Review of performance testing methods for AP1000 passive safety systems

Heerim Choi [a], Youngjae Park [a], Seong-Su Jeon [a*]
[a] FNC Technology Co., Ltd., 32F, 13 Heungdeok 1-ro, Giheung-gu, Yongin-si, Gyeonggi-do, 16954, Republic of Korea
* Corresponding author: ssjeon@fnctech.com

***Keywords : passive safety system, performance testing method, AP1000, PXS, PCS**

1. Introduction

The safety of conventional nuclear power plants has been established based on active safety systems. After the Fukushima accident, the need for Passive Safety Systems(PSS) has been emphasized. These systems must be able to maintain safety functions during conditions such as a station blackout or when operator actions are not possible. Consequently, various types of PSS has been developed, and they have become essential elements for ensuring the safety of new reactor designs.

PSS operate based on fundamental natural driving forces such as gravity, density differences, and pressure differences. Therefore, performance tests are required to confirm the thermal-hydraulic behavior based on these natural phenomena. To address this need, each reactor design has developed and applied its own testing methods for passive safety systems.

This study reviews the performance tests of the AP1000 passive safety systems. Based on these cases, it aims to provide insights for developing future approaches to the design and performance testing of PSS.

2. Performance testing methods for AP1000 passive safety systems

2.1. Passive Core Cooling System(PXS) in AP1000

The Passive Core Cooling System (PXS) of the AP1000 is designed to supply adequate coolant to the reactor core during design-basis accidents (DBAs) such as a Loss Of Coolant Accident (LOCA), thereby preventing fuel damage. When a LOCA occurs and a PXS actuation signal is generated, the injection valve of the Core Makeup Tank (CMT) opens automatically, allowing coolant to be injected into the reactor vessel by gravity (see Fig. 1). As the pressure in the Reactor Coolant System (RCS) decreases, the nitrogen-pressurized accumulators are activated and supply additional coolant. When the pressure is further reduced through the Automatic Depressurization System (ADS), coolant from the In-containment Refueling Water Storage Tank (IRWST) is then injected into the reactor vessel. In the early stage of the accident, the residual heat generated in the RCS is removed by the Passive Residual Heat Removal Heat Exchanger (PRHR HX) connected to the steam generator. The PRHR HX is submerged in the IRWST, where it condenses steam and dissipates heat (see Fig. 2).

These processes are accomplished without external power or operator action, gravity, pressure differences, and condensation phenomena, thereby maintaining core cooling over an extended period. The performance of the PXS has been evaluated through two performance tests conducted to verify its capability to ensure core cooling and residual heat removal during DBAs.

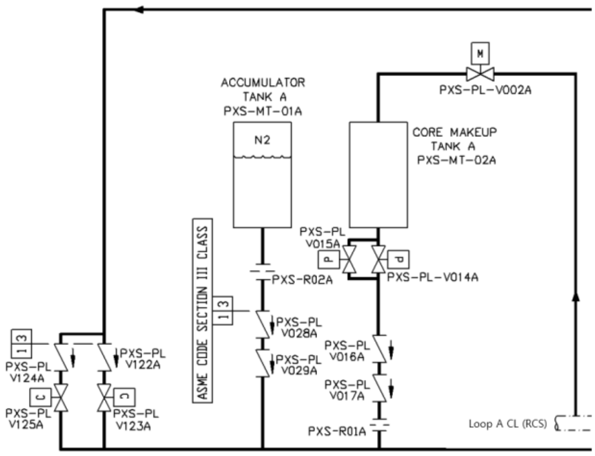

Fig. 1. PXS P&ID – Safety Injection [1]

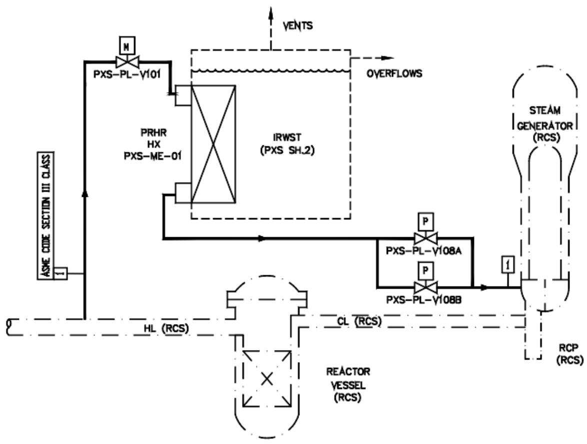

Fig. 2. PXS P&ID – Residual Heat Removal [1]

