One-Region Model Predicting Water Temperature and Level in a Spent Fuel Pit during Loss of All AC Power Supplies*

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Abstract
A prediction system with a one-region model was developed to predict water temperature in a spent fuel pit (SFP) after the shutdown of its cooling systems based on three-dimensional (3D) thermal hydraulic behavior calculated by using the CFD software, FLUENT 6.3.26. The system was extended to calculate the water level in the SFP during loss of all AC power supplies. In the prediction system, decay heat calculated by using the burn-up calculation software, ORIGEN 2.2, and the previously proposed correlation for evaporation heat fluxes from the water surface to air were used. Predicted results were compared with 3D calculations and measured temperatures for the shutdown of cooling systems and with the water temperature and level measured in SFPs at the Fukushima Daiichi Nuclear Power Station for loss of all AC power supplies. As a result, the predicted temperatures were found to agree well with the 3D calculations and it was confirmed that ORIGEN 2.2 well predicted decay heat for fuel assemblies with large decay heat which had been taken relatively recently from the shutdown reactor core. However, it was shown that decay heat predicted by ORIGEN 2.2 was overestimated for longtime cooled fuel assemblies with small decay heat and the previously proposed evaporation heat flux correlation overestimated the water temperature in the SFP, too.

Key words: Nuclear Power Generation, Spent Fuel, Decay Heat, Loss of All AC Power Supplies, Evaporation, Water Temperature, Water Level

1. Introduction
A spent fuel pit (SFP) is generally equipped with two cooling systems, which are operated by external AC power supplies, to remove decay heat from spent fuel assemblies and to keep the SFP water at a low temperature. Above the water surface, an air curtain is formed by air ventilation systems, which are operated normally by external AC power supplies or by emergency diesel generators when external AC power supplies fail. Therefore, cooling systems stop with loss of external AC power supplies but air ventilation systems stop with loss of all AC power supplies including external AC power supplies and emergency diesel generators. The water temperature and level in a SFP during the shutdown of its cooling systems have not been well discussed, because it has been considered that there is a large amount of water above the spent fuel assemblies to provide radiation shielding, and the water temperature increasing rate and water level decreasing rate are very small. After the accident in the Fukushima Daiichi Nuclear Power Station, however, the water temperature and level in a SFP during loss of all AC power supplies have drawn...
The USNRC (1) reported on accident risk for a SFP during decommissioning of nuclear power plants, where the water level in the SFP and integrity of spent fuel assemblies after the pool was dried out were evaluated. According to this report, spent fuel assemblies which are cooled less than five years after unloading from the core would be damaged when they are exposed in the air. In calculations of the water level, however, heat losses from the SFP water to air and concrete were neglected. With neglect of heat losses, water temperature is overestimated especially when decay heat is not large. Important uncertainties for prediction of the water temperature in a SFP during the shutdown of cooling systems are decay heat and evaporation heat transfer from the water surface to ventilation air.

Decay heat is generally predicted in reactor safety analyses by using a correlation such as recommended by ANS-5.1-1973 (2) or AESJ (3). The Way-Wigner correlation (4) is also used for decay heat prediction of spent fuel assemblies which are under longtime cooling. The correlations give the decay heat ratio to the rated power as a function of the operation time in the reactor and cooling time after the reactor shutdown, but do not include the effects of fuel specifications. It is desirable to include effects of fuel specifications in order to predict decay heat of spent fuel assemblies more accurately.

An evaporation heat transfer correlation which can be applied in the temperature range of 20-65 °C is required to calculate the water temperature in the SFP during the shutdown of cooling systems because the temperature is limited less than 65 °C by the technical specification under normal operation conditions. In a general ocean circulation model (5), evaporation heat transfer correlations are used to calculate heat transfer from the sea surface to the atmosphere. However, they cannot be applied to calculate the water temperature in the SFP even during operation of cooling systems, because humidity of bulk air and evaporation heat transfer may be greatly different from each other. Fujii et al. (6) proposed an evaporation heat transfer correlation for higher water temperatures than 100 °C under stagnant air conditions (i.e. natural convection), but it is not applicable to the calculation of the water temperature in the SFP.

