ANALYSIS OF THE SBLOCA ON THE IMPROVED CPR1000 WITH PASSIVE SYSTEMS

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ABSTRACT

As the development of the nuclear industry, passive technology turns out to be a remarkable characteristic in the design of advanced nuclear power plants. Since the 20th century, much effort has been given to the passive technology, and a number of evolutionary passive systems have developed. Even more interest is placed on the passive technology after Fukushima because of its independence on off-site power.
In this paper, the CPR1000 plant, which is one kind of mature pressurized water plants in China, is improved with some passive systems to enhance safety. The passive systems selected are as follows: (1) the RMT (reactor makeup tank); (2) the A-ACC (advanced accumulators); (3) the IRWST (in-containment refueling water storage tank); (4) the PEFS (passive emergency feed water system), which is installed on the secondary side of SGs; (5) the PDS (passive depressurization system). These passive systems operate as a backup system for the original safety system of the CPR1000.
Utilizing the RELAP5/MOD3.3 code, an analysis of SBLOCA (small-break loss-of-coolant accident) of this passive CPR1000 plant was presented to demonstrate whether the passive systems could mitigate the consequences caused by the accident.
When the SBLOCA occurred, the RMTs were initiated to inject water into the pressure vessel. The low water level in the RMTs trigged the PDS, which depressurized the coolant system drastically. As the pressure of the coolant system decreased, the A-ACCs and the IRWST were put into work to prevent the core uncovery. The results show that, after the small-break loss-of-coolant accident, the passive systems can prevent the core uncovery and guarantee the safety of the plant.

KEYWORDS
CPR1000, passive systems, RELAP5/MOD3.3, SBLOCA

1. INTRODUCTION

After Fukushima, public requirements on the nuclear power plants became much stricter, so that the generation III nuclear power plant was decided to be constructed instead of the prior generations. It is obvious that the safety systems of most existing reactors cannot satisfy the safety requirements for the generation III NPP.[1] Consideration have been given to adopt passive technologies, so that the safety of the reactors could be enhanced. According to IAEA, the passive technologies are which utilize natural forces, such as gravity and natural circulation. And the passive safety systems should be composed entirely of passive components and structures. [2]

The advantages of the passive safety systems can be summarized into three aspects. Firstly, when normally functioning, the passive safety systems do not depend on pumps or external power[3], which lowers the risk faced by the reactor during some accidents(like SBO). Secondly, operators' action is not needed for the successful performance of the passive safety systems, which rules out human errors. Thirdly, when compared with "active" safety systems, the passive safety systems are more economical[4] because of their relatively concise layout. Recently, the passive safety systems are widely applied on advanced reactor designs such as the AP1000 in the USA, the Next Generation PWR in Japan[5], the WWER-1000 in Russia, the ESBWR in the Europe and so on.

Although the passive systems have become a remarkable characteristic in the design of advanced nuclear power plants, they face the risk of function failure as well. It is noted that, the combination of the passive safety systems and the "active" safety systems[6] is going to be the most optimized method to enhance the safety of the reactor. This method can be applied in the upgrade of the mature reactor designs, which are mostly equipped with "active" safety systems.

In this paper, a passive safety system, as a backup system for the original safety system, was applied on the CPR1000 plant to enhance the plant's safety. Utilizing the RELAP5/MOD3.3 code, an analysis of SBLOCA (small-break loss-of-coolant accident) of this passive CPR1000 plant was carried out to illustrate whether the passive systems could mitigate the accident consequences. The SBLOCA accident was chosen to be analyzed because it triggered all components of the passive safety system.

2. Description of the passive safety system

The components of the passive safety system are as follows: (1) the RMTs (reactor makeup tank); (2) the A-ACCs (advanced accumulator); (3) the IRWST (in-containment refuelling water storage tank); (4) the PEFS (passive emergency feed water system), which are installed on the secondary side of SGs; (5) the PDS (passive depressurization system).

