Estimation of the Spent Fuel Pool Water Temperature at a Loss-of-Pool-Cooling Accident

Chan Hee Park, Arim Lee, Jung Min Lee, and Joo Hyun Moon

***Abstract*—**Accident in spent fuel pool (SFP) of Fukushima Daiichi Unit 4 showed the importance of continuous monitoring of the key environmental parameters such as water temperature, water level, and radiation level in the SFP at accident conditions. Because the SFP water temperature is one of the key parameters indicating SFP conditions, its behavior at accident conditions shall be understood to prepare appropriate measures. This study estimated temporal change in the SFP water temperature at Kori Unit 1 with 587 MWe for 1 hour after initiation of a loss-of-pool-cooling accident. For the estimation, ANSYS CFX 13.0 code was used. The estimation showed that the increasing rate of the water temperature was 3.9^{0}C per hour and the SFP water temperature could reach 100^{0}C in 25.6 hours after the initiation of loss-of-pool-cooling accident.

***Keywords*—**Spent fuel pool, water temperature, Kori Unit 1, a loss-of-pool-cooling accident.

I. Introduction

FUKUSHIMA Dai-ichi Units 1 through 6 were struck by a large tsunami with the height of over 14m following a powerful 9.0-magnitude earthquake in March 2011. The tsunami caused extensive damage to site facilities and a complete loss of AC power, a condition known as station blackout.

Due to prolonged loss of AC power, spent fuel pools (SFPs) of Fukushima Dai-ichi Units 1 through 4 were also impaired. The accident at Fukushima Daiichi Unit 4 SFP evidently showed importance of continuous monitoring of the key environmental parameters, including water temperature, water level and radiation level, in SFP at accident conditions. Because of loss of all AC power, it was not able to monitor SFP of Fukushima Daiichi Unit 4 and secure information on spent fuel in the SFP. It contributed to a poor understanding of possible radiation releases and to confusion about the need and priorities for support equipment [1].

The Task Force established by U.S NRC made several recommendations for the improvement of SFP safety, one of which is for NRC staffs to order licensees to provide sufficient safety-related instrumentation, able to withstand design-basis natural phenomena, to monitor key SFP parameters (i.e., water level, temperature, and are radiation levels) from the control room [2].

The lessons of Fukushima Dai-ichi accidents require continuous monitoring of key SPF parameters even at loss of AC power accident condition. Among them, the SFP water temperature is one of the key environmental parameters indicating SFP conditions, hence, its behavior at accident conditions shall be well understood to prepare appropriate measures. As long as the SFP is at normal condition, the water temperature is within its normal range specified by technical specifications for a nuclear power plant. If the cooling capability to the SFP is partially or totally lost for a long time, the water temperature would be deviated from the normal range. Hence, it is important to acknowledge how soon SFP water temperature rises during loss-of- pool-cooling accident, to establish proper countermeasures [1].

The SFP cooling and purification system is usually designed to accommodate decay heat of spent fuel stored up to maximum design capacity to keep the SFP water temperature lower than the limit defined by its technical specification. For Shin-kori units 1 and 2, for example, the SFP water temperature shall be kept to be below 48.9°C during normal operation and below 60°C during refueling outage period. Also, the SFP at Shin-kori Units 1 and 2 are equipped with cooling system, providing cooling capability that the water temperature shall be maintained to be sufficiently lower than the boiling point even if the spent fuel assembly is loaded fully to the maximum design capacity [3].

Using ANSYS CFX 13.0, this paper estimated temporal change in the SFP water temperature at Kori unit 1 with 1,723 MWt during 1 hour after initiation of a loss-of-pool-cooling accident, in order to acknowledge how soon SFP water temperature rises during loss-of-pool-cooling accident.

