PRELIMINARY DESIGN OF THE I^{2}S-LWR CONTAINMENT SYSTEM

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ABSTRACT

The Integral Inherently Safe Light Water Reactor Light Water Reactor (I^{2}S-LWR) is a novel reactor design concept which aims at delivering an electric power output level comparable to that of large LWRs (approximately 1,000 MWe), while at the same time achieving an overall level of safety that is enhanced with respect to large Generation III+ LWRs. One of the main safety goals is to achieve indefinite cooling following design basis accidents (DBAs) using atmosphere air as ultimate heat sink. In order to accommodate these goals, the I^{2}S-LWR incorporates several innovative safety features, including an integral Reactor Pressure Vessel (RPV), enhanced passive Decay Heat Removal (DHR) systems and several containment passive cooling systems. The present work is focused on a passive and reliable containment design, which plays a significant role in LOCA scenario and is the last boundary to prevent the release of radioactivity to the environment. In this paper, several innovative passive systems located in the I^{2}S-LWR containment are proposed, including Core Make-up Tanks (CMT), Accumulators (ACC), a Passive Suppression System (PSS), an Automatic Depressurization System (ADS), a Passive Containment Cooling System (PCCS) and a Passive Reactor Cavity Cooling System (PRCCS). The best-estimate thermal-hydraulic code RELAP5 has been used to model the I^{2}S-LWR RPV and containment passive systems. A stuck-open PORV (Pilot-operated Relieve Valve) accident scenario has been simulated in order to study the containment response, including the coupling between RPV and containment. The results show that, through the activation of the ADS, pressure equilibrium between containment and reactor pressure vessel is achieved, while maintaining a water level sufficient to cover the reactor core at all times. The containment passive cooling systems ensure that the containment pressure remains at acceptable levels throughout the transient.

KEYWORDS
Inherent Safety Integral Reactor, Containment, SBLOCA, Passive cooling system

1. INTRODUCTION

Nuclear safety is the most important issue to be considered in the nuclear industry. Core effective cooling and containment integrity are required even in the most extreme conditions. The advanced nuclear reactor designs have incorporated new safety features and adopted several innovative systems, mainly based on water gravity or other passive methods to remove heat from the primary system or the containment atmosphere in case of a postulated accident. The improvement in these safety systems generally involved the development of suitable passive containment systems.

The passive containment systems have been studied and adopted in several representative reactors, including ESBWR from GE, KERENA from AREVA, APR+ from KEPCO, AP600 and AP1000 from Westinghouse. In the ESBWR design, cooling pools are located outside the containment. The steam generated by the decay heat flows inside heat exchangers (HXs) and is condensed by water in the cooling pools. The condensate is stored in the gravity-driven cooling system and injected into the reactor passively [1]. The Passive Containment Cooling System (PCCS) of the KERENA reactor design is quite similar to that of the ESBWR. Four containment cooling condensers are located on the top of the containment to transfer decay heat from steam to the shielding pool located above the containment [3]. Integral test studies have been performed for validation of the system using the INKA test facility [4]. For APR+, a conceptual design of PCCS was proposed [5]. In the APR+ PCCS design, decay heat removal rate is maximized by introducing Air Holdup Tanks (AHT), which is an isolated space positioned above the In-containment Refueling Water Storage Tank (IRWST) and is connected to the containment free space by vent lines through IRWST water and Passive Auxiliary Feed-water System (PAFS) HXs. For the AP1000 instead, a double-wall containment is adopted and the decay heat is removed to the atmosphere by water sprays and air naturally moving upward along a steel containment. No additional HXs are foreseen inside the containment due to the higher thermal conductivity of steel compared with concrete. All the passive systems in AP1000 have been verified by extensive experimental programs and eight nuclear power plants are under construction; four in China [6,7] and four in the United States. Various other passive safety system design concepts are described in an IAEA report [8].

The new I^2S-LWR concept aims to advance performance and safety beyond that of the current Gen-III+ systems, while maintaining large GW-level unit power, and providing other performance parameters at least comparable to those of current Gen-III+ designs. The I^2S-LWR concept was proposed by a consortium of several universities and in collaboration with Westinghouse in response to a US Department of Energy's (DOE's) solicitation for Nuclear Engineering University Programs (NEUP) Integrated Research Projects (IRP) on the topic of inherently safe LWRs [9].