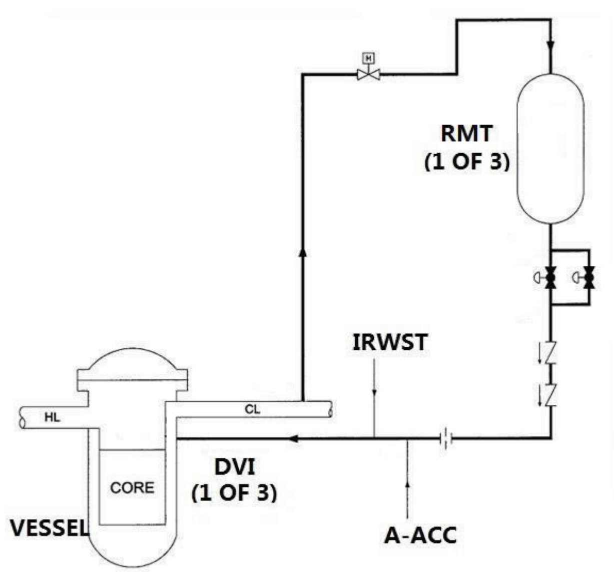

Figure 1. Schematic of RMT

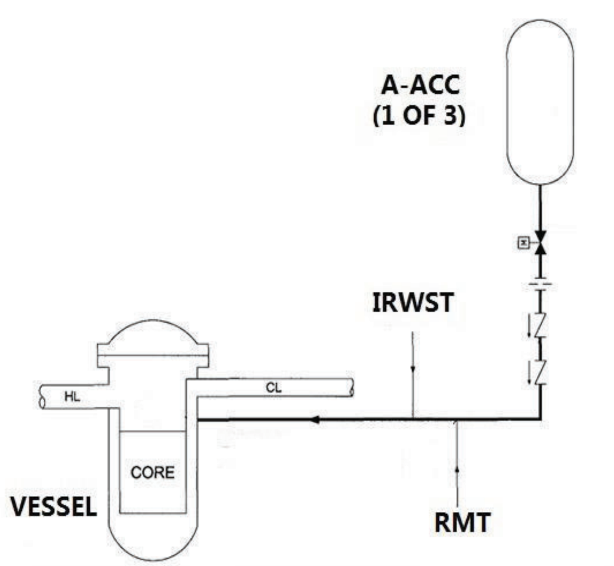

Figure 2. Schematic of A-ACC

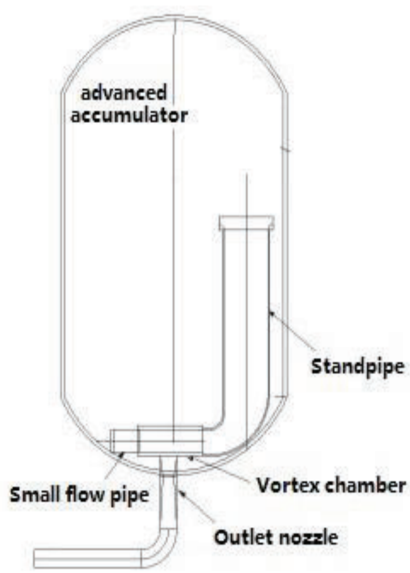

Figure 3. The advanced accumulator[9]

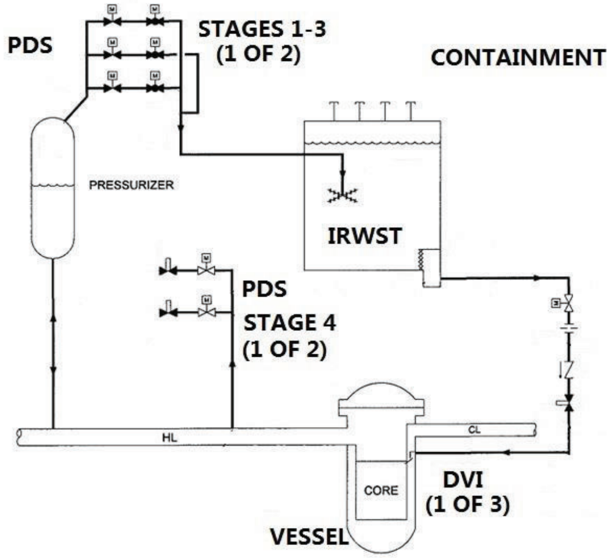

Figure 4. Schematic of IRWST and PDS

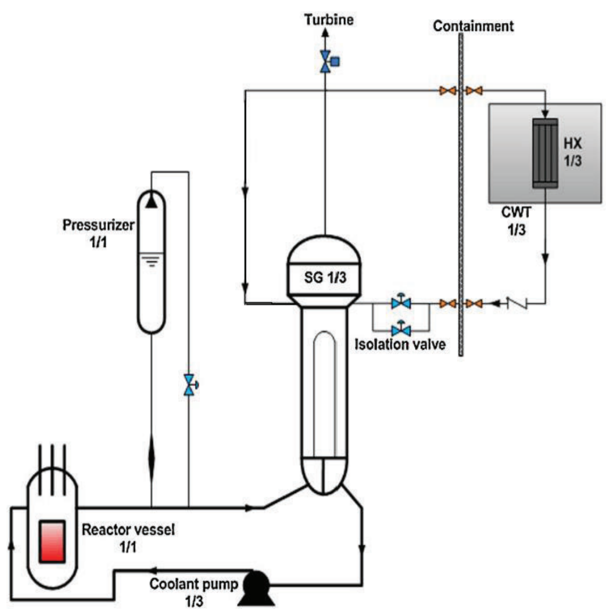

Figure 5. Schematic of PEFS[10]