II. Analysis Model and Tools

A. SFR at Kori Unit 1 [4]

The spent fuel pool at Kori Unit 1 is located in the auxiliary building and is separated from the reactor containment building. The SFP is for the underwater storage of spent fuel assemblies and control rods after their removal from the reactor. It normally contains 42,990 ft^{3}of borated water. It accommodates a total of 14/3 cores. Space is provided in the pool for 562 fuel assemblies. The spent fuel shipping cask loading pit and the spent fuel storage pool is constructed of reinforced concrete. The fuel in the spent fuel pool is store vertically in an array with sufficient

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center-to-center distance between assemblies to assure $k_{eff} \leq 0.95$, even if unborated water were to fill the space between the assemblies.

The spent fuel pooling cooling system (SFPCS) is designed to remove decay heat from spent fuel stored in the pool. The normal design heat load for the system is based on 1/3 core placed in the pool during a refueling operation 155.4 hours after shutdown. The spent fuel is normally stored in the pool until it can be transported to a fuel processing facility. The SFPCS has a cooling capability of 6.29×10^6 Btu/hr during normal operation when 1/3 core is stored and 17.44×10^6 Btu/hr when 1-1/3 cores are stored.

The SFPCS consists of two pumps, one heat exchanger, one filter, one demineralizer, piping, and associated valves and instrumentation. The two pumps, connected in parallel, draw heated water from the pool, circulate it through the heat exchanger for cooling, and return it to the pool. Part of the flow is diverted through the demineralizer and filter for purification. Component cooling water cools the heat exchanger. An independent skimmer circuit with a separate pump and filter is included for removing foreign matter from the pool surface. No cooling is accomplished in the skimmer loop.

The spent fuel pool fluid is a solution of boric acid in water, having a boron concentration of 2,000ppm. The fluid originates from the demineralized water and boric acid blender systems. Makeup fluid is injected into the SFP inlet line downstream of the heat exchanger.

B. Analysis Tools

To estimate the SFP water temperature, ANSYS CFX 13.0 was used, which is a general purpose fluid dynamics program based on finite elements method [5]. The 3D geometry models for structures were created using CATIA software, and then were incorporated into the fluid dynamic models. These models were analyzed by using meshing tool built in ANSYS CFX 13.0 workbench. The meshes were generated using the basic algorithm provided by the ANSYS CFX 13.0. Regarding mesh generation, the areas such as the vicinity of a structure edge where flow rate and direction could change abruptly were finely divided, while the areas where flow could change smoothly were coarsely divided.

C. Initial and Boundary Conditions

Initial conditions and boundary conditions used in this estimation are depicted and summarized in Fig. 1 and Table I, respectively. The initial air temperature outside of the SFP was set at 25^0C and the initial water temperature of the SFP was set at 40^0C. The SFP at Kori Unit 1 was assumed to be filled with fuel assembly of a third of design capacity.

The important variable for fluid dynamics analysis is heat flux. The heat flux for this analysis was derived by using the data from Final Safety Analysis Report for Kori Unit 1. The resultant heat flux is 36.53 kW/m^2 [4].