The I^2S-LWR concept is based on combining large power (enhancing economics) with integral configuration (enhancing safety). It is built on the proven technology provided by over 40 years of operating PWR experience, and on the established use of passive safety features pioneered by Westinghouse in the NRC certified AP600 and AP1000 plant designs. Each unit generates 1000 MWe, to meet market needs for larger units and to improve economic competitiveness. The reactor employs an integral primary circuit configuration because of its inherent safety features: for example, it avoids large-break loss-of-coolant accident (LOCA) and control rod ejection by design. The design includes a compact core with a high power density, and it has an innovative compact in-vessel primary heat exchanger (PHX). Its fuel and fuel cladding has enhanced accident tolerance to address concerns arising from Fukushima. All safety systems have as high a degree of passivity as is practical. The concept has enhanced resilience to seismic and other external events. It is equipped with a passive decay heat removal system, capable of removing heat indefinitely (in most scenarios) or, in the remaining cases, providing an extended grace period beyond that of Gen III+ plants before any operator action would be required.

While large and intermediate LOCA scenarios are eliminated by design, small break LOCA accidents arising from the break of a CVS (control volume system) line or PORV should be considered for the reactor safety analyses. In SBLOCA scenarios, the I^2S-LWR containment plays an important role in mitigating the consequences of the accident, and preventing the release of radioactivity to the environment. In this paper, the behavior of the I^2S-LWR concept is evaluated based on a stuck-open PORV scenario. Several innovative passive systems located in the containment were proposed and designed, including Core Make up Tanks (CMT), Accumulator (ACC), a Passive Suppression System (PSS), an Automatic Decompression System (ADS), a Passive Containment Cooling System (PCCS) and a Passive Reactor Cavity Cooling System (PRCCS). Figure 1 shows the preliminary I^2S-LWR containment layout. All the proposed systems are introduced in detail in the following sections. A detailed RELAP5 model has been developed for the entire I^2S-LWR reactor with containment, and is introduced in section 3. Finally, the stuck-open PORV accident is simulated using RELAP5 code and the responses of RPV and containment following the accident are discussed in section 4.

2. SYSTEM DESIGN AND DESCRIPTION

The containment is designed to have a cylindrical shape, with a height of about 40 m and a diameter of about 16.7 m. Unlike other light water reactor designs, the I^2S-LWR features a high pressure steel containment structure and the core uncovery in case of LOCAs is prevented by achieving quick pressure equilibrium between RPV and containment. Based on the structural mechanics calculation, the preliminary containment design allowable pressure is about 1.0 MPa. Several passive safety systems in the containment, including CMT, ACC, PSS, ADS, PCCS and PRCCS, are proposed and introduced in this section.

CMT: the CMT was proposed to provide a diverse means of reactor shutdown by delivering pressurized, borated water into the reactor [10]. For the I^2S-LWR, the CMT injects coolant into the RPV downcomer directly and provides a limited gravity feed makeup water to the primary system with its operation. It is connected to the I^2S-LWR downcomer and tripped by a valve. The CMT is a 6.0 m height tank with a cross section area of 12.56 m^2. A total of two CMTs are foreseen for the I^2S-LWR.

ACC: Accumulators drive borated water with nitrogen gas filled at the tops of their tanks and provide emergency borated water into the reactor in medium pressure phase during reactor depressurized in case of LOCAs. Four ACCs are designed for I^2S-LWR and connected to DVI line directly. The ACCs are activitated while the I^2S-LWR primary loop pressure drops to 4.5 MPa. The total volume of each ACC is about 67.7 m^3 and the borated water in tank is about 53.2 m^3.

PSS: the containment Pressure Suppression System consists of a water tank and corresponding ADS valves. Each suppression water tank is connected to the containment atmosphere through a vent pipe so that steam released in the containment following a loss of coolant or steam line break accident is condensed. The suppression system limits the peak containment pressure to acceptable values. Also, the suppression system water tanks provide an elevated source of water that is available for gravity injection into the RPV through the DVI lines in the event of a SBLOCA [11]. The PSS tank is 8.0 meter high and has a cross section area of 12.56 m^2, similar to the CMT tank. There are totally four tanks designed for the I^2S-LWR.

ADS: the Automatic Depressurization System aims to assist the DHRS in depressurizing the RPV when the RPV coolant inventory drops below a specific level. The ADS consist of four parallel lines, each line with two normally closed valves. Based on the two parallel lines design, ADS systems can be in operation in series to optimize the depressurization rate. The single ADS line downstream of the closed valves discharges into the pressure suppression system pool tank. This ADS function ensures that the RPV and containment pressures are equalized in a timely manner, limiting the loss of coolant from the RPV into the containment and thus preventing core uncovery following postulated LOCAs. The ADS is a valve with a flow area 0.00114 m^2. Its actuation is initiated by a RPV pressure signal.