In order to evaluate the water temperature in a SFP after the shutdown of its cooling systems, Yanagi et al. (7) derived an evaporation heat transfer correlation from hot water to ventilation air based on heat transfer data obtained by Koizumi et al. (8) under water temperatures of 35-65 °C. In another study, Yanagi et al. (9) also carried out three-dimensional (3D) thermal hydraulic calculations of the SFP water during the shutdown of cooling systems using FLUENT6.3.26. In those calculations, they made and used a database for decay heat of spent fuel assemblies, which was calculated for several fuel types using the burn-up calculation software ORIGEN 2.2 (10) and the nuclear physics library JENDL3.3 (11). However, 3D calculations require a long computing time. On the other hand, the calculated results indicated that a one-region model might be able to obtain the average water temperature accurately because water temperatures were almost uniform.

In this study, a prediction system has been developed for the water temperature in the SFP during the shutdown of cooling systems using a one-region model based on results of the 3D calculations (9), and it was extended to predict the water level during loss of all AC power supplies. Temperatures calculated for the shutdown of cooling systems were compared with 3D calculations and measured temperatures. The calculated results for loss of all AC power supplies were verified using measured values from the Fukushima Daiichi Nuclear Power Station (12).

2. One-region Model Predicting Water Temperature and Level

Figure 1 shows the conceptual diagram of a SFP. The layout and size of the SFP differ in each reactor unit. Further, the SFP is generally located in the fuel handling building.
outside of the reactor building in a PWR (pressurized water reactor) and on the operation floor in the reactor building in a BWR (boiling water reactor). The height of spent the fuel racks is about 4.5 m and the water depth of the SFP is about 12 m to provide radiation shielding. The length in the direction of ventilation air flow is about 10 m.

Figure 2 outlines the prediction system for the water temperature and level in the SFP, which consists of subsystems to calculate decay heat of spent fuel assemblies and the water temperature and level in the SFP. In the calculation of the water temperature and level, the user has to select the calculation conditions for the shutdown of cooling systems or loss of all AC power supplies, where the evaporation heat transfer correlation is forced convection or natural convection, respectively.

![Conceptual diagram of spent fuel pit](image1)

**Fig. 1** Conceptual diagram of spent fuel pit

![Prediction system for water temperature and level](image2)

**Fig. 2** Prediction system for water temperature and level

### 2.1 Prediction of Decay Heat

The subsystem to calculate decay heat is basically the same as that previously used\(^9\). Fuel assemblies in a SFP can be classified into two kinds: fuel assemblies with large decay heat which had been taken relatively recently from the shutdown reactor core and fuel assemblies with small decay heat which was cooled for a long time in the SFP. The burn-up calculation software, ORIGEN 2.2 \(^10\), and the nuclear cross section libraries \(^13\) for ORIGEN 2 based on JENDL 3.3 \(^11\) were used to calculate decay heat of fuel assemblies. Calculation conditions were for uranium fuel assemblies of PWRs and the maximum burn-up was 48 GWD/t or 55 GWD/t with three cycles. Decay heat of the shutdown reactor core was calculated for operation periods of 3, 6 and 13 months and the operation period reaching the maximum burn-up, and the tables of decay heat were made with the parameters
of operation periods and the cooling time after the reactor shutdown. Decay heat of the maximum burn-up fuel assemblies with longtime cooling was calculated after the reactor shutdown, and the tables of decay heat were made for the time after the reactor shutdown. From the data of the spent fuel assemblies stored in the SFP, decay heat of each fuel assembly was complementally calculated using the tables of decay heat.

In the previous study (9), decay heat was constant because the calculation period for the shutdown of cooling systems was short and about one day. The calculation period for loss of all AC power supplies, however, is generally long and sometimes about several months, so time-dependent decay heat was calculated in the present study.

2.2 Prediction of Water Temperature

Figure 3 shows calculation models for heat transfer and water temperature. The hypothetical surface layer was for calculation of the evaporation heat transfer rate from the water surface to air $Q_{E}$.

The average water temperature $T_w$ [°C] in the SFP is calculated from heat balance among heat stored in water, decay heat $Q_D$ [kW], heat transfer from water to concrete $Q_C$ [kW], and evaporation heat transfer from the water surface to air $Q_{E}$ [kW]:

$$C_p \cdot M_w \cdot \frac{dT_w}{dt} = Q_D - Q_E - Q_C \cdot T_w \leq 100 \degree C$$  \hspace{1cm} (1)

where $C_p$ [kJ/(kg·K)] is the specific heat of water, $M_w$ [kg] is the water mass, and $t$ [s] is the time after the shutdown of cooling systems or loss of all AC power supplies. In Eq. (1), the limitation of $T_w \leq 100 \degree C$ automatically gives transition from evaporation to boiling with $(Q_E = Q_D - Q_C)$.