2.1.1. The Low-pressure Injection Performance Testing Method

The low-pressure injection test of the AP1000 PXS was conducted under conditions in which all injection line valves of the CMT, the Accumulator, and the IRWST were fully opened during a LOCA(see Fig. 1). The test procedure for each component was as follows. First, the CMT was filled with water, and all injection valves were opened to measure the flow resistance of the injection path to the reactor vessel driven by gravity. Second, the Accumulator was partially filled with water and pressurized with nitrogen; under these conditions, all valves were opened and sufficient flow was passed to fully open the check valve, allowing the flow resistance to be determined. Finally, the IRWST was filled with water, the injection line was opened, and sufficient flow was supplied through both Line A and Line B to evaluate the flow resistance of the injection paths leading to the reactor vessel.

Through this procedure, it was verified that the measured flow resistance remained within the allowable range. Although the test was performed under low-pressure conditions, it was interpreted that achieving the design flow rate under such conditions is sufficient. This result suggests that adequate coolant injection would also be ensured under the complex high-pressure transient conditions of an actual accident.

2.1.2. The Decay Heat Removal Performance Testing Method

The decay heat removal performance test was conducted to verify whether the residual heat generated in the reactor core could be sufficiently removed by the natural circulation of the PRHR HX. The test was carried out under conditions where the reactor coolant pumps (RCPs) were shut down. The test was performed under the following conditions: the hot leg temperature of the RCS at or above 540 °F, the PRHR HX submerged in the IRWST, and the RCPs in a shutdown state.

According to the acceptance criteria presented in Table I, the test was conducted from an initial RCS hot leg temperature of at least 540 °F until it decreased to 420 °F. During this process, it was verified that the heat removal rate of the PRHR HX was at least 1.11×10^{8} Btu/hr, thereby demonstrating compliance with the acceptance criteria.

The acceptance criteria for the PRHR HX heat removal rate in the AP1000 was established on the basis of heat transfer coefficients and natural circulation flow data obtained from separate-effects tests (SETs) conducted during the AP600 development program, which were used to validate the predictions from system analysis codes. Therefore, this value can be regarded as one derived from a code prediction that had been experimentally validated. As noted in the NRC's FSER for the AP1000 "*The applicant asserts that the AP1000 design represents an incremental change to the AP600 design, and that the AP600 test program and the computer codes used for the analyses of the AP600 design-basis events also apply to the AP1000 design*" [2].

By satisfying this minimum heat removal rate, it is regarded that the PRHR HX can reliably remove core decay heat over extended periods. It is also considered capable of performing its intended heat removal function under a variety of thermal-hydraulic conditions during accidents.

Table I: PRHR HX heat transfer rate according to high temperature conditions[1]

PRHR HX heat transfer rate (10^{8}Btu/hr)	HL Temperature (°F)
≥ 1.78	520
≥ 1.11	420

2.2. Passive Containment Cooling System(PCS) in AP1000

The PCS functions to maintain the pressure and temperature inside the containment below the design limits following an accident. This capability thereby ensures long-term stability. The PCS consists of the Passive Containment Cooling Water Storage Tank (PCCWST) installed at the upper part of the containment exterior, the spray piping and nozzles, the outer surface of the containment wall, and the air cooling pathway surrounding the structure (see Fig. 3).

During a DBA, the hot steam generated inside the containment rises to the upper region, leading to an increase in internal pressure and temperature. At this stage, coolant supplied by gravity from the PCCWST flows along the external surface of the containment wall. In this process, it absorbs heat and dissipates it through evaporation or heat transfer to the atmosphere. Concurrently, the steam inside the containment condenses on the cooled wall surface, thereby reducing the internal pressure and temperature. In addition, natural convection is established within the external air cooling pathway. This airflow enhances the evaporative effect and contributes to further heat removal from the containment interior.

Through this operating principle, the PCS can maintain containment cooling for an extended duration without external power or pump operation, relying solely on natural convection. It is considered capable of sustaining stable performance for at least 72 hours. The performance of the PCS has been demonstrated through the three tests described below.