PCCS: the Passive Containment Cooling System consists of two heat exchangers, a cooling tower and corresponding pipes. One of the HXs is located in the upper part of containment and the other is located in the cooling tower. It is utilized to condense the steam blown out from the RPV and remove the decay heat following postulated SBLOCA accidents. The HX inside the containment consists of 500 heat transfer tubes, with tube diameter of 0.05 m and a height of 8 m. Thus, the total heat transfer area is 628.0 m^2.

PRCCS: the Passive Reactor Cavity Cooling System that collects the liquid break flow, as well as any condensate from the containment, is located around the RPV. The I^2S-LWR vessel diameter is 5.25 m, while the cavity diameter is 7.25 m. The cavity height is 11.2 m. A helical coil heat exchanger is located in the cavity space. Following a SBLOCA accident, the cavity is filled with coolant, creating a gravity head of water to provide coolant makeup to the RPV through the DVI lines. This cavity also guarantees that the lower outside portion of the RPV surface is wetted following postulated core damage events. The PRCCS shares the same cooling tower with the PCCS.

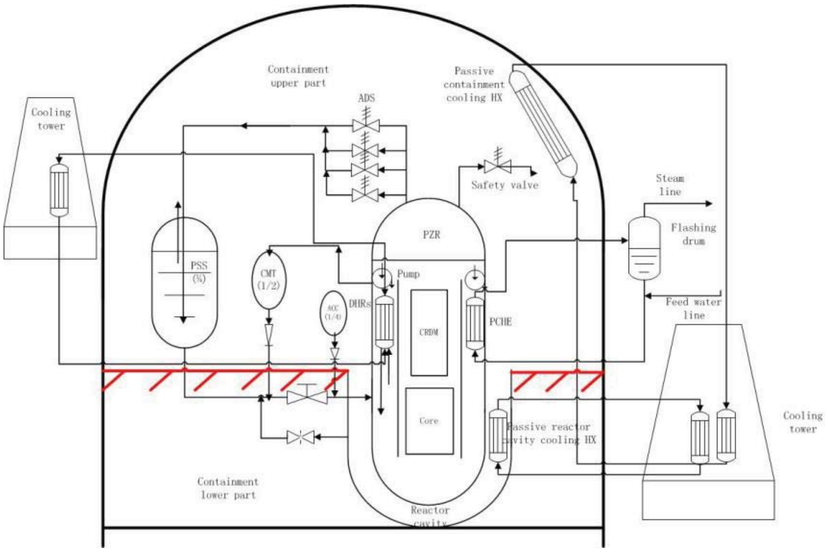

Figure 1. I^2S-LWR containment design concept

3. RELAP5 MODEL

The RELAP5 model presented in a companion paper [12]is extended to the containment in the present work. A complete RELAP5 nodalization diagram is shown in Figure 2. The slice method is adopted to simulate different containment altitudes in RELAP5 code. This method is the most accurate way to model the flow characteristic (such as natural circulation and crossing flow) in large volumes using the RELAP5 code. All the designed safety systems, including CMT, PSS, ADS, PCCS and PRCCS are modeled based on the detailed geometry and operation parameters. The CMT and PSS are simulated using some pipe and junction in RELAP5, while the ADS is modeled utilizing the valve. For the PRCCS, the same helical coil heat exchanger as DHRs is adopted for the sake of economic factor. The PCCS contains a pipe-type traditionally HX, which is modeled using several pipes in both sides and heat structures to realize the heat transfer. The PCCS and PRCCS share the same cooling tower outside of the containment. Before using the RELAP5 nodalization for transient simulations, a model verification study was performed through comparison between RELAP5 calculated results and nominal values in steady state conditions [12].

