A Method to Reduce the Human Error in the Design Process of the Auxiliary Feed-water System of APR+

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ABSTRACT

Objective: This paper introduces a method to reduce the human error during the design process of the Auxiliary Feed-water System (AFS) of Advanced Power Reactor plus (APR+). **Background:** Korea Hydro & Nuclear Power Co. has been developing APR+, a type of GEN III+ reactor. The AFS feeds emergency water to steam generators to cool down the reactor coolant system when the main feed-water is lost. Specially, The AFS is important for core cooling against station black out like Fukushima accident. The AFS consists of two motor driven pumps, two turbine driven pumps, two water storage tanks and related pipes and valves. So, the AFS has a possibility to make human errors by operator. **Method:** In order to reduce the human error, The Passive Auxiliary Feed-water System (PAFS) replaces the conventional active AFS by introducing a natural driving force mechanism while maintaining the system's basic function of cooling down the primary side and removing the decay heat. The PAFS design consists of steam condensing heat exchanger, passive condensation cooling water tank, check valves, battery(Class 1E DC) powered isolation valves, piping, and instrumentation and control systems. **Conclusion:** It is shown that human error is significantly reduced due to the adoption of passive system by reducing human's intervention for system control during accident operation.

Keywords: Human Reliability, Passive Feed-water System, Auxiliary Feed-water System, Advanced Power Reactor plus

1. Introduction

The Advanced Power Reactor Plus(APR+) is a new evolutionary reactor based on the Advanced Power Reactor 1400(APR1400). The configuration of the APR+ nuclear steam supply system(NSSS) is same as the APR1400, a reactor vessel(RV), two coolant loops, each containing one hot leg, two cold legs, one steam generator(SG), two reactor coolant pumps(RCPs), and one pressurizer(PZR) connected to one of the hot legs. But, the core thermal power is uprated to 4,290 MWth with electrical power of 1,500 MWe and the safety design requirements are consolidated, a core damage frequency lower than 10^{-6}/RY, and a frequency of large radiation release lower than 10^{-7}/RY.

To enhance the safety and reduce human errors, The Passive Auxiliary Feedwater System(PAFS) is a potential candidate of the passive safety systems in APR+. The Auxiliary Feedwater System(AFS) in APR1400, which is the reference plants of APR+, consists 2 motor driven pumps, 2 turbine driven pumps, 2 water storage tanks, and pipes and valves.

The AFS feeds emergency water to steam generators to cool down a reactor coolant system when the main feedwater is lost. This AFS is replaced to a heat exchanger, a condensation water storage tank, and a few valves and pipes. The main driving forces of the PAFS are steam condensation and two phase natural circulation.

2. Working Principle of Natural Circulation System

Figure 1 is The working principle of natural circulation with reference to the simple uniform diameter rectangular loop with adiabatic pipes. At the source, the fluid absorbs heat becomes lighter and rises. At the sink the fluid rejects heat becomes heavier and sinks thus establishing a circulation. If the source and sink conditions are maintained constant, a steady state is expected to be achieved when the heat absorbed at the source is equal to the heat rejected at the sink. Under steady conditions we assign a density of ρ_h to the vertical leg with upward flow and ρ_c to the other vertical leg with downward flow. Now we can obtain the hydrostatic pressure, p_a and p_b at the stations 'a' and 'b' located at the extremes of the bottom horizontal leg as:

$$p_a = \rho_c g H \quad (1)$$

$$p_b = \rho_h g H \quad (2)$$

Where H is the loop height and g is the acceleration due to gravity. Clearly, since $\rho_c > \rho_h$, $p_a > p_b$ leading to a pressure difference between stations 'a' and 'b' which is the cause of the flow. At steady state, the driving pressure differential is balanced by the retarding frictional and accelerational forces, thus providing a basis for the estimation of the induced flow. What is more important to us is that this induced flow is unidirectional and while it passes through the source it absorbs heat and rejects it while flowing through the sink thus enabling transfer of heat from the source to the sink. In this function, it is indistinguishable from forced flow. It is easy to note that the induced pressure differential and hence the flow is enhanced by the loop height and the density difference between the two vertical legs.