2.2.1. Coolant Supply Performance Testing Method

This test was conducted to verify whether sufficient coolant could be continuously supplied from the PCCWST to the upper region of the containment. In the test, the flow rates of the three parallel flow paths were individually measured. It was then confirmed that the supply flow rate at the specified water level of the storage tank satisfied the acceptance criteria. In addition, the continuous coolant supply was analyzed by considering the initial water level conditions of the storage tank. The results confirmed that sufficient coolant could be delivered to the upper containment for at least 72 hours.

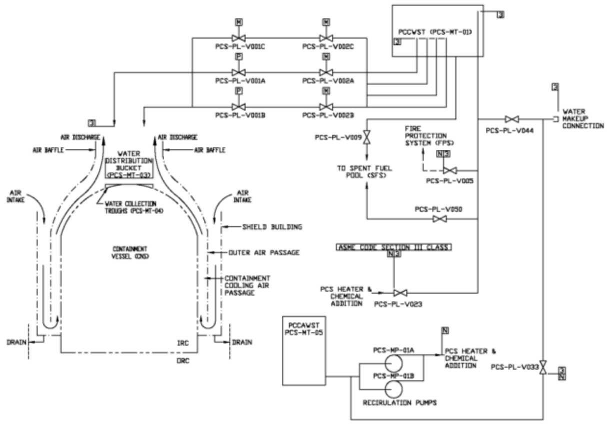

Fig. 3. Passive Containment Cooling System(PCS) P&ID [1]

2.2.2 Containment Wetting Performance Testing Method

The Containment Wetting Test was conducted to verify whether the entire outer surface of the containment could be uniformly covered with coolant. This condition is regarded as essential for ensuring its heat removal capability. In the test, the distribution of coolant supplied from the PCCWST to the outer wall surface was measured, and the wetting ratio around the containment circumference was calculated for each water level condition. The evaluation results, as shown in Table II, confirmed that the minimum required wetting ratio was achieved under all tested conditions. (The acceptance criteria in Table II was not reported in [2].) This performance test is regarded as focusing not on directly demonstrating heat removal capability during transients, but rather on verifying, through the calculation of wetting ratios, that the coolant supplied via the external flow paths can uniformly wet the entire outer surface of the containment.

Table II: Wetness according to water level[1]

Level (ft)	Degree of Wetness (%)
24.1 ± 0.2	90
20.3 ± 0.2	72.9
16.8 ±0.2	59.6

2.2.3 Inspections of the Air Flow

The Natural Circulation Air Inlet Inspection was conducted to verify whether evaporation on the outer surface of the containment could be effectively sustained. It also examined whether external airflow could support this process and enhance heat removal. The inspection involved physical examinations of major flow path sections, including the air inlets, the outer annular space, the inner annular space, and the exhaust structures. Based on these inspections, the focus was placed on confirming whether a continuous natural convection pathway could be secured throughout all sections. This performance test is regarded as not directly demonstrating the steam condensation capability inside the containment vessel. Instead, it focuses on verifying the integrity of the external flow paths and the stable supply of coolant to the outer containment wall.

3. Conclusions

PSS operate based on fundamental natural driving forces such as gravity, density differences, and pressure differences, and therefore require a different approach to performance testing compared with active safety systems. Accordingly, this study reviewed the performance tests of the AP1000 PSS. For the PXS, the low-pressure injection test was conducted by measuring the flow resistance with all injection valves fully opened. The decay heat removal test was also performed not by simulating actual transient conditions of decay heat generation, but by confirming whether the heat removal rate of the PRHR HX exceeded the minimum required value under the specified test conditions

For the PCS, the performance evaluation was not focused on directly measuring the heat removal rate inside the containment, but rather on verifying the coolant supply from the PCCWST and calculating the wetting ratio of the outer containment surface. In addition, heat removal through natural convection along the containment wall was verified simply by inspecting the integrity of the relevant flow paths. Overall, these test methods are regarded as being established by considering both practical constraints and the inherent characteristics of passive systems. These review results are considered to provide useful insights for developing performance testing strategies in future passive safety system designs.

Acknowledgement

This paper was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government(Ministry of Trade, Industry and Energy, MOTIE) (No. RS-2024-00404240).

REFERENCES

[1] Nuclear Regulatory Commission, AP1000 Design Control Document, Revision 19, 2011

[2] Nuclear Regulatory Commission, Final Safety Evaluation Report Related to Certification of the AP1000 Standard Design Chapter 21, 2004