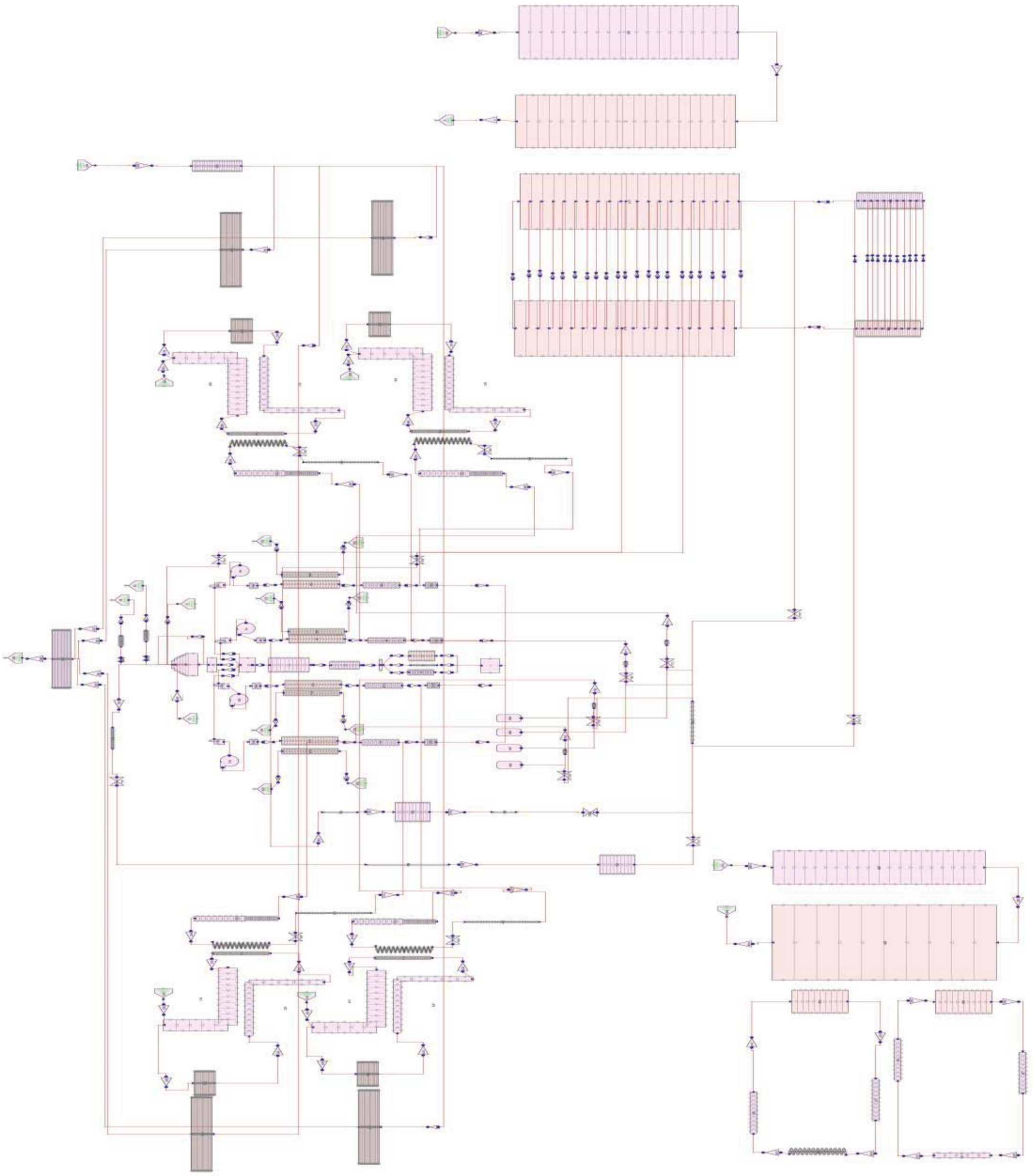

Figure 2. I^2S-LWR containment nodalization

4. STUCK-OPEN PORV ACCIDENT STUDY

A stuck-open PORV accident scenario is simulated to study the containment response and the coupling between RPV and containment. This study aims at demonstrating the safety performance of the preliminary design of the I^2S-LWR containment passive systems during a SBLOCA.

The stuck-open PORV accident is assumed to occur at 0 s, with the reactor operating at nominal conditions, and the break area is assumed to be 0.0081 m2. The primary coolant begins to blow out via the break to the containment. The reactor control rods begin to drop, leading to reactor shutdown due to the containment high pressure signal (0.3 MPa). The primary circuit pumps begin to coast down following reactor shutdown with a 10 s delay for the pump protection consideration because of the close distance between pressurizer and pumps. The PCHE secondary feed water is assumed to decrease to 0 kg/s within 200 s after the containment high pressure signal. No credit is taken for the heat transfer through the PCHEs after the first 250 s of transient for the most conservative considerations. Also, no credit for diesel generators is taken in the I^2S-LWR concept. Three out of four DHRs are assumed to start functioning (opening of the DHR valves) following the signal generated by the reactor shutdown. The ACCs are actuated while the primary loop pressure decreases to 4.5 MPa and then the CMT and ADS run with the RPV lower pressure signal (2.0 MPa) and begin to inject water into the RPV and depressurize the RPV, providing sufficient coolant in the core and avoiding the core channel boiling, respectively. In the later stage, with the coolant level decrease, the PSS are put in operation with low pressure difference between PRV and containment (0.1 MPa) to provide additional coolant to the reactor core. For the long term cooling, with the cavity water level increasing, the reactor cavity injects the condensed water from the upper region of the containment back into the RPV. And then a sustained and steady coolant circulation is established. During the whole transient, the HXs in the upper part of the containment and in the cavity remove the decay heat to the outside environment through an intermediate loop located in the cooling tower outside the containment. Also the containment wall heat removal is also considered in the simulation. The accident logic for the SBLOCA event discussed here is listed in Table 1.