Heat transfer from water to concrete $Q_C$ is calculated using the one-dimensional unsteady heat conduction equation with the natural convection heat transfer correlation proposed by Kataoka et al. (14):

$$Nu = \frac{h \cdot Z}{\lambda_w} = 0.13(Gr \cdot Pr)^{1/3}, \hspace{0.5cm} Gr = g \beta \left( T_w - T_{cs} \right) \frac{Z^3}{\nu^2}$$  \hspace{1cm} (2)

where $Nu$, $Gr$ and $Pr$ are Nusselt number, Grashof number and Prandtl number, respectively, $g$ [m/s²] is the gravitational acceleration, $h$ [kW/(m²·K)] is the heat transfer coefficient, $T_w$ and $T_{cs}$ [°C] are the respective water and concrete surface temperatures, $Z$ [m] is the height from the SFP bottom, $\beta$ [1/K] is the water expansion coefficient, $\lambda_w$ [kW/(m·K)] is the water thermal conductivity of water, and $\nu$ [m²/s] is the water
kinematic viscosity. Adiabatic condition was used on the outer surface of the concrete walls. In the decay heat of 1 MW, the calculated temperature increase there was about 0.1 °C at 100 hours, and adequacy of the adiabatic condition on the outer surface of the concrete walls was confirmed.

The water surface temperature \( T_{ws} \) is lower than the average water temperature \( T_w \) due to heat loss to air \(^{(9)}\). Therefore, the hypothetical surface layer is considered, and \( T_{ws} \) [°C] is calculated from heat balance there:

\[
T_{ws} = T_w - \frac{Q_E}{2C_p \rho_w G_{ws}}, \quad T_w < 100 \, ^\circ \text{C} \tag{3}
\]

where \( G_{ws} \) [kg/s] is the natural circulation flow rate. A correlation for natural circulation flow rates \( G_{ws} \) is derived as a function of decay heat based on 3D calculations. In Eq. (3), \( T_{ws} \) is defined by the average of inlet and outlet temperatures in the hypothetical surface layer (\( T_{ws,in} = T_w \)). Equation (3) is effective only before initiation of boiling, so \( T_w \) limitation is attached.

Evaporation heat transfer from the water surface to air \( Q_E \) is calculated using the correlation proposed by Yanagi et al. \(^{(7)}\) for evaporation heat flux \( q_E \) [kW/m²]:

\[
q_E = 0.010 \rho_u U_a 0.60 \left( \frac{0.622 P_{S_0}}{P - 0.378 P_{S_0}} - \frac{0.622 P_{S_v}}{P - 0.378 P_{S_v}} \right) h_{fg} \tag{4}
\]

or

\[
q_E = h_{fg} \rho_u \left( \frac{0.622 P_{S_0}}{P - 0.378 P_{S_0}} - \frac{0.622 P_{S_v}}{P - 0.378 P_{S_v}} \right) h_{fg},
\]

\[
Sh = \frac{h_{fg} l}{D} = 1.65 \times 0.0185 G_{ws}^{0.4} S_{sc}^{0.4} \tag{5}
\]

where \( Sh \) and \( Sc \) are Sherwood number and Schmidt number, respectively. \( \rho_u \) [kg/m³] is the air density, \( U_a \) [m/s] is the air velocity, \( h_{fg} \) [kJ/kg] is the latent heat of evaporation, \( P = 0.10 \) [MPa] is the total pressure, \( P_{S_0} \) [MPa] is the saturated vapor pressure on the water surface, \( P_{S_v} \) [MPa] is the vapor pressure in air, \( h_{fg} \) [kJ/kg] is the latent heat of evaporation, \( D \) [m²/s] is the mass diffusion coefficient, and \( l \) [m] is the characteristic length of the heat transfer area. \( P_{S_0} \) and \( P_{S_v} \) are functions of the water surface temperature \( T_{ws} \) and the air temperature \( T_a \), respectively. Equation (4) for forced convection air flow and Eq. (5) for natural convection air flow are used for heat flux calculations in cases of the shutdown of cooling systems and loss of all AC power supplies, respectively. Equation (5) was derived from the analogy between natural convection heat transfer and mass transfer of vapor.