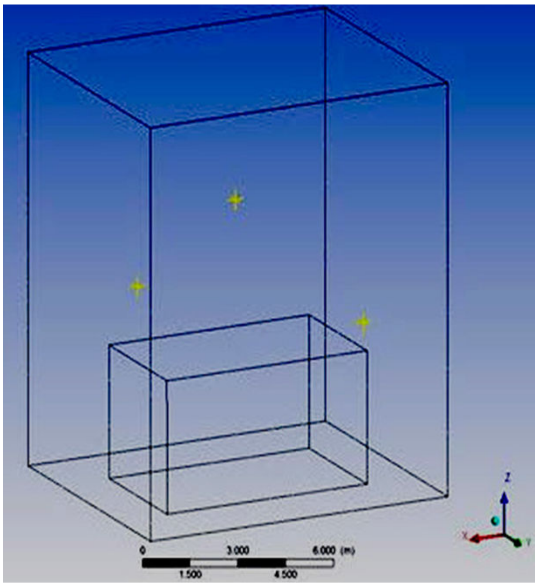

Fig. 1 A simple model of spent fuel pool at Kori Unit 1

TABLE I
INITIAL CONDITIONS AND BOUNDARY CONDITIONS FOR THIS ESTIMATION

Water Property		Boundary Condition	
Molar mass	18.02kg/kmol	Heat Flux	36530W/m^2
Density	992.2907kg/m^3	Air Temperature	25℃
Temperature	40℃	Turbulence Model	BSL(Baseline)
Pressure	1atm	Heat Transfer	Nusselt Number 1
Specific Heat Capacity	4178.656J/kg·K	Water Air Surface tension	0.074N/m
Dynamic Viscosity	6.53E-4kg/m·s	Outer wall Heat Transfer	Adiabatic
Thermal Conductivity	0.6286571W/m·K	Initial Water Fraction	11.810m

III. RESULTS AND CONCLUSION

Figs. 2 and 3 show the SFP water temperature changes for 1 hour after initiation of loss-of-pool-cooling accident at Kori Unit 1. At 50 minutes after the initiation of loss-of-pool- cooling accident, the SFP water temperature was estimated to be about 43.5°C at top area of fuel assembly, and about 45°C at side area of fuel assembly. But the temperature at water surface remained at 40°C, same as the SFP initial temperature. The temperature at the upper part of SFP was found to be increased more slowly than that around the fuel assembly.