2.1. RMT (reactor makeup tank)

Each loop contains a core makeup tank. The RMT(Figure 1), filled with boron water, is located above the RCS loops. Its inlet pipe, which keeps the system pressure balance, leads to one of the cold legs. The outlet pipe of the RMT leads to the DVI(direct vessel injection line). Boron water is going to be injected into the RPV downcomer through the DVI, when the RMT is triggered. The temperature of water in the RMT is roughly 323K. In this study, the RMTs will be trigged when the water level in the pressurizer drops below 3.305 meters.

2.2. A-ACC (advanced accumulator)

The advanced accumulator (Figure 2) includes a flow rate control device in the lower portion of the tank. When the accumulator is initiated, water will flow through the standpipe and pass directly through the control device to the outlet pipe. When the water level drops below the top of the standpipe, the flow path through the standpipe is broken and the flow switches to the side connection. This path sets up a vortex that causes a high pressure drop and a reduced outflow rate. In this way, a high initial flow rate followed by a much lower prolonged flow rate is achieved. The A-ACCs will be put into work when the system pressure drops below 4.5MPa. The internal structure of the A-ACC is showed in Figure 3.

2.3. IRWST (in-containment refuelling water storage tank)

The IRWST, which is showed in Figure 4, provides long-term injection water after the depressurization of the RCS. This large water tank locates above the vessel, and is isolated from the RCS by check valves. There are three pipes, leading from the bottom of the IRWST to the DVI.

2.4. PEFS (passive emergency feed water system)

The PEFS[7](Figure 5) is connected to the SG secondary side and includes a HX, a PEFS water tank, pipes and valves. It removes the core decay heat and primary loop sensible heat by natural circulation. There are three PEFSs, connecting to three SGs respectively.

2.5. PDS (passive depressurization system)

The design of PDS system, which is showed in Figure 4, consists of four stages depressurization valves that open sequentially. Each stage is arranged into two identical flow paths. [8] The stages (1-3) of PDS connect the top of pressurizer with a common discharge line to the IRWST. And the stage (4A and 4B) of PDS connect the RCS hot legs to the reactor containment.

3. Relap5 modeling

The best-estimate transient simulation code Relap5/MOD3.3 is utilized to carry out the calculation presented here. Figure 6 and Figure 7 show the nodalization of the CPR1000 and the passive system. The components (reactor vessel, core, pressurizer, coolant pumps, steam generators, RMTs, A-ACCs, IRWST and PDS) are modeled specifically by the code. The core of the reactor is divided into three parts, the average channel, the hot channel and the bypass channel. Other systems, such as the steam turbine, main feed water system, are modeled by time-dependent volume (TMDPVOL) and time-dependent junction (TMDPJUN).

The model for the PEFS is showed on Figure 8. Utilizing the RELAP5 code, the HX tank, the external cooling water tank(CWT) and the corresponding pipes are simulated. The HX tubes heat transfer is modeled by heat structure.