In the case of the shutdown of cooling systems, the air outlet temperature \( T_{a,out} \) is calculated from the heat balance equation for ventilation air, and the average value of the air inlet and outlet temperatures is used to calculate the evaporation heat transfer rate \( Q_E \). In case of loss of all AC power supplies, the average temperature in the fuel handling building \( T_a \) is calculated from the heat balance equation for air in the fuel handling building:

\[
\left( \frac{dQ_a}{dt} \right) = Q_D - Q_C - C_p M_w \left( \frac{dT_a}{dt} \right) - Q_{out}, \quad T_a = f \left( \frac{Q_a}{V_a} \right) \tag{6}
\]

where \( Q_a \) [kJ] is the stored enthalpy of air in the building, \( Q_{out} \) [kW] is the heat transfer rate outside the building, and \( V_a \) [m³] is the volume of the building. \( Q_{out} \) is calculated using a turbulent natural convection heat transfer outside of the building neglecting effects of wind. The function \( f \) is obtained from the relationship between air temperature and its enthalpy [kJ/m³] with 100% relative humidity. Values of physical properties were calculated as a function of temperature.
2.3 Prediction of Water Level

The water level \( H_w \) [m] is calculated from the mass balance equation:

\[
H_w = \frac{M_w}{\rho_w A_{ws}}, \quad \left( \frac{dM_w}{dt} \right) h_{fg} = -\left( Q_D - Q_C \right) + C_p M_w \left( \frac{dT_w}{dt} \right)
\]

where \( \rho_w \) [kg/m\(^3\)] is the water density and \( A_{ws} \) [m\(^2\)] is the water surface area. The last term is heat stored in the SFP water and it becomes zero after the water temperature reaches the saturated temperature of \( T_w = 100 \) °C. In Eq. (1), when \( T_w \) is 100 °C, \( dT_w / dt = 0 \) (i.e. \( Q_E = Q_D - Q_C \)), and so \( Q_D - Q_C \) is used instead of \( Q_E \) in Eq. (7).

3. Water Temperature after Shutdown of Cooling Systems

Water temperatures calculated for the shutdown of cooling systems were compared with 3D calculations and measured temperatures to evaluate effectiveness of the one-region model.

3.1 Comparison with 3D Calculations

Figure 4 compares predicted water temperatures after the shutdown of cooling systems with average temperatures in 3D calculations \(^9\) to evaluate the accuracy decline by using one-region model prediction. The width, length and depth of the SFP under the water surface were about 15, 10 and 12 m, respectively. The thickness of the side-wall concrete was about 1.8 m. Decay heat was constant at \( Q_D = 1, 5 \) and 10 MW because the calculation period was short. Equations (2) and (4) were used for boundary conditions of heat transfer. In the calculation of the evaporation heat transfer coefficient using Eq. (4), constant temperature (20 °C) and humidity were used for ventilation air. The average air velocity near the water surface of \( U_a = 1.36 \) m/s, which was obtained from the calculation of the ventilation air flow, was used in Eq. (4). The temperature of the SFP water at the shutdown of cooling systems was 22.5 °C.

The predicted water temperatures with the one-region model shown by broken lines agreed well with average temperatures in 3D calculations shown by solid lines. However, the one-region model slightly overestimated the average temperature for the small decay heat of 1 MW. The computing time needed was from two days to two weeks for the 3D calculations depending on the shutdown period of cooling systems but was less than one second in the one-region model. The result indicated the effectiveness of the one-region model.

![Fig. 4 Water temperatures after shutdown of cooling systems (3D: 3D calculations, 1R: prediction with one-region model)](image-url)
3.2 Comparison with Measured Temperatures

