Cooling Capability of Pool Water for a 5-MW Pool-Type Research Reactor

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1. Introduction

A lot of attention to a long-term cooling capability of nuclear reactors has been paid especially following the Fukushima Daiichi accident [1]. In pool-type research reactors, pool water plays an important role as a final heat sink. Thus in design of the pool and its connecting systems it should be taken into account that sufficient pool water is absolutely preserved in design basis loss of coolant accidents [2].

This paper deals with a long-term cooling capability of a recently developing 5-MW research reactor. In order to take account the lessons learned from the Fukushima Daiichi accident, a long-term cooling capability was analysed for a loss of coolant accident with long-term station blackout.

2. Description of the Reactor and Service Pools

The reactor and service pools as shown in Figure 1 are connected each other above 5.1 m high from the pool bottom. Spent fuels are stored in the service pool. The top of the spent fuels and the fuels in the reactor core is around 2.0 m high from the pool bottom.

The primary cooling system (PCS) is arranged below the reactor bottom to achieve a sufficient net positive suction head at the inlet of the primary cooling pumps. Thus siphon breakers are contained on the core exit and pool inlet pipes of the PCS to keep sufficient pool water when a loss of coolant accident occurs at the PCS. Other systems connected to the pool are arranged at the sufficiently higher elevation than that of the reactor core. Accordingly, as shown in Figure 1, the pool water level always remains above 6 m even in loss of coolant accidents.

3. Analysis Methods

In long-term cooling phase, the cooling capability of the pool water can be predicted from the heat balance equation as follows:

$$\int_{to}^{t}(Q_{rf}+Q_{sf})dt=\int_{To}^{T}\rho C_p\, V dT+\int_{Vo}^{V}\rho h_{fg} dV \qquad (1)$$

where Q_{fr} and Q_{sf} are the residual heat of the reactor and spent fuels, respectively. The right-hand side of Eq. (1) is the sensible and latent heat capacity of the pool water.

The residual heat of the reactor fuels is calculated as a function of time from the ANSI/ANS-5.1 decay heat power [3]. The reactor is assumed to operate at 5.25 MW by considering the measurement uncertainty of 5%. Additionally, the 120% of the decay heat power is taken into consideration in this analysis. The residual heat of the spent fuels is assumed to be 35.4 kW, which is predicted from all fuels stored during 40-year operation.

4. Results

4.1 Short-Term Cooling

The reactor trip can be accomplished by the trip parameters of the pool water level, PCS flow, and core differential pressure. The reactor trip by the PCS flow and core differential pressure depends on the break size. Regardless of the break size and location, however, the reactor trip is always assured by the trip signal of pool water level of 9.5 m. The residual heat of the reactor fuels is removed by a discharge flow while the pool water spills out of the pool and by a natural circulation flow after the discharge flow stops at the pool level height of 6 m due to siphon break. The reactor core cooling during the short-term phase was analyzed by RELAP5/MOD3.3. As a result of the analysis, it is ensured that the reactor fuels are not damaged in the loss of coolant accident. After the siphon break is completed, the reactor core heat is removed to the pool water by natural circulation via the flap valve and the reactor exit pipe. The pool water temperature slowly increases up to the saturation temperature, and the pool water finally evaporates. After the pool water level decreases below the flap valve height of 3.9 m, the natural circulation between the fuel channels and fuel bypass gaps in the reactor core removes the residual heat. Meanwhile, the small holes on the upper guide structure (UGS) maintain the same water level in and out the UGS even after the pool level decreases below the UGS top by evaporation.

The residual heat of the spent fuels is removed to the service pool water by natural circulation and the service pool water is cooled by the pool water management system (PWMS) during normal operation. However, the PWMS does not cool down the service pool water when station blackout occurs. In this event the sensible and latent heat capacity of the pool water plays an ultimate heat sink to remove the residual heat.

4.2 Long-Term Cooling

Table 1 summarizes the cooling capability with the amount of water and heat transfer type in the most severe loss of coolant accident with station black out. The cooling capabilities by sensible heat transfer are calculated while the pool water temperature increases from 50℃ to 100℃. No heat transfer between the reactor pool and the service pool is assumed during the sensible heat transfer. First, the reactor pool water between 3.9 m and 6.0 m (S1) is considered for calculating the long-term cooling by sensible heat. The sensible heat capacity of S1 can accommodate the residual heat generation of the reactor fuels for 35.8 hrs. On the other hand, the sensible heat capacity of S2 corresponding to the service pool water above 2.5 m can cover the residual heat generation of the spent fuels for 5.6 days.