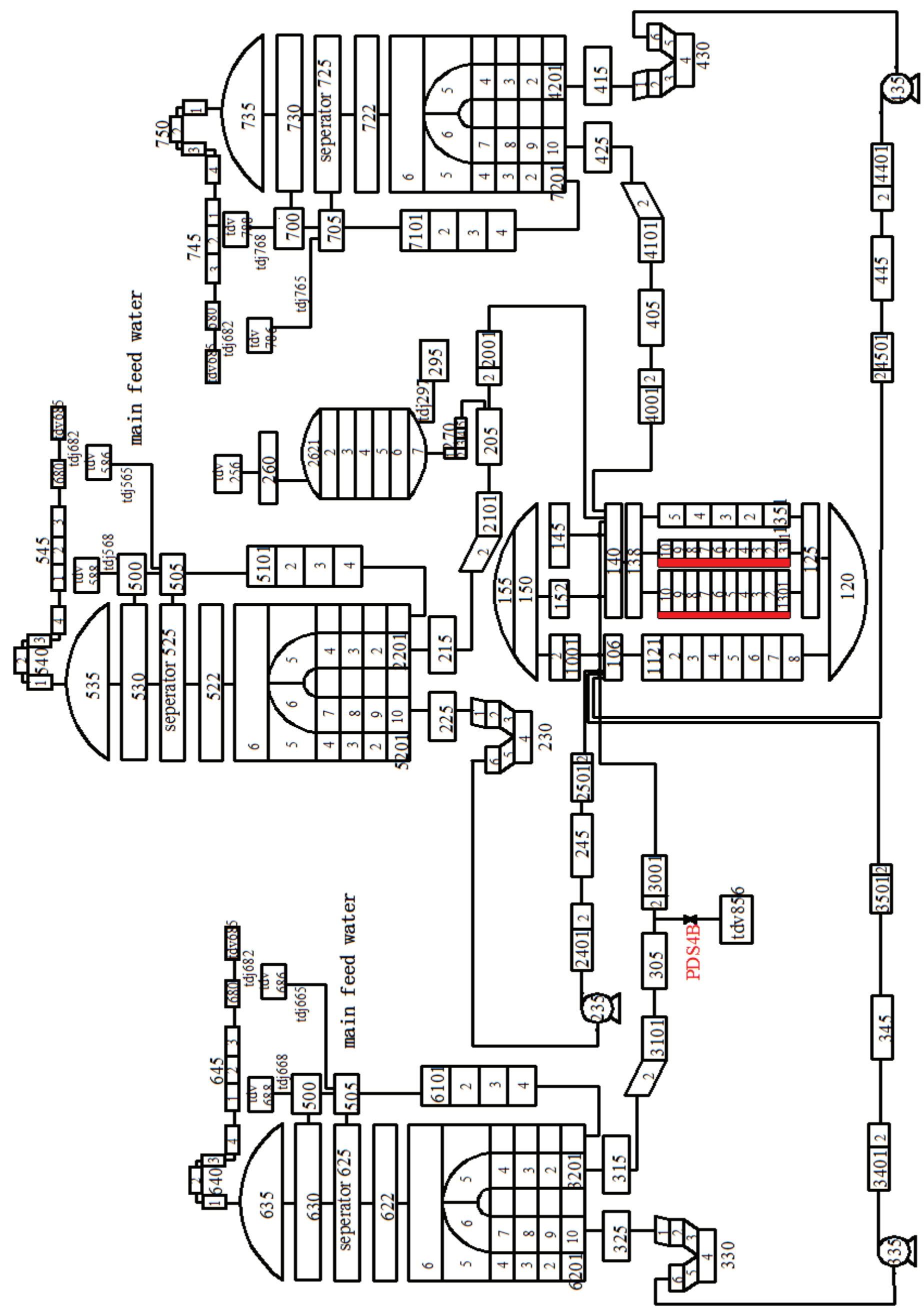

Figure 6. Relap5 nodalization of the CPR1000

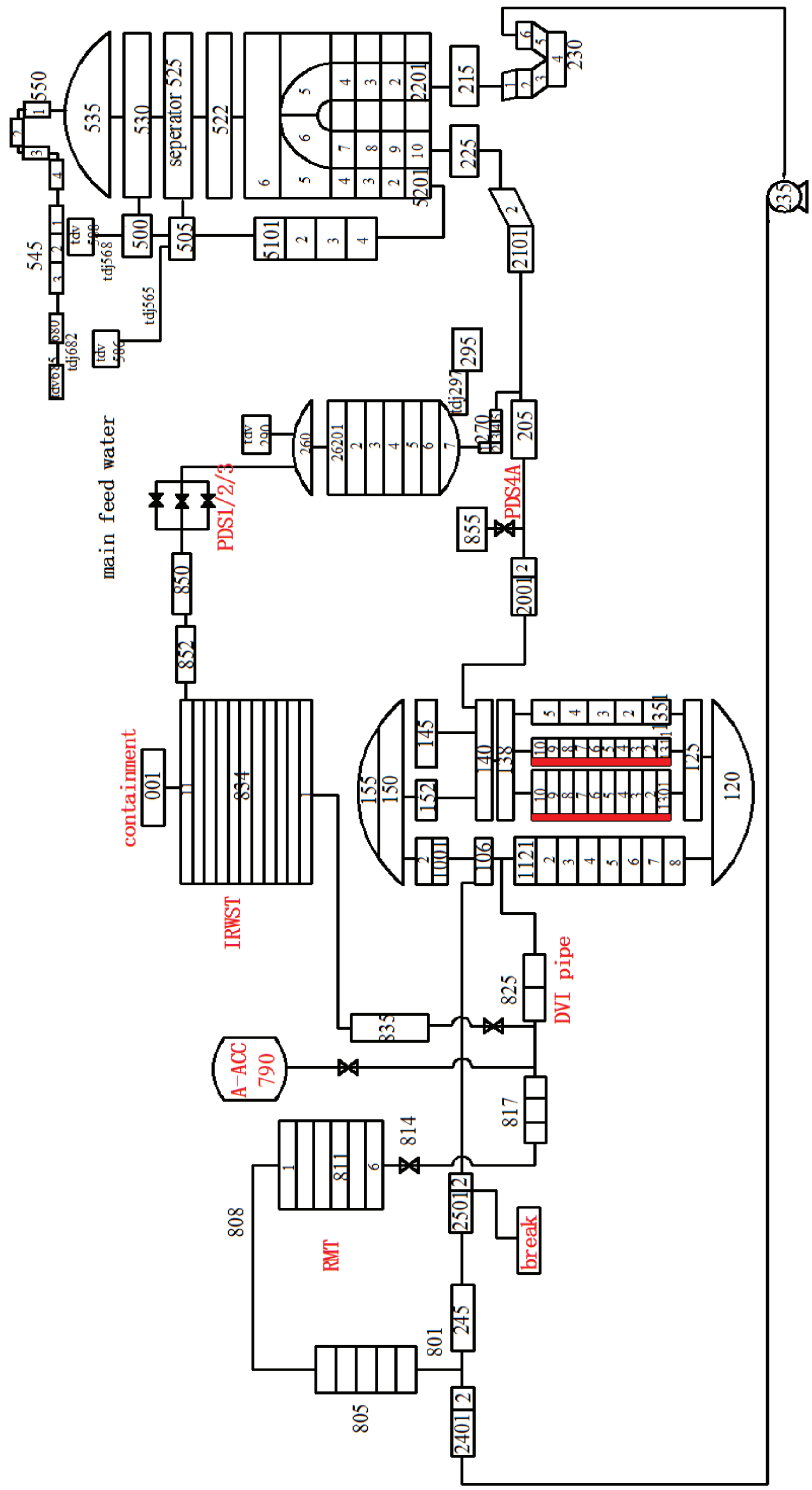

Figure 7. Relap5 nodalization of the passive system