Table Ⅰ Event sequence of SBLOCA

Event	Trip
Reactor stuck-open PORV	0 s
DHR in operation (3/4)	40 s
Reactor shutdown	40 s
Secondary side flow rate trip	40 s (0-200s decrease to 0 kg/s)
Primary circuit pump trip time	50 s
ACC in operation	45 s
CMT in operation	700 s
ADS in operation	700 s
Cavity in operation	2840 s
PSS in operation	2840 s
PCCS in operation	All the time
PRCCS in operation	All the time

The time traces of the relevant thermal hydraulic parameters are shown in Figure 3 to Figure 14. Figure 3 shows the time evolution of the pressure in the RPV and in the containment. The initial pressures of RPV and containment are 15.5 MPa and 0.2 MPa, respectively. Following release of coolant inventory into the containment as a consequence of the stuck-open PORV, the RPV pressure decreases while the containment increases. For the RPV pressure variation, there is an oscillation in the beginning due to insufficient heat removal for the reactor core and ACCs in operation. Then it decreases smoothly with the combined function of DHR system heat removal capacity increase, core decay heat decrease and reactor depressurization. For the containment, the pressure increases sharply and then drops to a steady value due to effective heat removal from containment. The maximum containment pressure could reach about 0.5 MPa, which is less than the containment allowable pressure 1.0 MPa as achieved in the above section. Finally, the pressure equilibrium of about 0.38 MPa between RPV and containment is reached at about 3000 s.

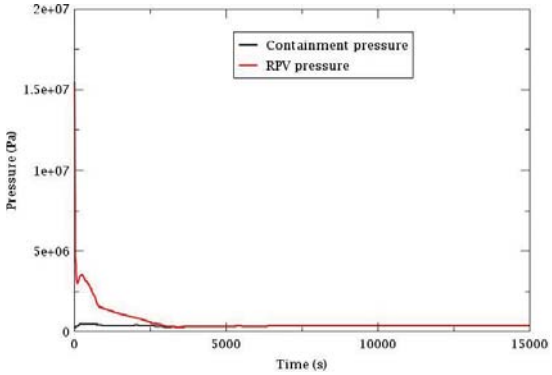

Figure 3. Variation of RPV and containment pressures vs. time

The containment temperature variation with time is reported in Figure 4. The containment temperature variation trend is similar with the containment pressure variation. It initially increases sharply due to the high temperature coolant discharge from the RPV to containment. Once the PCCS and PRCCS heat removal start (see Figure 5) and the coolant temperature decreases inside of the RPV due to the effective heat removal from DHR, the containment temperature begins to decrease and maintains a steady value. As shown in Figure 5, the DHR, PCCS and PRCCS could establish steady natural circulation and take the decay heat to outside environment from about 4000 s. Also, all of them could provide an infinitive decay heat removal due to the application of two cooling tower, one for four DHRs and the other one for the PRCCS and PCCS. As shown in Fig. 5, the DHR and PCCS can take more decay heat out than that from PRCCS at the later stage.