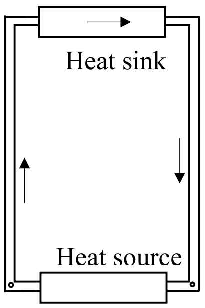

Figure 1. A simple natural circulation system

3. The concept and the basic design of PAFS

A diagram of PAFS in APR+ is shown in Figure 2. The PAFS consists of heat exchanger, passive condensation cooling water tank (PCCT), check valves, isolation valves powered by battery (Class 1E DC), piping, instrumentation and control systems. A schematic diagram of PAFS in APR+ is shown in Figure 1. As shown in Figure1, the PAFS has two independent high-pressure closed loops and each loop has a heat exchanger submerged in the PCCT. The steam supply line branched from the main steam line upstream of main steam isolation valves (MSIVs) is normally opened, and the condensate return line is connected to the feed water line downstream of main feed water isolation valves(MFIVs) and redundant check valves are normally closed. The PAFS is in standby condition during power operation, plant startup, plant shutdown and refueling operation. The PAFS is actuated by steam generator low level signal. When the PAFS actuation signal occurs, one or two isolation valves in parallel on the condensate return line are slowly opened by the Class 1E DC power. The supplied steam is condensed on the tube side and condensed water goes into the steam generator(SG). The circulation force is driven by the natural convection and gravity force.

The PAFS cools down the secondary system by heat transfer in a horizontal U-tube in PCCT. High pressure steam from the steam generator is condensed in the horizontal heat exchanger. The cooling water in PCCT is maintained at an atmospheric pressure, so that boiling heat transfers at the outside wall of heat exchanger and natural convection occurs in PCCT pool. The heat exchanger and PCCT are higher location than steam generator, so condensed water can be drained and injected to feed water injection line without any active system.

The PAFS condensate return line isolation and check valves are arranged in parallel so that single valve failure does not prevent PAFS actuation. In PAFS, we assume the common cause failure for valves. To avoid this problem, there are two distinct types of condensate return line valves; Motor-Operated Valve(MOV) and Electro Hydraulic Valve(EHV).

The PAFS is composed of two independent trains; each train has a PCCT used as a heat removal source for the PAFS. This is a rectangular shaped concrete tank located at an elevation 200 feet from the auxiliary building. A schematic diagram is shown in Figure 3. The PCCT capacity has to be determined based on the mission time of the PAFS, which is defined by the duration of the cooling down of the RCS from the initial conditions by PAFS actuation to the shut down cooling entry condition for all design basis accidents. The PCCT preliminary capacity included dead volume determined at 370,000 gallons. This means that the PAFS can operate from five minutes after reactor trip occurrence time to eight hours, without refill. However, in fact, the PCCT level will be controlled by the makeup water system operated by the PCCT level controller during normal operating conditions.