Table 1 shows measured conditions for the two cases considered. In the calculations, decay heat was calculated using the method discussed in section 2.1. Figure 5 compares the calculated water temperature with the data measured by using a permanent thermocouple. The time and temperature were normalized by the shutdown period of cooling systems \((t_e - t_0)\) and temperature increase during the shutdown of cooling systems \((T_e - T_0)\), respectively. The measurement error of the temperature increase was about 2.5%. \(t_0\) is the time at the shutdown of cooling systems, and \(t_e\) is the time at restart of cooling systems. \(T_0\) is the water temperature at \(t_0\), and \(T_e\) is the water temperature at \(t_e\). In the previous study\(^{(9)}\), it was shown that decay heat calculated in this study by using ORIGEN2.2 \(^{(10)}\) was smaller than that predicted by the correlation of ANS-5.1-1973 \(^{(2)}\) or AESJ \(^{(3)}\), but the average temperature increase was overestimated in both Cases 1 and 2. In Case 1, there were fuel assemblies with large decay heat which had been taken relatively recently from the shutdown reactor core and the period of cooling systems was short. Therefore, effects of the initial transient might be relatively significant. The predicted temperature increase with the one-region model shown by the broken line agreed well with that obtained by 3D calculations shown by solid lines and the overestimation of the temperature increase was about 7% in Case 1. However, overestimations of the temperature increase with 3D calculations and the one-region model were large and respectively about 36% and about 45% in Case 2. The results in Case 2 showed that decay heat predicted by ORIGEN 2.2 was overestimated for longtime cooled fuel assemblies with small decay heat.

|       | Decay heat | Shutdown period of cooling systems | Highest water temperature |
|-------|------------|-----------------------------------|---------------------------|
| Case 1| High       | Short                             | About 30 °C               |
| Case 2| Low        | Long                              | About 40 °C               |

Fig. 5  Comparison of predicted temperatures with data
(3D: 3D calculations, 1R: prediction with one-region model)

4. Water Temperature and Level during Loss of All AC Power Supplies

4.1 Effects of Decay Heat

The water temperature and level during loss of all AC power supplies were calculated using the one-region model. The SFP had a surface area of about 150 m² and was about 12 m deep. Three initial decay heats at loss of all AC power supplies were used: \(Q_{D,0} = 5\) MW, 0.9 MW and 0.3 MW. These conditions were example calculations and they are shown in Figs. 6, 7 and 8, respectively.
For $Q_{D,0} = 5$ MW (Fig. 6), decay heat $Q_D$ was large comparing with heat losses to air and concrete, $(Q_E + Q_C)$. At about 1.4 days after loss of all AC power supplies, the average water temperature $T_w$ was 100 °C and boiling was initiated. The water surface temperature $T_{ws}$ was lower than $T_w$ due to heat loss to air. The concrete average temperature $T_c$ was low because of low thermal conductivity of concrete. The water level $H_w$ slightly increased before $T_w$ reached 100 °C due to thermal expansion and was rapidly decreased due to boiling after $T_w$ reached 100 °C. The adiabatic calculations neglecting heat losses to air and concrete overestimated water temperature and underestimated the water level but effects of heat losses were not significant because of large decay heat.

For $Q_{D,0} = 0.9$ MW (Fig. 7), heat losses to air and concrete, $(Q_E + Q_C)$, became equal to decay heat $Q_D$ before $T_w$ reached 100 °C, and $T_w$ was lower than 100 °C. Heat loss to concrete $Q_C$ initially increased due to the increase in the temperature difference, $(T_w - T_c)$, and then decreased due to the decrease in the water level $H_w$.

For $Q_{D,0} = 0.3$ MW (Fig. 8), the average water temperature $T_w$ was much lower than 100 °C. Therefore, the adiabatic calculations neglecting heat losses to air and concrete
overestimated the water level due to overestimation of heat stored in the SFP water. The results indicated that the adiabatic calculations were not always conservative.

![Graph showing temperature and water level over time]

Fig. 8  Calculated results ($Q_{D0} = 0.3$ MW, * without heat loss)

4.2 Calculations for the Fukushima Daiichi Nuclear Power Station

The objective of calculations with the one-region model for spent fuel pools (SFPs) in the Fukushima Daiichi Nuclear Power Station was not to reproduce thermal-hydraulics but to validate prediction of decay heat and the correlation for evaporation heat fluxes used in the one-region model. Table 2 shows decay heat calculated by TEPCO \(^{(12)}\) using ORIGEN2.2 \(^{(10)}\). In this study, decay heat was calculated using the correlation recommended by ANS-5.1-1973 \(^{(2)}\), which was fitted using two decay heats listed in Table 2.

Table 3 lists calculation conditions used in the TEPCO report \(^{(12)}\). The water surface area and depth of the SFPs are the same in Units-2, 3 and 4, and are about 120 m\(^2\) and 11.5 m, respectively. The initial water temperature of $T_{w,0} = 30 \, ^\circ C$ and outdoor temperature of $T_{out} = 10 \, ^\circ C$ were used in the calculations. The water temperature measurement point is about 300 mm under the water surface \(^{(12)}\).