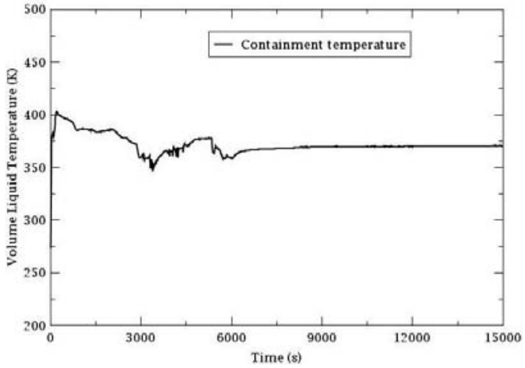

Figure 4. Variation of containment temperature vs. time

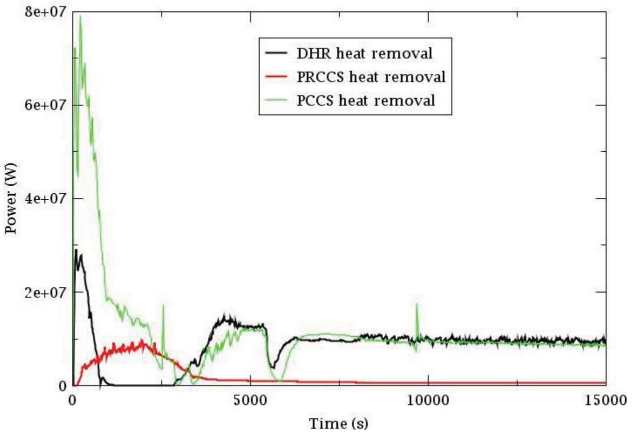

Figure 5. Variations of DHR, PCCS and PRCCS heat removal vs. time

Fig. 9 shows the flow rate of accumulator injection into RPV via DVI line. The ACC is actuated by the low RPV pressure signal at 45 s and then starts to inject borated water into reactor core. Then the flow rate decreases to 0 kg/s due to the shortage of ACC water inventory at about 2400 s. The variation of CMT injection flow rate is shown in Figure 7. With the RPV low pressure signal at 700 s, the CMT isolation valve opens and coolant is injected into the reactor downcomer through DVI line. At the initial stage, the injection flow rate jumps to a high value, and then the injection coolant flow rate decreases to a very low value due to the short of tank water. One sharp jump of the flowrate at about 2800s is due to the PSS in operation with an obvious RPV pressure drop. The ADS is also tripped following the RPV low pressure signal, accelerating the RPV depressurization. The ADS flow rate as function of time is presented in Figure 8. When the RPV pressure and PSS pressure reach the equilibrium, the ADS flow rate decreases due to the little pressure difference. Figure 9 illustrates the variation of PSS injection flow rate. The low pressure signal also trips the PSS valve to open, and then the coolant of PSS tank is injected into RPV via DVI line and floods to reactor cavity. Similarly, the injection coolant flow rate decreases to a very low value due to the short of tank water at around 4000 s.

