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Research Article

Design, Experiment, and Commissioning of the Passive Residual Heat Removal System of China's Generation III Nuclear Power HPR1000

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In response to a station blackout accident similar to the Fukushima nuclear accident, China's Generation III nuclear power HPR1000 designed and developed a passive residual heat removal system connected to the secondary side of the steam generator. Based on the two-phase natural circulation principle, the system is designed to bring out long-term core residual heat after an accident to ensure that the reactor is in a safe state. The steady-state characteristic test and transient start and run test of the PRS were carried out on the integrated experiment bench named ESPRIT. The experiment results show that the PRS can establish natural circulation and discharge residual heat of the first loop. China's Fuqing no. 5 nuclear power plant completed the installation of the PRS in September 2019 and carried out commissioning work in October. This debugging is the first real-world debugging of the new design. This paper introduces the design process of the PRS debugging scheme.

1. Preface

HPR1000 reactor, an advanced third-generation reactor, has been developed by China National Nuclear Corporation (CNNC). The design is based on CP1000 [1] and upgraded according to the experience feedback from Fukushima accident. CDF and LRF of HPR1000 are less than 1×10^{-6}/reactors years and 1×10^{-7}/reactors years, respectively [2].

A major improvement of HPR1000 design is using three passive systems to mitigate beyond design-basis accident. They are PRS (passive residual heat removal system), PCS (passive containment cooling system), and CIS (core injection system).

Similarly, the passive systems are used in third-generation reactors all over the world, such as AP1000 [3, 4], VVER1000 [5], and APR1000 [6]. The passive safety system can not only improve the safety performance but also reduce the cost of the NPPs, making nuclear power a safer and economical choice.

The secondary passive residual heat removal system of HPR1000 is one of the means to remove residual heat of the reactor; it can improve the ability of defense in depth and enrich mitigation measures to severe accidents. It is designed to comply the following functions: in the event of SBO and the auxiliary feedwater system failure conditions, to export decay heat of the core and heat stored in each device within 72 hours to maintain the reactor in a safe shutdown condition, and to ensure the safety of the reactor and reduce the CDF.

2. Introduction to the PRS

The PRS [1] consists of three trains associated to the RCS loops. Each train (Figure 1) includes an emergency heat exchanger, two emergency make-up tanks, a heat transfer tank, and the necessary piping, valves, and instruments.

Taking the first train, for example, the steam line equipped with a motor-driven valve connected to the main

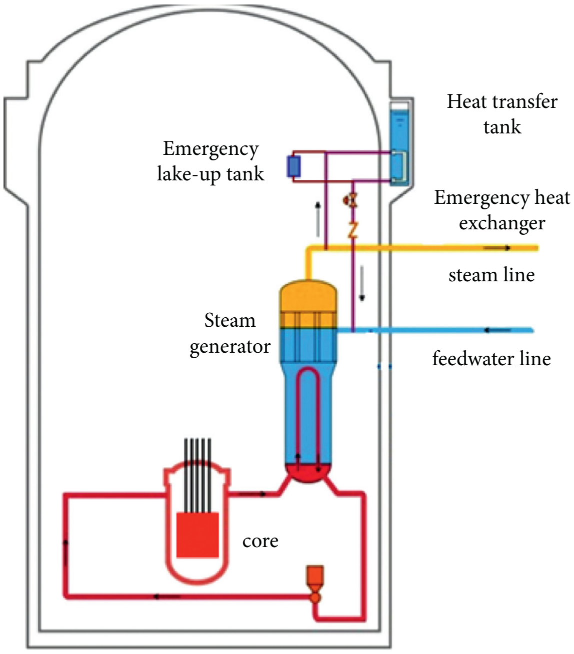

Figure 1: Schematic diagram of the PRS.

steam line penetrates through the containment and splits into two branches outer containment: one branch connects to the emergency heat exchanger and another one connects to the emergency make-up tanks. The emergency heat exchanger is seated on the bottom of the heat transfer tank and submerged in it, while the emergency make-up tanks are seated on the same level with the heat exchanger. The condensate line equipped with two parallel connected isolation valves from the heat exchanger combined with the one from make-up tanks, which is also equipped with two parallel connected isolation valves, penetrates back the containment and then connects to the feedwater line of the steam generator. There is a check valve on the condensate line inner containment so as to avoid back flow of feedwater during normal operation.

The PRS emergency heat exchanger is located in the accident cooling tank, which provides the heat sink for the PRS emergency heat exchanger. The PRS emergency heat exchanger consists of a bank of C-tubes, connected to a top (inlet) tube sheet and bottom (outlet) tube sheet. The PRS emergency heat exchanger is connected to the steam line through the inlet line and to the condensate line through the outlet line.