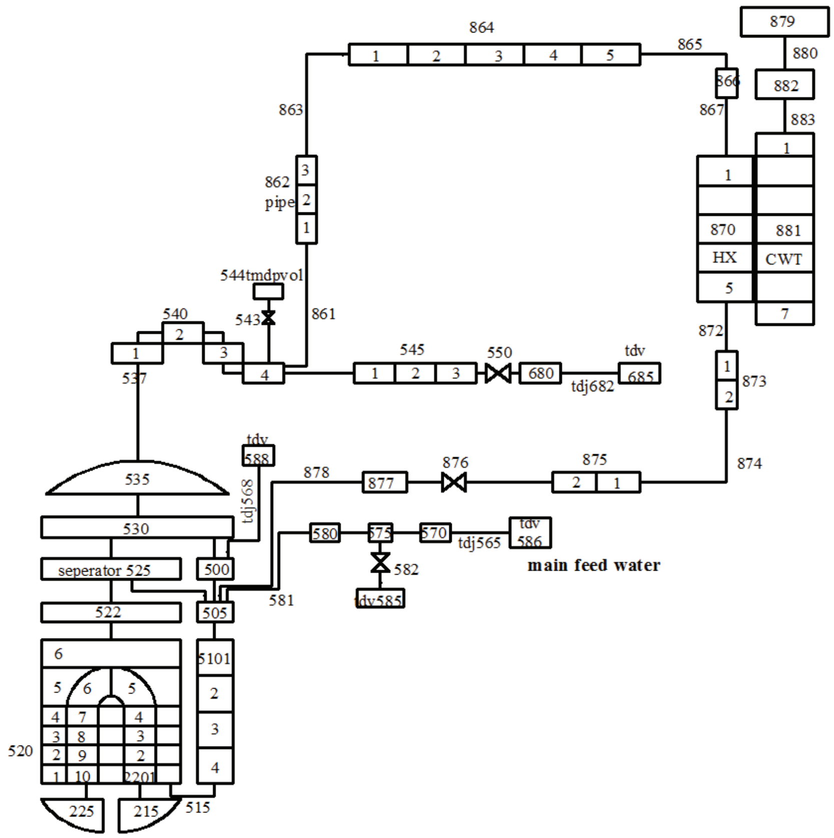

Figure 8. Relap5 nodalization of the PEFS

4. Results and discussions

4.1. Steady analysis

The initial state conditions of the reactor are showed in Table **I**.

