 is equal to that of AP600.

5. Conclusions and prospects

The IVR strategy is an option for CPR1000 as one of the severe accident mitigation method. Studies on IVR, including RPV failure modes analysis, IVR success probability calculation and steam explosion risk assessment had been performed. Preliminary results shown that, the IVR success probability is about 99% and the steam explosion will not threaten the integrity of the CPR1000 containment.

Note that the mentioned preliminary results are given using AP600 data as a reference. Further investigations on CPR1000, including the IVR test data and containment pressure bearing capability, are needed for the final decision whether or not to adopt the IVR strategy on CPR1000.

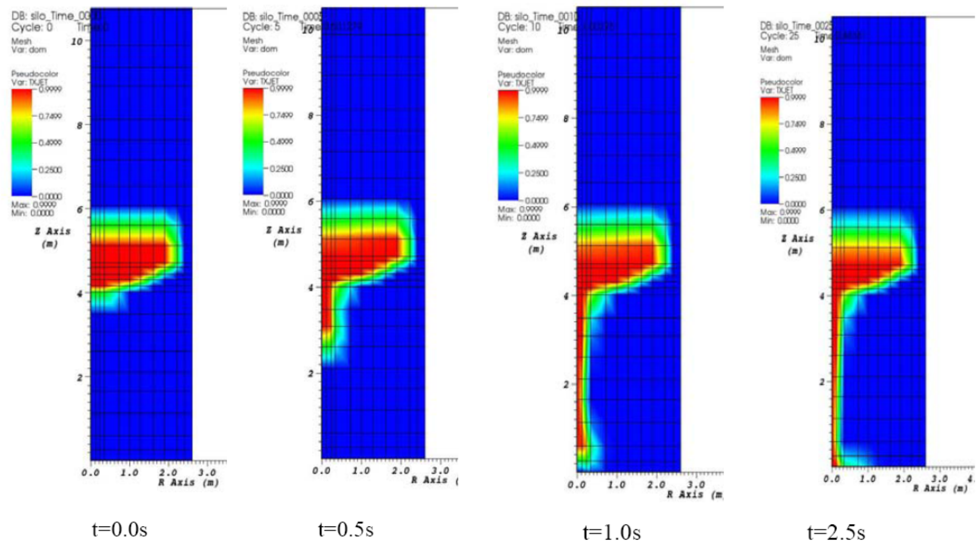

Figure 10 The steam explosion triggering process

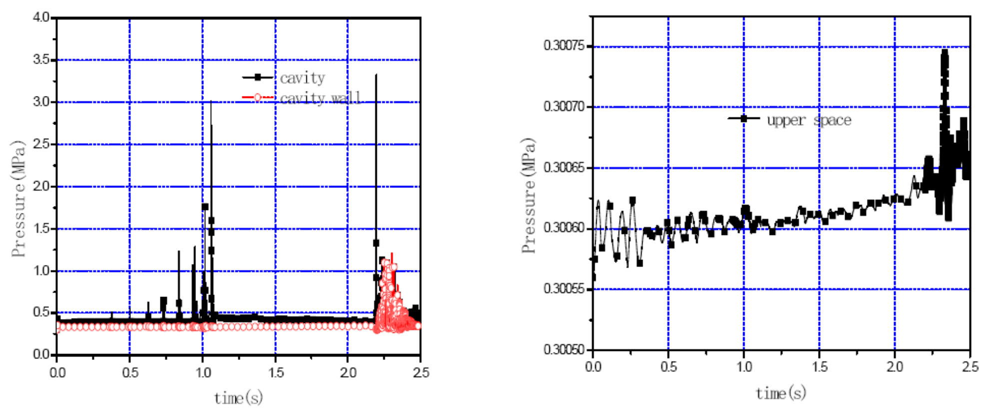

Figure 11 The maximum pressure value of the cavity (wall) and upper space during premixing phase

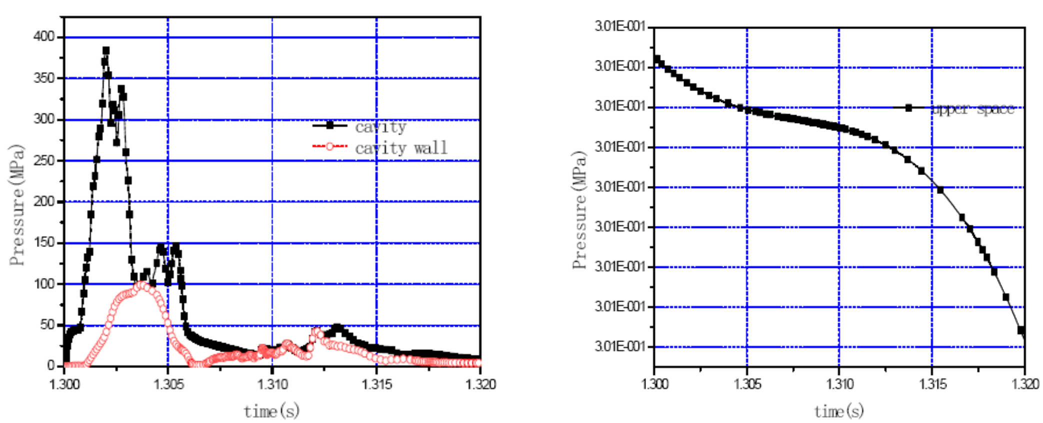

Figure 12 The maximum pressure value of cavity (wall) and upper space during Explosion phase

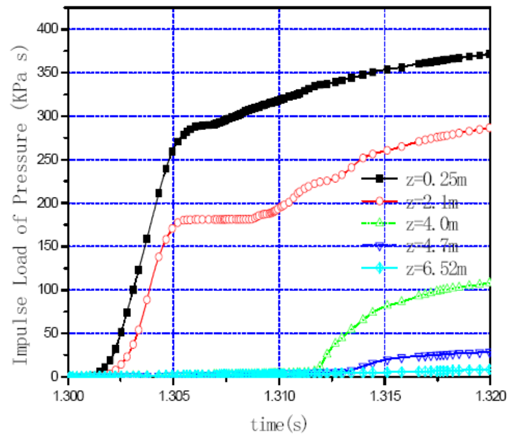

Figure 13 Impulse load of Pressure at different position

Table 2 The Maximum pressure and impulse load in steam explosion

Case and Explosion Time		Maximum Pressure in Cavity（MPa）	Maximum Pressure on Cavity（MPa）	Impulse Load of Pressure on Cavity Wall（kPa s）
1	1.3s	386	100	371
	1.5s	384	93	370
2	1.05s	300	94	316
	1.5s	414	101	381
3	1.3s	454	87	423
	1.4s	395	77	410
	1.6s	152	49	343
4	1.2 s	391	89	436
	1.4 s	252	56	390
	1.55 s	192	64	364

6. References

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