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# SGTR analysis on CPR1000 with a passive safety system

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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 been developed. The CPR1000 plant, which is one kind of mature pressurized water plants in China, is proposed to be improved with some passive systems to enhance safety. The proposed passive systems include: (1) the RMT (reactor makeup tank); (2) the ACC (accumulator); (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). In modifying the passive safety system, it is found that the actuation conditions of the passive safety system and the accident assumptions bring great effects on the accidental mitigation. It is necessary to study the influence induced by them. In this paper, the transient phenomenon of SGTR is analyzed to show the process in the modification of the actuation conditions and the assumptions. Finally, the most proper assumptions and actuation conditions are determined. Through the sensitivity analysis, it is found that the RMTs' and PEFSs' behaviors bring a great impact on the accident transient. The strong mutual effect between each passive safety component in the SGTR is the reason of choosing this accident to analyze in this paper.

## 1. Introduction

Passive safety systems are widely used nowadays to enhance the safety of reactors. According to the IAEA report, the passive technologies are those utilize natural forces, such as gravity and natural circulation. And the passive safety systems should be composed entirely of passive components and structures (Juhn et al., 2000). The advantages of the passive safety systems can be summarized as (1) independent on pumps or external power (Nayak and Sinha, 2007); (2) ruling out human errors; and (3) more economical.

The passive safety systems are widely applied on advanced reactor designs such as the AP1000 and the ESBWR in the USA, the Next Generation PWR in Japan, the WWER-1000 (Timofeev and Karzov, 2006) in Russia, and so on. Among them, the AP1000 (Sutharshan et al., 2011) adopts an entirely passive safety system. Its technology is relatively mature. The Nest Generation PWR (Tujikura et al., 2000) is equipped with a passive safety system which acts as a backup system to prevent core damage. The APR1400 (Kim and Kim, 2002a) in Korea applied several passive systems. Unlike AP1000, the APR1400 adopts a secondary passive heat removal system, which is also used to improve the CPR1000 technology (Zhang et al., 2011). As for the passive containment cooling system, Byun et al. (2000) designed a semi-passive containment cooling system for a large concrete containment and Gavrilas et al. (2000) designed a passively cooled containment for a high-rating pressurized water reactor.

CPR1000 (as shown in Fig. 1) is a Chinese GEN II PWR with 3 loops. Each loop consists of a pump, a steam generator, and corresponding pipes. A pressurizer is placed on the hot leg of one loop. The reactor's standard safety systems include a safety injection system, a containment spray system, an auxiliary feed water system, and so on. To further enhance CPR1000's safety, after the accident of Fukushima, the Chinese government started a national project which targeted to promote CPR1000's safety system. As a part of this project, a combined passive safety system is equipped on CPR1000 to enhance the plant's safety.

Due to the application of the passive safety system, the standard accident assumptions of the CPR1000 are not proper any more. Based on some advanced reactors' technologies, accident assumptions have to be adjusted firstly. With the changed assumptions, some actuation conditions of safety components also need modification to ensure that all components can co-operate smoothly to mitigate the accidents. With a set of more proper actuation conditions, sensitivity analyses are required to ensure whether these accident assumptions can lead to the most dangerous accidental transient. If the answer is no, further

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**Nomenclature**

*Symbol*

| | |
|---|---|
| RMT | Reactor makeup tank |
| ACC | Accumulator |
| IRWST | In-containment refueling water storage tank |
| PEFS | Passive emergency feed water system |
| PDS | Passive depressurization system |
| CWT | External cooling water tank |
| HX | Heat exchanger |
| SGTR | Steam generator tube rupture |
| PRZ | Pressurizer |
| RCV | Chemistry and volume control system |
| RCS | Reactor coolant system |
| MSIV | Main steam isolation valve |
| LOOP | Loss of the off-site power |

modifications should be continued to acquire the most proper accident assumptions and safety system's actuation conditions. In this paper, the modification process of the accident assumptions and the passive safety system's actuation conditions are presented. The SGTR accident is chosen as an example. The SGTR is considered as one of the design basis accidents having a significant impact on safety in a viewpoint of radiological release (Jiang et al., 2010; Park et al., 2013). The reason of choosing this accident is that the application of PEFSs greatly affects the transient phenomenon during SGTR, which attracts much research interest (Kang et al., 2006; Kang et al., 2012; Lee et al., 2011).