Table I. initial state conditions

Parameter	Value
Reactor power (MWth)	2895.0
Coolant average temperature (℃)	310.0
Primary loop pressure (MPa)	15.5
Pump flow rate (kg/s)	4750
SG pressure (MPa)	6.56
Main feed water temperature (℃)	226.0
Main feed water flow rate (kg/s)	537.0

4.2. Signals and Assumptions in the analysis

There are several assumptions in the analysis of the SBLOCA accident.

1. As the reactor shut-down signal created, the inlet valve of the steam turbine closes;
2. As the reactor shut-down signal created, the nuclear power plant loses its off-site power;
3. The break(d=25mm) is on the cold loop;
4. One of the forth stage PDS valves fails to open after the accident.

The signals used in this study as follows:

1. When the system pressure drops below 12.93MPa, the reactor shut-down signal is trigger;
2. The reactor should be shut down within 4.2s after the reactor shut-down signal;
3. The coolant pump and the main feed water pump stops after the reactor shut-down signal because of the loss of the off-site power assumption.

4.3. SBLOCA analysis

The characteristics of the reactor are analyzed through Figure 3 to Figure 18. The SBLOCA accident is assumed to occur at 0s. The accident sequence of the SBLOCA is on Table II.

Table II. SBLOCA accident sequence

Event	Time/s
SBLOCA occurs	0.0
RMT trigged	180.0
Shut-down signal	186.0
Loss of off-site power	186.0
PEFS trigged	200.0
Reactor shut down	200.4
PDS trigged	2650.0
A-ACC trigged	2750.0
IRWST trigged	3250.0