As the final heat sink for the PRS, the heat transfer tanks, shared with the PCS, are located equally out of the containment and integrated with the containment with a high level. Every cooling tank consists of two connective portions, i.e., water tank and heat exchanger room, where the emergency heat exchanger is located. The total volume of the tank (shared with 3 trains) is designed to supply the system operation in 72 hours.

3. Experiment of the PRS

3.1. ESPRIT Facility. A test facility called ESPRIT [7, 8] is built in CNNC, and some tests have been done to verify the running ability of the secondary passive residual heat removal system (PRS). The simulation factor of ESPRIT is 1/62.5. The main design parameters are as follows:

(i) The ratio for power and volume is 1 : 62.5
(ii) The elevation of the loop and the altitude difference between the cold core and the hot core are equaled to the prototype
(iii) The same working fluid is used
(iv) Working fluid, pressure, and temperature are the same with the prototype
(v) The same friction coefficient is used for the steam line and condensate line
(vi) The tube of SG is with the same outer diameter and spacing
(vii) The same tubes and tube spacing are used, and the number ratio is 1/62.5

The test facility consists of the following systems: steam-water natural circulation system, pool heat removal system, steam emission branch, and auxiliary systems. Figure 2 shows the flowchart of the ESPRIT facility.

3.2. Steady-State Test. Steady-state tests are used to test the PRS operating characteristics at different heating powers and different initial conditions. The initial conditions of four tests are listed in Table 1. The results of tests are shown in Table 2. The program RELAP5 [9] is used to simulate the experiment to verify the simulation ability of RELAP5.

It can be found that the results of RELAP5 are consistent with tests. The calculated pressure increased faster than tests. The calculated pressure is lower in SS1, but it is higher in SS4.

3.3. Transient Test. Transient test is used to validate the operation ability of the PRS in 72 hours. The test process is divided into two steps. Step one is to establish the initial condition of the SG simulator, a water level of 8.3 m, and a pressure of 7.85 MPa. Step two is to close the pneumatic control valve to make the pressure increase. Once the pressure reaches 7.85 MPa, the PRS is activated immediately.

During the first 800 s, steam has not entered the tubes, the depressurization rate of the transient test is greater than the value calculated by the RELAP5 program, and the times GCT-a valves open are less than results of RELAP5 as shown in Figure 3. This is because RELAP5 lacks the ability to simulate the steam direct contact condensation in the make-up tank. The larger direct contact condensation rate at the top of the make-up tank will reduce the top pressure and then cause the smaller flow at the outlet of the make-up tank.

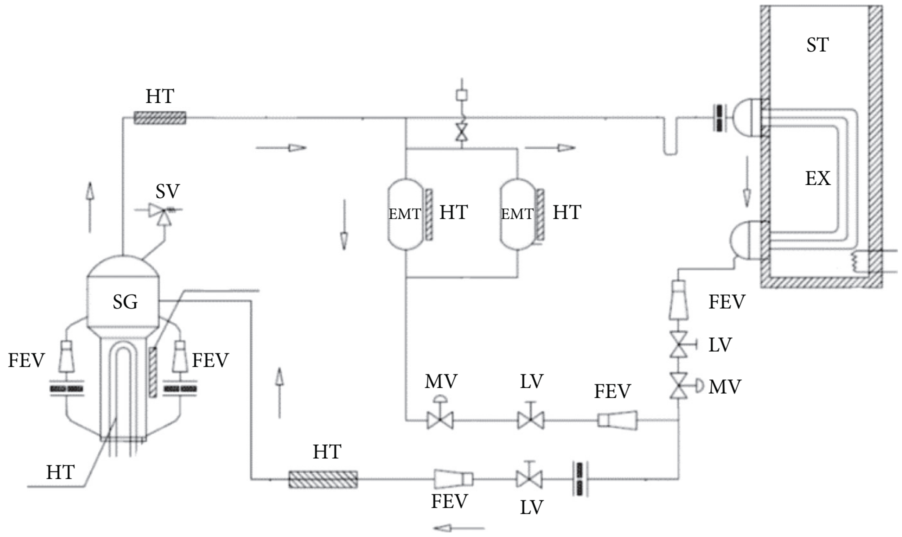

Figure 2: Flowchart of the ESPRIT facility. SG: steam generator; SV: safety valve; FEV: Venturi flowmeter; HT: heater; EMT: emergency make-up tank; ST: safety tank; EX: heat exchanger; LV: manual valve; MV: motor valve.

Table 1: The initial conditions of four steady-state tests.