The latent heat capacity of the pool water (L1) between 5.1 m and 6.0 m can remove the residual heat of the reactor and spent fuels for 15 days. When the pool level becomes lower than 5.1m, the reactor pool and the service pool are isolated and they separately cool down the reactor fuel and the spent fuel, respectively. The reactor pool water (L2) between 2.5 m and 5.1 m additionally provides a cooling capability of 73 days to remove the residual heat of the reactor fuels. Meanwhile, it takes additional 44 days for the service pool water level to reach the 2.5 m from the 5.1 m by evaporation. In other words, the reactor pool water has a cooling capability of 88 days in minimum without considering the sensible heat transfer. In case of the service pool water, the cooling capability is 59 days in minimum. The cooling capability of the reactor pool by sensible heat transfer is shorter than that of the service pool. Nevertheless, the cooling capability of the reactor pool by latent heat transfer is longer than that of the service pool. This is because the residual heat of the reactor fuels is considered to decrease continually while the residual heat of the spent fuels is assumed to be constant.

Figure 2 shows the heat flux at the hot spot and the critical heat flux (CHF) calculated from the Mishima correlation [4, 5], which was obtained from the vertical narrow rectangular channel experiment. The bottom of the test channel was blocked so that the bulk average flow was stagnant. The Mishima correlation is known to provide the lowest CHF at vertical narrow rectangular channels. Figure 2 ensures that fuel damage by CHF is not expected after several tens of seconds following the reactor trip although the bulk average flow between the fuel channels is stagnant and the coolant is saturated.

5. Conclusions

A cooling capability of the reactor and service pool water was analyzed in a loss of coolant accident with long-term station blackout for a 5-MW research reactor. Consequently, it is found that the pool water remained by the siphon breaker provides a sufficient long-term cooling capability. The fuels in the reactor core and service pool are covered with pool water for more than two months without fuel damage.

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Table 1. Cooling Capability of the Pool Water

Water volume	Heat transfer type	Cooling capability
S1 (27.3 m^3)	Sensible	35.8 hrs
S2 (84.9 m^3)	Sensible	5.6 days
L1 (34.9 m^3)	Latent	15 days
L2 (32.8 m^3)	Latent	88 days (15 days included)
L3 (62.2 m^3)	Latent	59 days (15 days included)

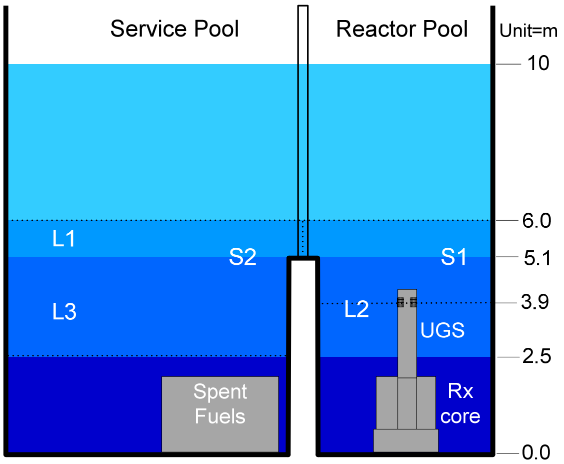

Fig.1. Reactor and Service Pools

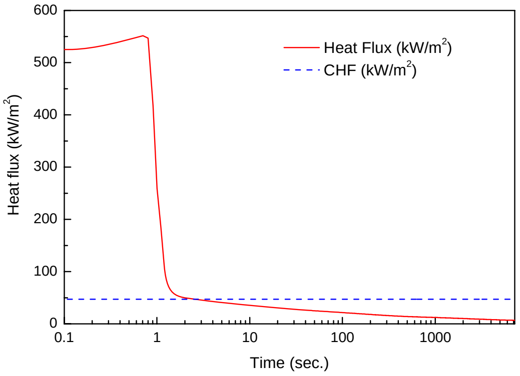

Fig.2. Heat Flux at the Hot Spot and CHF in the LOCA