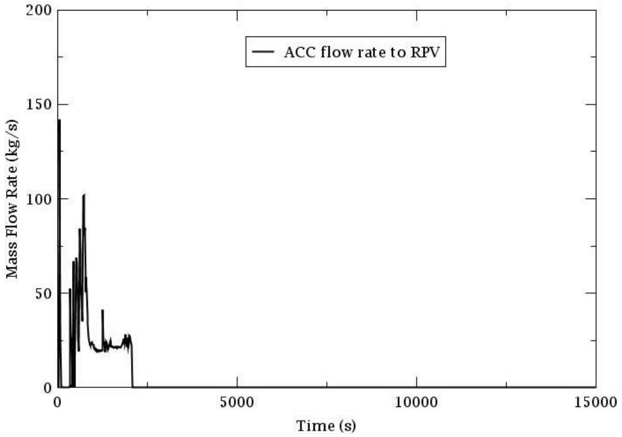

Figure 6. Variations of ACC flow rate vs. time

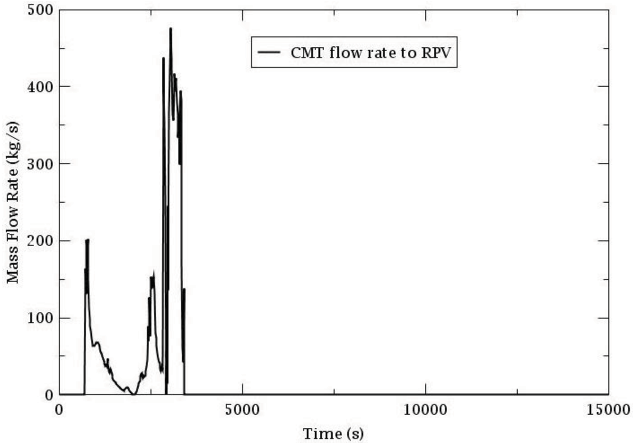

Figure 7. Variation of CMT flow rate vs. time

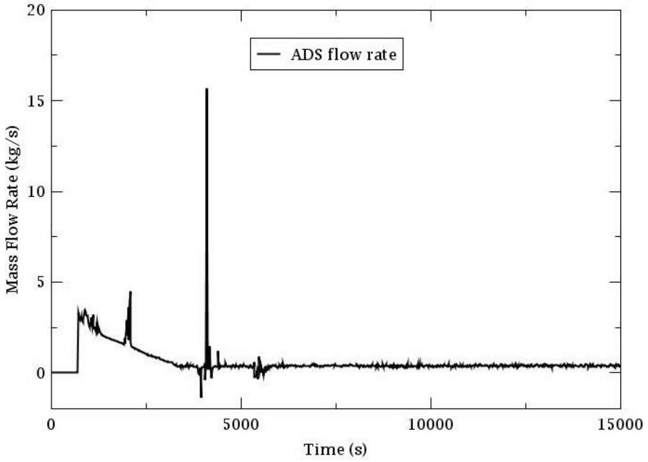

Figure 8. Variation of ADS flow rate vs. time

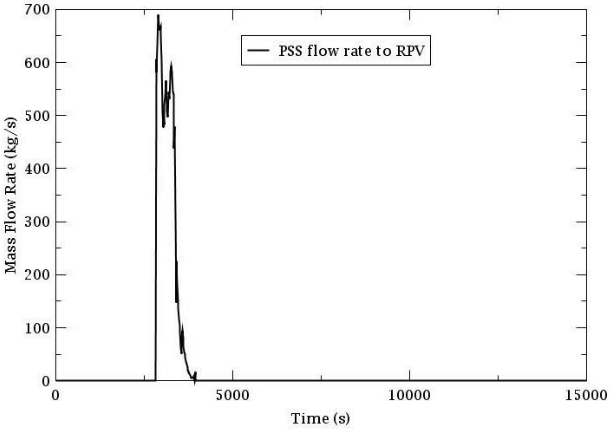

Figure 9. Variation of PSS flow rate vs. time

The temporal evolutions of the reactor core inlet and outlet temperatures are shown in Figure 10. They begin to decrease following the stuck-open PORV transient due to the reactor shutdown, and the effective heat removal from DHRS, PCCS and PRCCS. During the water injection state, the core inlet temperature is lower than core outlet temperature obviously due to the cold water injection. Then in the later coolant circulation stage, the boiling occurs in the reactor core, which leads to little temperature difference between core inlet and core outlet.

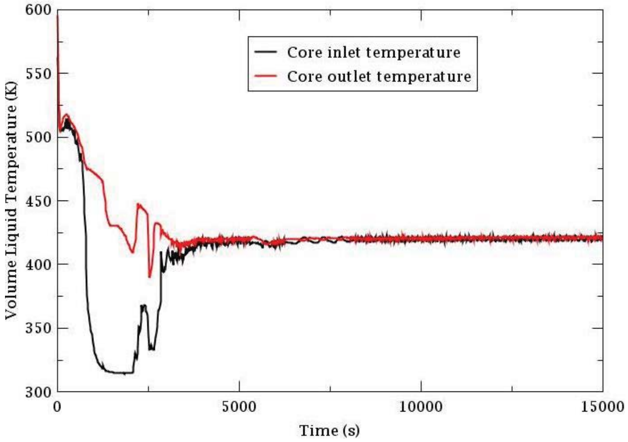

Figure 10. Variation of reactor core inlet and outlet temperatures vs. time

At the final stage, the cavity collects sufficient coolant from containment and PSS injection, leading to the cavity water level increasing from 0.0 m to 11.2 m. During this phase, the cavity long term cooling starts by the valve open between reactor cavity and RPV, which is tripped by the same signal with the PSS. Then the coolant in cavity flows back into downcomer and makes the long term cooling for reactor core become reality. The flow rate from cavity to RPV is illustrated as Figure 11. Fig. 12 shows the variation of cavity water level with time. The water level in cavity maintains a steady value in the long term recirculation among RPV, containment and reactor cavity.