	SG pressure (MPa)	SG level (m)	SG power (% FP)
SS1	0.35	13.7	0.1
SS2	0.35	13.7	0.5
SS3	7.85	13.7	0.5
SS4	7.85	13.7	0.8

Table 2: Comparisons between tests and RELAP5.

Parameters	SS1		SS2		SS3		SS4	
	Test	RELAP5	Test	RELAP5	Test	RELAP5	Test	RELAP5
Power (kW)	52.0	62.2	250.9	259.4	249.6	269.0	426.9	434.7
SG level (m)	13.07	13.06	13.62	13.62	13.78	13.64	13.78	13.76
SG pressure (MPa)	0.21	0.167	0.53	0.485	0.515	0.500	0.915	0.964
Flow rate (kg/h)	0~398	100.0	430	432.5	442	449.4	692	690.3
Inlet temperature of the heat exchanger (°C)	113.7	112.1	145	142.5	142.9	143.4	168.8	172.53
Outlet temperature of the heat exchanger (°C)	111.9	111.9	138.3	141.5	132.7	142.31	121.9	122.4

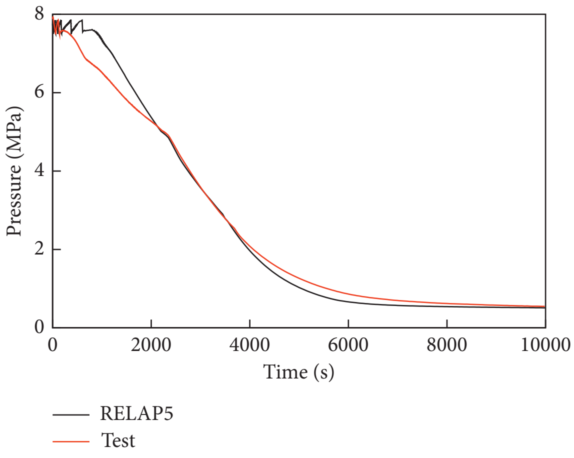

Figure 3: Pressure of the SG simulator.

Figure 4 shows the effect of direct contact condensation on the make-up tank flow.

During 800 s to 3400 s, steam flows into the heat exchanger, depressurization rate becomes larger because condensation in the tubes is the major reason, and direct contact condensation almost disappears. At about 2400 s, the depressurization rate of the test and the calculated value by RELAP5 decrease. It is caused by the change of heating power.

After 3400 s, the flow rate of the heat exchanger becomes larger after emptying of the make-up tank, which can be found in Figures 4 and 5. Before 8000 s, RELAP5-calculated pressure is lower than the test value, and after 8000 s, they are basically identical. During the long-term operation period from 3400 s to 72 h, the calculated results of PRS flow are basically consistent with the test results (Figure 6).

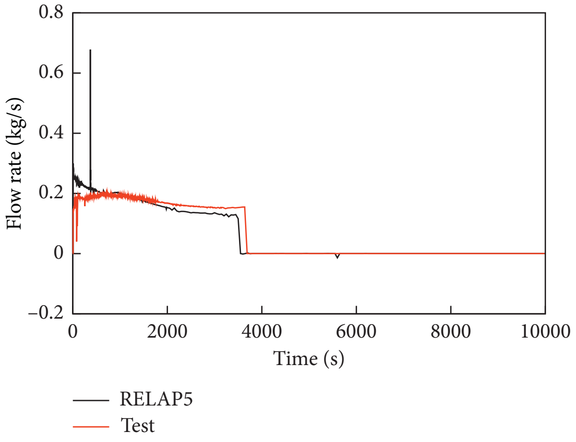

Figure 4: Flow rate of the make-up tank.

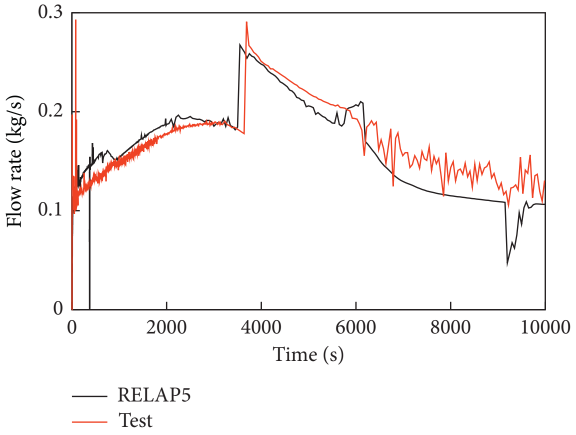

Figure 5: Flow rate of the heat exchanger.