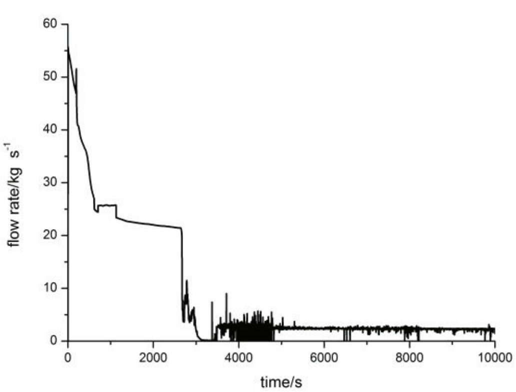

Figure 9. flow rate through the break

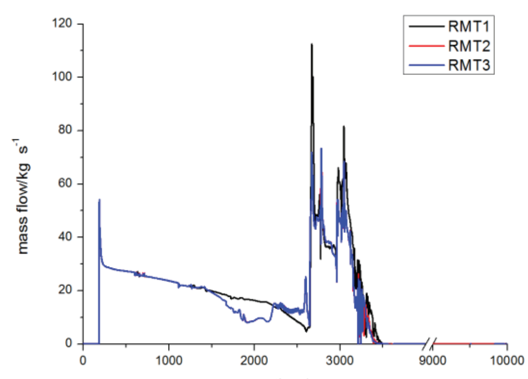

Figure 10. flow rate of RMTs

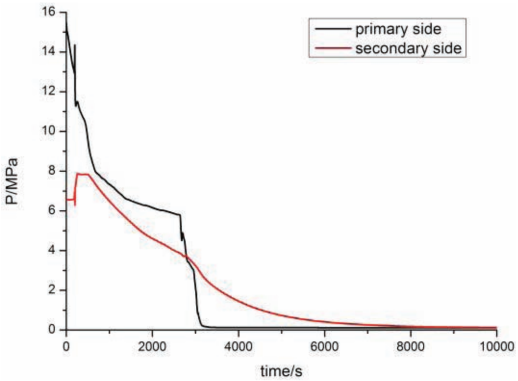

Figure 11. system pressure

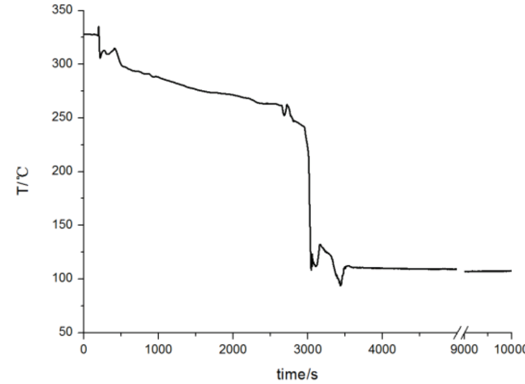

Figure 12. core outlet temperature

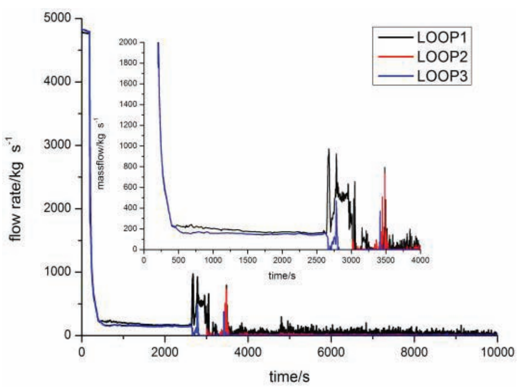

Figure 13. flow rate of the loops

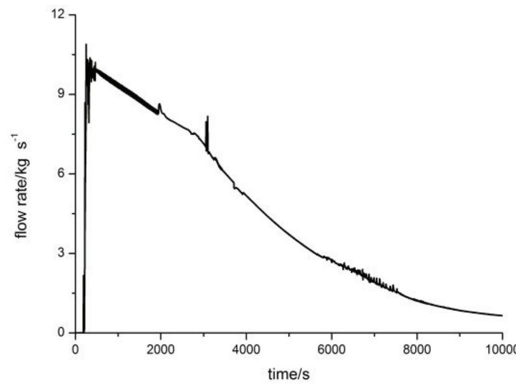

Figure 14. flow rate of the PEFS

After the SBLOCA accident occurred at 0s, the coolant flowed out of the RCS as showed in Figure 9. The break flow rate changed with the system pressure. When the PDS were triggered, the flow rate dropped. The loss of coolant decreased the PRZ water level and trigged RMTs (Figure 10) at 180s after the accident. Before the system depressurization, the boron water in the RMTs was injected into the downcomer due to natural circulation. After the depressurization, the water in the RMTs was injected into the pressure vessel due to gravity.

Figure 11 shows the variation of system pressure. When the pressure in the PRZ dropped to 12.93MPa, the shut-down signal was created and the reactor lost its off-site power immediately. Thus, the main feed water pump and the coolant pump were out of work. As the system pressure dropped, the PEFSs were trigged at 200s after the accident(showed in Figure 14). Before the PDS triggered, the system pressure and the coolant temperature dropped gently due to the function of the PEFSs and the RMTs.