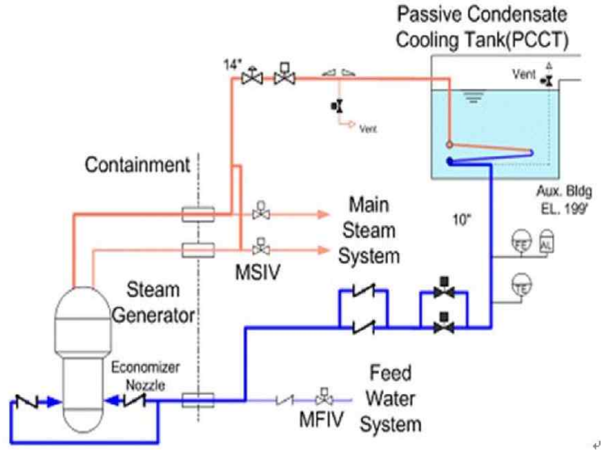

Figure 2 Schematic diagram of PAFS

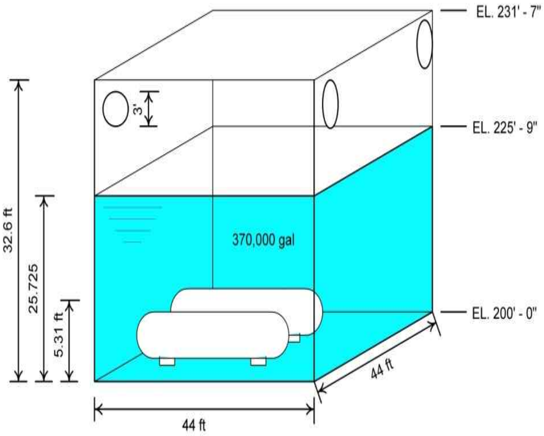

Figure 3. Schematic diagram of PCCT in PAFS

The PCHX(Passive Condensation Heat Exchanger) consists of slightly inclined stainless steel U-tubes. Figure 4 shows the design of the U-tube bundle in the heat exchanger. A total of four heat exchangers are installed in one PCCT. The tube bundles are shaped to minimize thermal stress during their operation. The heat exchanger tubes are filled with condensate water during normal operation. The heat exchanger tubes start to remove heat from the SG after the PAFS actuation signal occurs. The cooling water in the PCCT is heated through convection heat transfer at the outside of the heat exchanger tubes. Boiling starts after the PCCT pool temperature rises beyond the saturation temperature of the PCCT pressure.

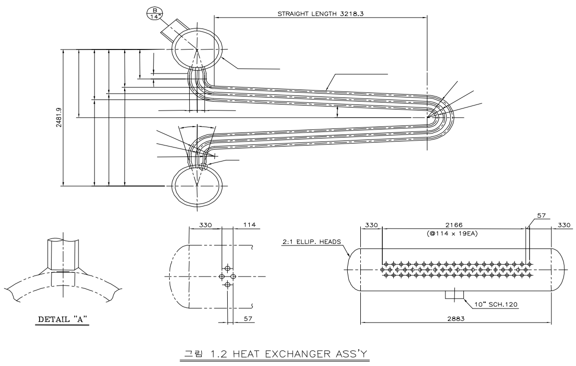

Figure 4. Design of U-tube bundle

4. The Result of PSA and Validation Test

Currently, preliminary PSA(Probabilistic Safety Analysis) and cost analysis has been done. According to the preliminary analysis, core damage frequency is reduced more than 60% and the construction cost is reduced to half of the cost for the current auxiliary feed-water system by the adoption of PAFS.

A diagram of PASCAL is shown in Figure 5. The PASCAL facility was constructed to validate the cooling performance of the PAFS and investigate the condensation heat transfer and natural convection phenomena in the PAFS. The objective of the validation test is to investigate the cooling performance and natural circulation characteristics of the PAFS by simulating a quasi-steady state condition of the thermal power according to the volumetric scaling methodology. With a given thermal power of electrical heaters in the steam generator, a heat removal rate in the PCHX was measured and the characteristics of the natural circulation in the loop were examined. The test results showed that the current design of the PCHX satisfied the heat removal requirement for cooling down the reactor core during an accident condition. Therefore, it can be preliminarily concluded that the PAFS can replace a conventional active AFS in the APR+, utilizing the natural convection flow driven by the natural convection of two-phase flow.

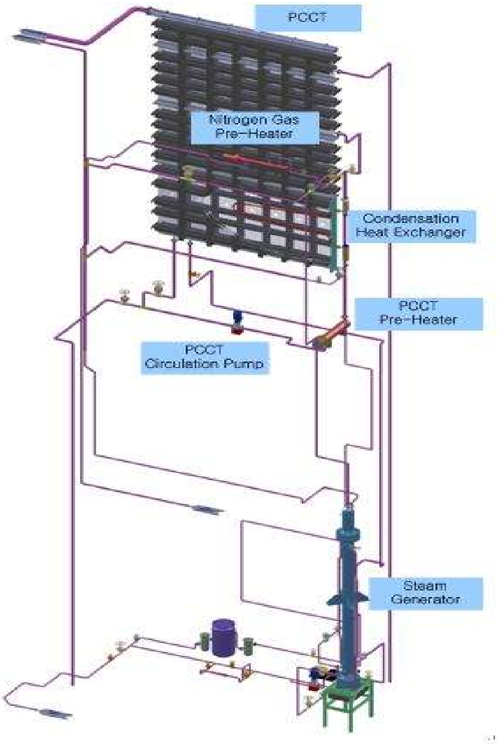

Figure 5 3- D view of the PASCAL

5. CONCLUSION

The PAFS is not expected to fail like the fluid moving machineries such as pumps and simple, highly reliable and enable to eliminate human errors, because it's not require operator action during any accidents.

The most apparent economic advantage of PAFS is the elimination of the auxiliary feed water pumps (AFPs). Elimination of the AFPs not only reduces capital, operating and maintenance costs but also eliminates all safety issues associated with the failure of the AFPs.

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