Size of the fuel handling building differs in each reactor unit. In this calculation, the area of the operation floor in the reactor building was about 47 m $\times$ 42 m and its height was about 20 m.

| Table 2  Decay heat \(^{(12)}\) calculated with ORIGEN2.2 |
|-------------------|-------------------|
|                   | March 11, 2011    | Three months later |
| Unit-2 pool       | 0.62 MW           | 0.52 MW            |
| Unit-3 pool       | 0.54 MW           | 0.46 MW            |
| Unit-4 pool       | 2.26 MW           | 1.58 MW            |

| Table 3  Calculation conditions \(^{(12)}\) |
|-------------------|-------------------|
| Water volume*     | Water level*      | Water temp.*      | Outdoor temp. | Feed water temp. T_{w,in} [°C] |
| $V_{w,0}$ [m$^3$] | $H_{w,0}$ [m]     | $T_{w,0}$ [°C]    | $T_{out}$ [°C] | $T_{w,in}$ [°C]               |
| 1390              | 11.5              | 30                | 10             | 10                            |

* initial conditions

Figure 9 shows results calculated for the Unit-3 pool without cooling water injection into the pool. In Eq. (5), after destruction of the building due to a hydrogen explosion, the outdoor temperature of $T_{out} = 10 \, ^\circ C$ was used to calculate evaporation heat transfer (i.e. $T_{a} = T_{out}$ in Fig. 3 (b)). Therefore, the heat transfer coefficient and heat loss to air increased after destruction of the building. The adiabatic calculations neglecting heat losses overestimated
the water level due to overestimation of heat stored in the SFP water. After 20 days, the calculated evaporation heat transfer coefficient was about 65 kW/(m²K). The calculated average temperature of about 80 °C was higher than the measured temperature of about 62 °C. The reasons for this might be (a) the overestimation of decay heat predicted by ORIGEN 2.2, (b) the effect of cooling water injection at about 10 °C, (c) the underestimation of evaporation heat flux by Eq. (5), and (d) measurement error of water temperature. The measurement error of water temperature is not clear but might be about ±2.5 °C (class 2 of JIS C 1605-1995).

After 8 days, cooling water was periodically injected into the Unit-3 pool and a high water level was kept. Figure 10 compares water levels during the period of no cooling water injection to evaluate accuracy of decay heat prediction. The decreasing rate of the water level was overestimated in the case of 100% decay heat predicted by ORIGEN 2.2 (1.0 \( Q_D \)) and the 70% value of decay heat predicted by ORIGEN 2.2 (0.7 \( Q_D \)) gave good agreement with the measured water level.

Figure 11 compares water temperatures in the Unit-3 pool. It was not clear whether the measured temperature of about 62 °C was affected by cooling water injection or not. The temperature of about 62 °C was lower than the temperature of about 70 °C measured in the Unit-2 pool with a similar decay heat. The water temperature calculated with 70% decay heat (0.7 \( Q_D \)) was about 73 °C and that was still higher than the measured value of about 62 °C. In order to get good agreement between the calculated and measured values, evaporation heat flux calculated by Eq. (5) should be made 2.3 times larger (0.7 \( Q_D \) with 2.3 \( q_E \)).
Figure 12 shows results of sensitivity calculations for the Unit-4 pool during the period of no water injection. The building of Unit-4 collapsed due to a hydrogen explosion, and the outdoor temperature of $T_{\text{out}} = 10^\circ \text{C}$ was used to calculate evaporation heat transfer in Eq. (5) (i.e. $T_a = T_{\text{out}}$ in Fig. 3 (b)). In Fig. 12 (a), the decreasing rate of the water level was overestimated in the case of 100% decay heat predicted by ORIGEN 2.2 ($1.0 \ Q_d$) and the 80% value of decay heat predicted by ORIGEN 2.2 ($0.8 \ Q_d$) gave good agreement with the measured water level. In Fig. 12 (b), water temperature was overestimated even for $0.8 \ Q_d$. In order to get good agreement between the calculated and measured values, evaporation heat flux calculated by Eq. (5) should be made 1.55 times larger ($0.8 \ Q_d$ with 1.55 $q_E$). On the other hand, it was reported that there was water leakage from the reactor well to the SFP because the water level in the reactor well decreased. In this study, however, water leakage was not simulated and that was one of the uncertainties in the calculation conditions.