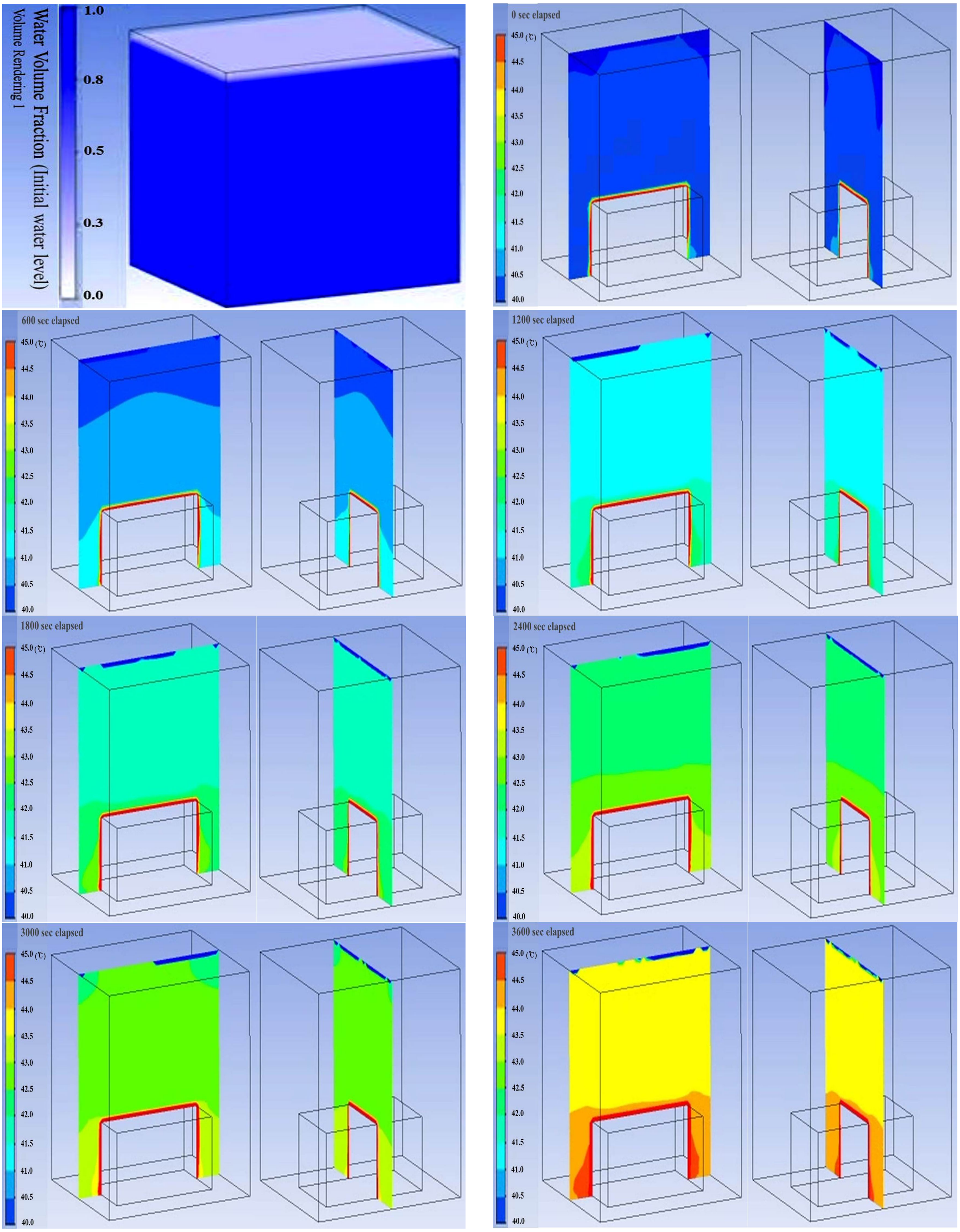

Fig. 2 The SFP water temperature distribution with time after initiation of a loss-of-pool-cooling accident

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In particular, temperatures at both sides of spent fuel assembly increased above 45^0C with the trapezoid form.

Fig. 3 shows that the SFP water temperatures almost linearly increase. Further analyses found that the increasing rate of the water temperature was 3.9^0C per hour and the SFP water temperature could reach 100^0C in 25.6 hours after the initiation of loss-of-pool-cooling accident. It meant that evaporation of the water in spent fuel pool could begin after that time. These results were consistent with the analysis results of Fukushima Daiichi unit 4 accidents shown in Fig. 4 [6], which indicated that the SFP water temperature would reach the equilibrium point where the heat loss through evaporation was equivalent to the decay heat load of the SFP within 2 days.

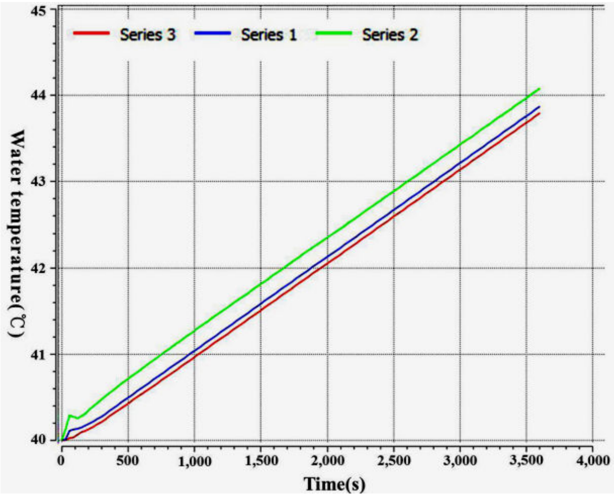

Fig. 3 The SFP water temperature with the time after initiation of a loss-of-pool-cooling accident

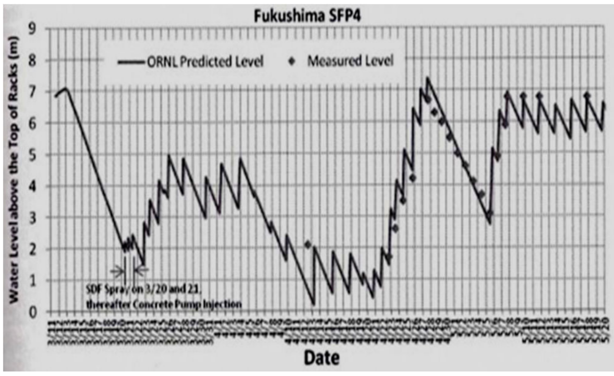

Fig. 4 Calculated SFP water level for Fukushima SFP4 [6]

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