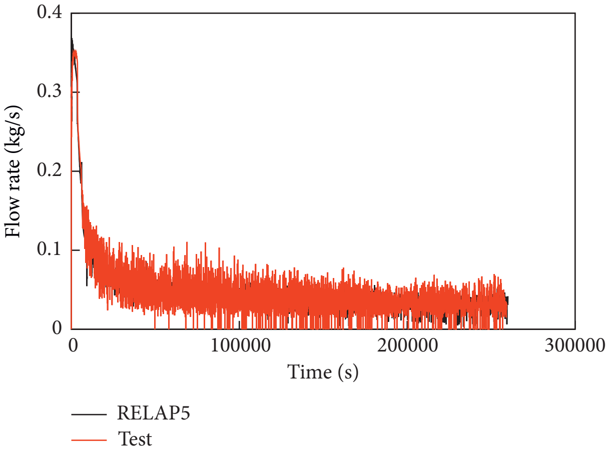

Figure 6: Flow rate of the SG feedwater line.

4. Commissioning Test Design

The Fuqing no. 5 nuclear power plant is the first power plant of HPR1000 and planned to carry out the commissioning test of the PRS. The purpose of this commissioning test is to verify the capacity of the PRS in the real reactor.

It is not necessary to completely simulate SBO. At the same time, in order to avoid the safety risks of simulating SBO accidents, the designed verification method does not simulate SBO accident sequences and only considers a hypothetical sequence. This hypothetical sequence can reflect the operating phenomenon of the PRS during SBO.

The RELAP5 procedure is used as a means to obtain a feasible test plan. After design evaluation, the commissioning test method is as follows:

(1) The test is carried out during the hot-state commissioning.

(2) The reactor system is controlled as the following initial state:

  (a) The three main pumps remain operational
  (b) To prevent the pressurizer heater from being exposed, the initial level of the regulator is controlled at 50% of the span
  (c) In order to provide sufficient heat capacity, the initial average temperature of the primary circuit is controlled at 291.7°C
  (d) To ensure adequate subcooling, the initial pressure of the pressurizer is controlled at 15.5 MPa
  (e) The initial level of the steam generator is controlled at 50% of the range, and the secondary side pressure is automatically controlled at 7.6 MPa through the steam bypass valves to atmosphere

(3) The feedwater system is closed, and the isolation valve of one PRS is manually opened.

(4) The three main pumps are kept running, and the water level and pressure of the pressurizer are automatically controlled.

(5) The pressure and temperature of the first and second circuits and the level of the steam generator during the test are monitored. When the test stop condition is reached (the average temperature of the hot section is lower than 270°C), the PRS is stopped.

(6) The reactor is recovered at the thermal shutdown state.

(7) The heat transfer power of the PRS is calculated, and it is compared with the acceptance criteria. If the test power is greater than the acceptance criterion, it indicates that the heat transfer capacity of the PRS meets the design requirements.

The preanalysis of the above test procedure is done by the RELAP5 program. It is assumed that feed water will be shut down first at 0 s, but the PRS has not been put into operation. In this stage, the heat removal through SG will be reduced, and the coolant temperature (Figure 7) and the pressure of the pressurizer (Figure 8) will rise. With the operation of the PRS, the flow rate of the PRS (Figure 9) increases rapidly, the heat removal through the SG increases, the coolant

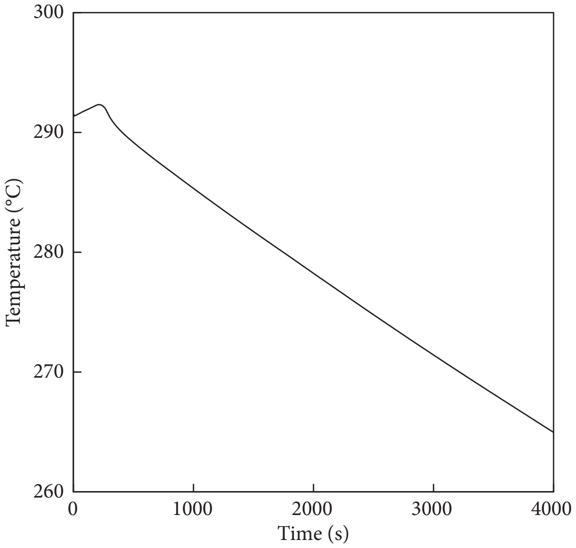

Figure 7: The average temperature of the primary circuit.