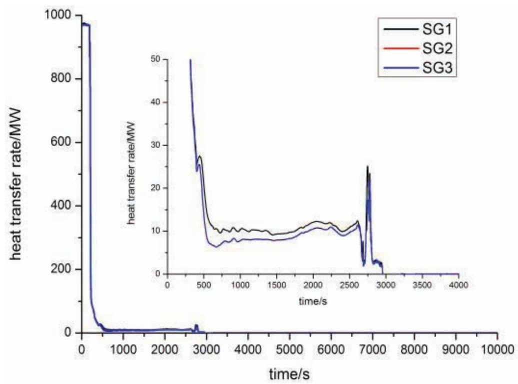

Figure 15. SGs heat transfer rate

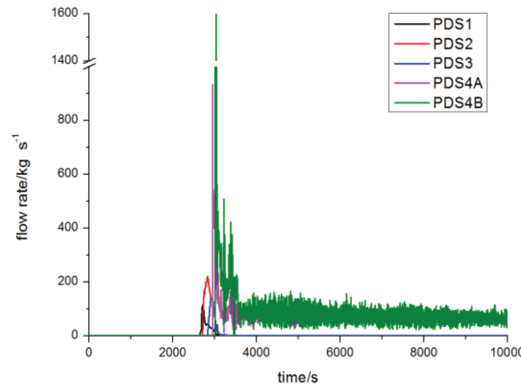

Figure 16. PDS flow rate

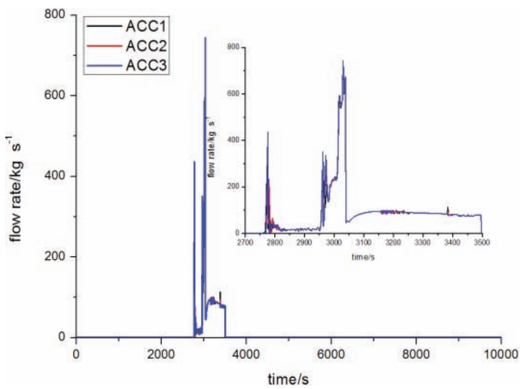

Figure 17. A-ACC flow rate

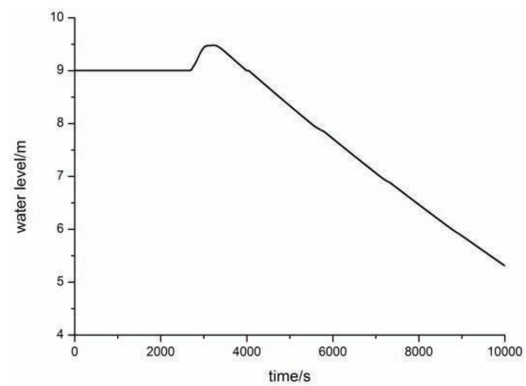

Figure 18. water level in the IRWST

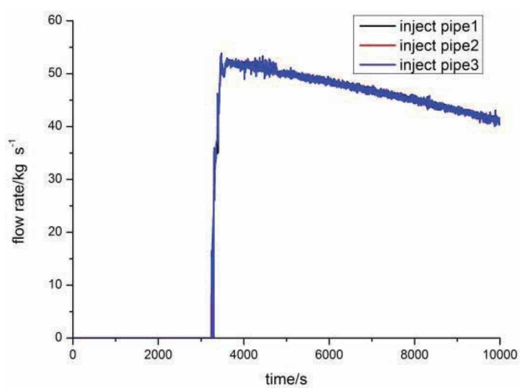

Figure 19. IRWST flow rate

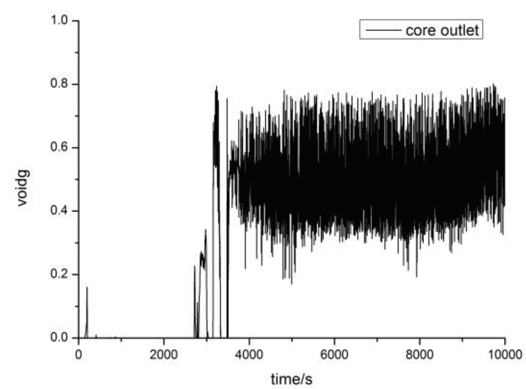

Figure 20. void fraction of the core outlet zone

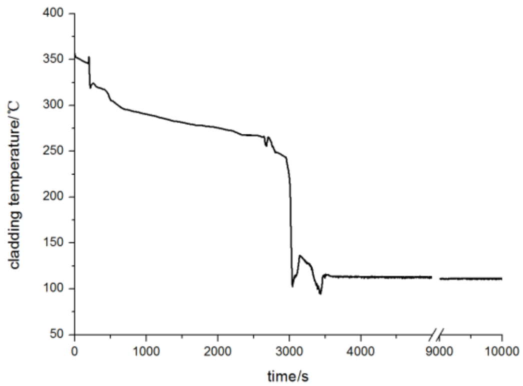

Figure 21. maximum cladding temperature

At 2600s after the accident, the low water level in the RMTs activated the PDS. The flow rate of each stage PDS is presented in Figure 16. The system pressure dropped drastically because of coolant's loss. The initiation of the PDS also led to the fluctuation in heat transfer rate of the SGs and stopped the natural circulation in the loops. After that, the PEFSs stopped cooling the primary system. As showed in Figure 18, the water level in the IRWST increased when the PDS was activated. It was because the first three stags of the PDS connected the PRZ and the IRWST, the discharged coolant contributed to the water inventory of the IRWST.

As the pressure dropped to 4.5MPa, the A-ACC started to work. The flow rate of the A-ACC is showed in Figure 17. Its large-flow-rate period lasted for about 300s. And the small-flow-rate period lasted for about 500s. The void fraction of the core outlet zone rose after the A-ACCs stopped injecting water into the system, which can be discovered in Figure 20.

Trigged by the low system pressure, The IRWST started to inject water into the vessel at 3250s after the accident. After 3500s, only the IRWST provided the subcooled water for the reactor core. The system pressure, the coolant temperature, the flow rate of the PDS valves and the flow rate of the break became stable within 5000s after the SBLOCA accident. As presented in Figure 20, there was no core uncovery after the accident. The maximum cladding temperature, which is showed in Figure 21, was controlled below the limit(1204.44 ^{o}C) .

5. CONCLUSIONS

To improve the safety of the CPR1000 NPP, a set of passive safety system was applied on the plant as the backup for the original safety system. Utilizing the RELAP5/MOD3.3 code, the thermal-hydraulic behavior of the improved reactor after the SBLOCA accident was studied. Based on the analysis, the following conclusions can be acquired:

- After the SBLOCA, the components of the passive safety system were put into work sequently, which prevented the core uncovery and kept the cladding temperature below the limit.
- With the water injected by the IRWST, the reactor's thermal-hydraulic state became relatively stable within 5000s after the SBLOCA accident.
- The analysis of this paper verified the reliability and effectiveness of the designed passive safety system after the SBLOCA accident.

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