In the Unit-2 pool, water was periodically injected and subcooled enthalpy of injected water was subtracted from decay heat in calculations. From the results shown in Fig. 10 for the Unit-3 pool, 70% decay heat ($0.7 \ Q_d$) was used for calculations, because decay heat in the Unit-2 pool was similar to that in the Unit-3 pool (cf. Table 2). The calculated results are not shown in a figure, but water temperature was overestimated even for $0.7 \ Q_d$. In order to get good agreement between the calculated and measured values, evaporation heat flux
calculated by Eq. (5) should be made 1.9 times larger.

4.3 Evaporation Heat Fluxes

In this study, Eq. (5) for evaporation heat fluxes, which was derived from the analogy between natural convection heat transfer and mass transfer of vapor, was used. However, Eq. (5) overestimated water temperatures in the Unit-3 and 4 pools as shown in Figs. 11 and 12 (b), respectively. Therefore, evaporation heat fluxes to fit the measured water temperatures were obtained and are shown in Fig. 13 including comparisons with Eq. (5) and the correlation proposed by Fujii et al. The data fitted evaporation heat fluxes were bigger by a factor of about 1.7 than evaporation heat fluxes calculated by Eq. (5).

Fujii et al. measured evaporation heat fluxes with surface areas of 0.034 and 0.29 m² under pressures of 0.1-0.32 MPa and water temperatures of $T_w \geq 100$ °C. The data-fitted evaporation heat fluxes were between Eq. (5) and the correlation proposed by Fujii et al. To evaluate accurate evaporation heat fluxes, however, effects of uncertainties of measuring conditions in the Fukushima Daiichi Nuclear Power Station should be investigated.

4.4 Discussion on Decay Heat Prediction

Decay heat predicted by ORIGEN 2.2 was overestimated. The overestimation was 43% (1/0.7) for the Unit-3 pool and 25% (1/0.8) for the Unit-4 pool as shown in Figs. 10 and 12 (a), respectively. We found that evaluation of evaporation heat flux ($q_E$) did not directly affect decay heat calculated from the decreasing rate of the water level. The reasons of the decay heat prediction error might be (a) the evaluation error of decay heat predicted by ORIGEN 2.2 (+5%), (b) effects of radiation heat transfer, and (c) the estimation error of burn-up of fuel assemblies. The effect of the radiation heat transfer error was 10% for the Unit-3 pool and 5% for the Unit-4 pool at relatively high emissivity. So this overestimation of decay heat might consist, for the most part, in the estimation error of burn-up of fuel assemblies. In this study, the maximum burn-up of 48 GWd/t or 55 GWd/t was used, as discussed in section 2.1. To predict decay heat accurately, actual burn-up should be used for each spent fuel assembly.

5. Conclusions

The prediction system with a one-region model was developed to predict water temperature in a SFP after the shutdown of its cooling systems based on 3D
thermal-hydraulic behavior calculated by using the CFD software, FLUENT 6.3.26. The calculation of water surface temperature needed the natural circulation flow rate. This natural circulation flow rate was determined to give the same average water temperature as that obtained from 3D calculations and was correlated as a function of decay heat. Then the system was extended to calculate the water level in the SFP during loss of all AC power supplies. The calculated results were compared with 3D calculations and measured temperatures for the shutdown of cooling systems and with the water temperature and level measured in SFPs at the Fukushima Daiichi Nuclear Power Station for loss of all AC power supplies. The following results were obtained.

1. The water temperatures predicted with the one-region model agreed well with 3D calculations for large decay heat but were slightly higher than 3D calculations for small decay heat.

2. ORIGEN 2.2 well predicted decay heat for fuel assemblies with large decay heat which had been taken relatively recently from the shutdown reactor core in the case of the shutdown of cooling systems. Decay heat predicted by ORIGEN 2.2, however, was overestimated for longtime cooled fuel assemblies with small decay heat in both cases of the shutdown of cooling systems and loss of all AC power supplies mainly due to overestimation of burn-up of fuel assemblies.

3. The correlation for evaporation heat fluxes, which was derived from the analogy between natural convection heat transfer and mass transfer of vapor, overestimated water temperatures. The data fitted evaporation heat fluxes were bigger by a factor of about 1.7 than evaporation heat fluxes calculated by the correlation from the analogy.

4. The water level calculated neglecting heat losses overestimated the water level with heat losses in the case of small decay heat, because the water temperature and stored enthalpy were overestimated. This showed that neglect of heat losses was not always conservative.