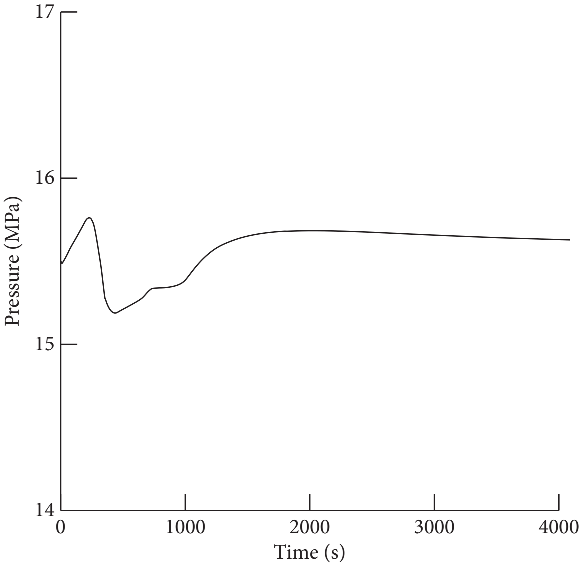

Figure 8: The pressure of the pressurizer.

temperature decreases continuously, and the pressure of the pressurizer decreases. When the pressure drops to the setpoint, the electric heater runs, the electric heater is put into operation, and the pressure rises. Figure 10 shows the heat transfer power criterion value of the PRS which is calculated by the flow rate and enthalpy difference between the inlet and outlet of the heat exchanger.

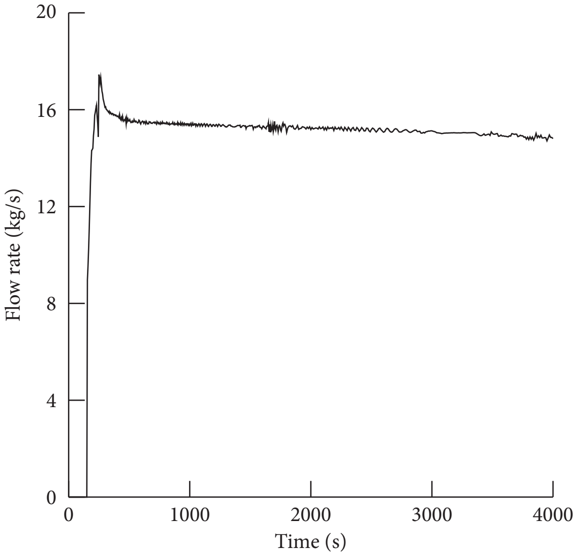

Figure 9: The flow rate of the PRS.

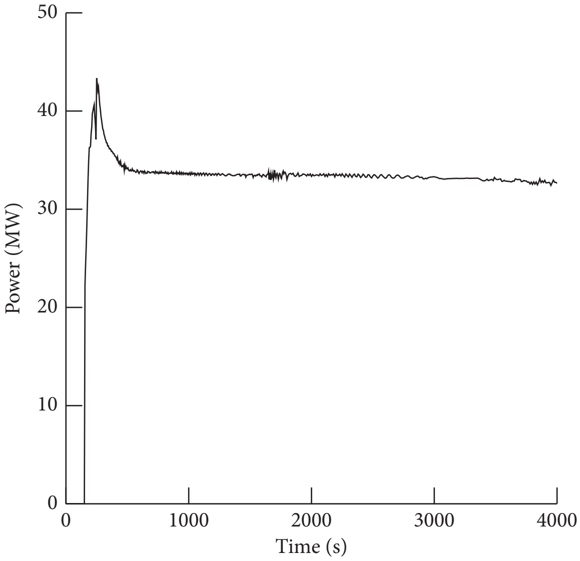

Figure 10: Heat transfer power of the PRS.

5. Conclusion

HPR1000 designed and developed a passive residual heat removal system connected to the secondary side of the steam generator to migrate a station blackout accident similar to the Fukushima nuclear accident.

The steady-state characteristic test and transient start and run test of the PRS were carried out on the integrated experiment bench named ESPRIT. The experiment results show that the PRS can establish natural circulation and discharge residual heat of the first loop.

The results obtained by RELAP5 are compared to these tests, and it showed that the RELAP5 program has a relatively accurate simulation capability.

The Fuqing no. 5 nuclear power plant planned to carry out the first commissioning test of the PRS. In order to obtain a reasonable test method, RELAP5 is used. The designed debugging test method can meet the goal of verifying the heat removal capacity of the PRS and minimizing the thermal safety risk. The test method could be used in the first commissioning test of the PRS.

Data Availability

The data used to support the findings of this study were supplied by Li Feng under license and so cannot be made freely available. Requests for access to these data should be made to Li Feng (104122587@qq.com).

Disclosure

The initial version of this article was published in the NURETH-16 conference. After further in-depth research, the content was modified and enriched, and finally, this article was obtained.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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