## 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 ACCs (accumulator); (3) the IRWST (in-containment refueling water storage tank); (4) the PEFSs (passive emergency feed water system), which are installed on the secondary side of SGs; (5) the PDS (passive depressurization system). The main parameters of the combined passive safety system are shown on Table 1.

### *2.1. RMT (Reactor makeup tank)*

Each loop contains a reactor makeup tank. The RMT (Fig. 2), 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 injected into the RPV down-comer through the DVI when the RMT is triggered. The temperature of water in the RMT is around 323 K. The RMT's height is 6 m and its volume is 50 $m^3$.

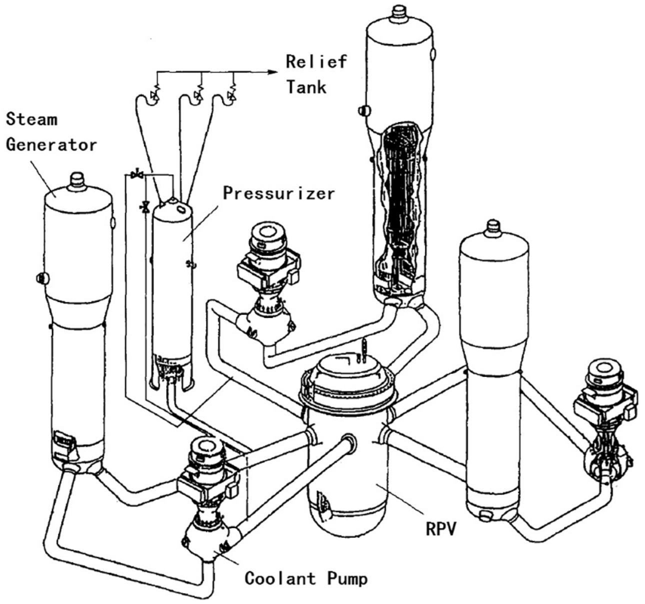

**Fig. 1.** Schematic of CPR1000 coolant system.

### *2.2. ACC (accumulator)*

Each loop contains a CPR1000's standard accumulator. The accumulators (Fig. 3) are connected to the direct vessel injection lines. The ACCs will be put into work when the system pressure drops below 4.5 MPa. Its total volume is 90 $m^3$, and its water volume is 72 $m^3$.

### *2.3. IRWST (in-containment refueling water storage tank)*

The IRWST, which is shown in Fig. 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. The water level in the IRWST is 8.5 m in height. And the water volume is 2000 $m^3$.

### *2.4. PEFS (passive emergency feed water system)*

There are three PEFSs, connecting to three SGs respectively. The PEFS (Fig. 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 the primary loop sensible heat by the natural circulation. When it is put into work, the steam in the SG goes into the heat exchanger tubes. The condensation occurs in the heat exchanger, and the water flows into the SG to cool down the primary system. Two parallel isolation valves are located on each PEFS. The heat transfer area of each heat exchanger is 100 $m^2$. The water tank contains 2500 $m^3$ water in it.

### *2.5. PDS (Passive depressurization system)*

The PDS system, which is shown in Fig. 4, consists of four-stage depressurization valves that open sequentially. Each stage is arranged into two identical flow paths (Hashim et al., 2014). The stages (1–3) of the PDS connect the top of pressurizer with a common discharge line to the IRWST. And the stage4 (4A and 4B) of the PDS connects the RCS hot legs to the reactor containment. The valves of the stage1 open as the water level in the RMTs drops to a specific position (67.5%). And other valves of the PDS will open in sequence. During the depressurization, the coolant is firstly injected into the IRWST through the valves of stage

**Table 1**
Main parameters of the combined passive safety system.

| Parameter | Value |
|---|---|
| RMT's height (m) | 6 |
| RMT's volume ($m^3$) | 50 |
| ACC's total volume ($m^3$) | 90 |
| ACC's water volume ($m^3$) | 72 |
| PEFS's heat transfer area ($m^2$) | 100 |
| IRWST's water volume ($m^3$) | 2000 |
| IRWST's water level (m) | 8.5 |
| PDS stage 1 valve area ($mm^2$) | 29.68 |
| PDS stage 2&3 valve area ($mm^2$) | 135.48 |
| PDS stage4 (A&B) valve area ($mm^2$) | 432.26 |