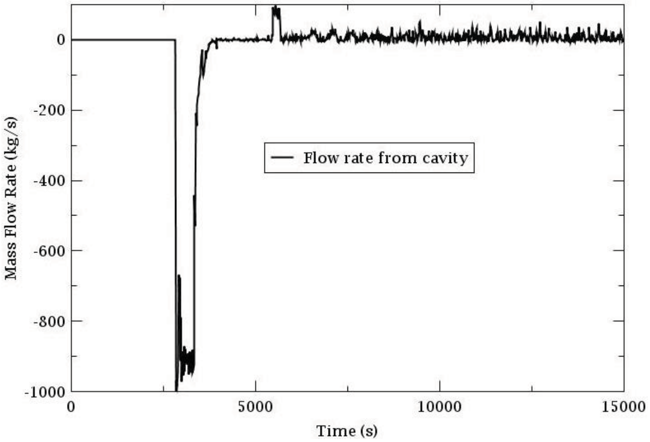

Figure 11. Variation of mass flow rate from cavity to RPV vs. time

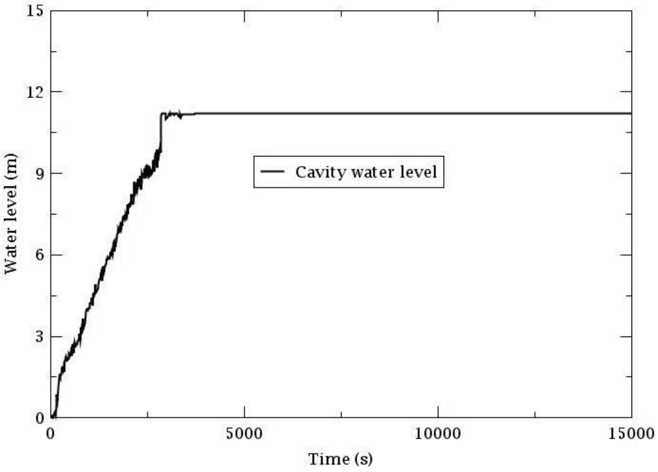

Figure 12. Variation of reactor cavity water level vs. time

The temporal evolution of the RPV water level is shown in Figure 13. The vessel water level is about 13.0 m in the later stage of SBLOCA, which is about 4 m above the reactor core outlet. Even in the most dangerous phase such as 5500 s, the vessel water level also is higher than core outlet. Thus, the reactor core is covered all the time during the accident and could be kept in a safety condition.

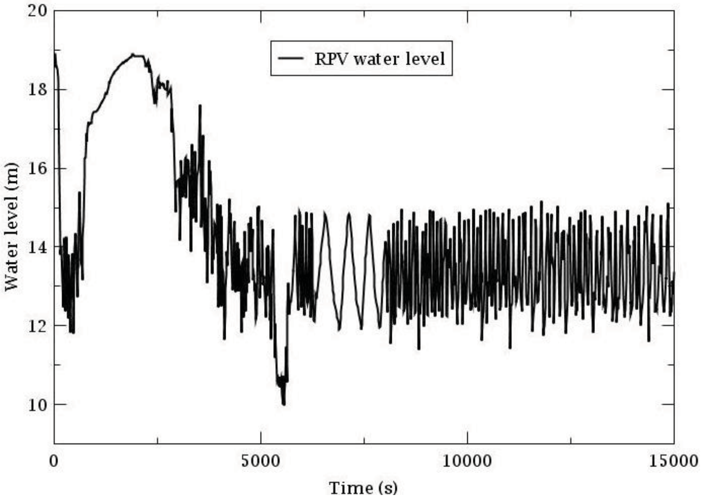

Figure 13. Variation of reactor vessel water level vs. time

Figure 14 shows the variations of the U3Si2 fuel centerline and cladding temperatures. At steady state, the fuel centerline temperature and cladding temperature in the average core channel are 962K and 632K, respectively. The fuel and cladding temperature decrease below steady-state values due to the effective cooling and coolant supply during the stuck open PORV accident. By the end of the transient, values stabilize at 425K and 421K respectively.

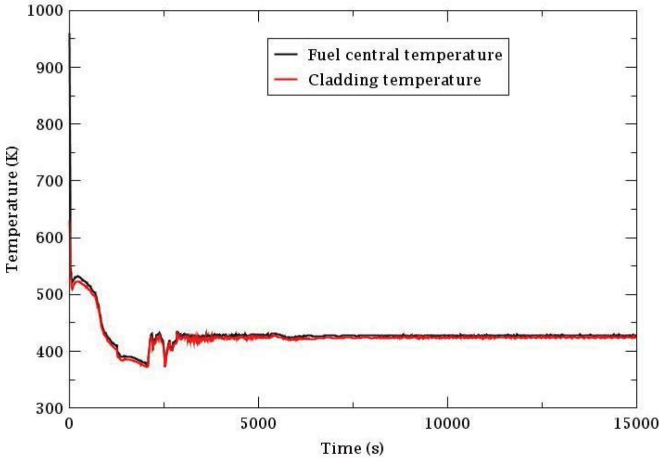

Figure 14. Variation of fuel central and coolant temperatures vs. time

In sum, all the important thermal hydraulic parameter variations with time are achieved in this section. Following a SBLOCA, from the reactor pressure vessel point, the reactor core temperature and pressure can be kept in a safety range. And the reactor core could be covered by the coolant all the time. From the containment point, the containment pressure and temperature could also maintain a safety state. All the designed passive safety system for the I^{2}S-LWR can be operated as the function required and their successes have been demonstrated.

5. CONCLUSIONS

In this paper, a preliminary containment design has been developed for the I^{2}S-LWR reactor concept. Several innovative passive systems have been proposed, including CMT, ACC, PSS, ADS, PCCS and PRCCS. The proposed passive systems for primary side and containment have been tested against a stuck-open PORV accident scenario, using the best estimate thermal-hydraulic code RELAP5. Results show that all the designed passive safety systems could work to efficiently and successfully guarantee reactor safety in the event of loss of coolant accident. Indefinite cooling without the need of operator actions is achieved, with atmospheric air as the ultimate heat sink. This is a considerable improvement with respect to current designs, where replenishment of outside pools is necessary after a grace period which varies from concept to concept between 72 hours up to 2 weeks. The stuck-open PORV accident is simulated to verify the feasibility of I^{2}S-LWR containment design.

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