References

1. T. E. Collins and G. Hubbard, *Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants*, NUREG-1738, U.S. Nuclear Regulatory Commission (USNRC), (2011).

2. American Nuclear Society, *Decay Energy Release Rates Following Shutdown of Uranium-Cooled Thermal Reactors*, ANS-5.1-1973 (1973).

3. Research Advisory Committee for Reactor Decay Heat Standard, *Nuclear reactor decay heat and its recommendation value*, Atomic Energy Society of Japan (AESJ) (1989).

4. K. Way and E. P. Wigner, *The Rate of Decay of Fission Products*, *Physical Review*, Vol. 73, (1948), pp. 1318-1330.

5. I. Ishikawa, H. Tsujino, M. Hirabara, H. Nakano, T. Yasuda and H. Ishizaki, Meteorological Research Institute Community Ocean Model (MRI.COM) Manual, Technical Report 47, Meteorological Research Institute (2005), pp. 101-106, [in Japanese].

6. T. Fujii, Y. Kataoka and M. Murase, *Evaporation and Condensation Heat Transfer in a Suppression Chamber of the Water Wall Type Passive Containment Cooling System*, *J. Nuclear Science and Technology*, Vol. 33, No. 5 (1996), pp. 374-380.

7. C. Yanagi, M. Murase, Y. Yoshida, T. Iwaki, T. Nagae and Y. Koizumi, *Evaporation Heat Flux from Hot Water to Air Flow*, *Transactions of the Japan Society of Mechanical Engineers*, B, Vol. 78, No. 786 (2012), pp. 363-372, [in Japanese].

8. Y. Koizumi, Y. Ebihara, T. Hirota and M. Murase, *Evaporation Heat Transfer of Hot Water from Horizontal Free Surface*, *Proceedings of The 14th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics*, Toronto, Canada, September 25-30 (2011), NURETH14-39 [CD-ROM].
(9) C. Yanagi, M. Murase, Y. Yoshida, Y. Utano, T. Iwaki and T. Nagae, Numerical Simulation of Water Temperature in a Spent Fuel Pit during the Shutdown of Its Cooling Systems, *Journal of Power and Energy Systems*, Vol. 6, No. 3 (2012), pp. 423-434.

(10) S. B. Ludwig and A. G. Croff, *Revision to ORIGEN2 – Version 2.2*, Transmittal memo of CCC-0371/17, Oak Ridge National Laboratory (2002).

(11) K. Shibata, T. Kawano, T. Nakagawa, O. Iwamoto, J. Katakura, T. Fukahori, S. Chiba, A. Hasegawa, T. Murata, H. Matsunobu, T. Ohsawa, Y. Nakajima, T. Yoshida, A. Zukeran, M. Kawai, M. Baba, M. Ishikawa, T. Asami, T. Watanabe, Y. Watanabe, M. Igashira, N. Yamamuro, H. Kitazawa, N. Yamano and H. Takano, Japanese Evaluated Nuclear Data Library Version 3 Revision-3: JENDL-3.3, *J. Nuclear Science and Technology*, Vol. 39, No.11 (2002), pp. 1125-1136.

(12) TEPCO, Report on Effects of the Earthquake in the Northeastern Japan on Nuclear Facilities in the Fukushima Daiichi Nuclear Power Station, The Tokyo Electric Power Company, (September, 2011), [in Japanese].

(13) J. Katakura, M. Kataoka, K. Suyama, T. Jin and S. Ohki, *A Set of ORIGEN2 Cross Section Libraries Based on JENDL3.3 Library: ORLIBJ33*, JAERI-Data/Code 2004-015, Japan Atomic Energy Research Institute (2004).

(14) Y. Kataoka, T. Fujii, M. Murase and K. Tominaga, Experimental Study on Heat Removal Characteristics for Water Wall Type Passive Containment Cooling System, *J. Nuclear Science and Technology*, Vol. 31, No. 10 (1994), pp. 1043-1052.

(15) H. Uehara, A. Ui, H. Asaka and Y. Masuhara, Thermal-hydraulic Assessment of the Fukushima Daiichi Accident (4) Initial Event Analysis of the Spent Fuel Pools, 2012 Annual Meeting of the Atomic Energy Society of Japan, University of Fukui, March 19-21 (2012), B07 [CD-ROM], [in Japanese].