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HOT-WATER LAYER, HEAT-LOSS CHARACTERISTICS OF AN OPEN-POOL-TYPE RESEARCH REACTOR FOR REDUCING THE POOL TOP RADIATION LEVEL

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ABSTRACT

During an open-pool-type research reactor operation, it is necessary to access the pool top area for un/loading irradiation test pieces by a required irradiation period. However, when the reactor pool top radiation level exceeds the limit of radiation level by the rising of reactor chimney water contaminated by radioactivity due to a natural convection of the pool water, access the reactor pool top area is denied due to the high radiation level. In the case of HANARO, a hot-water layer (HWL, hereinafter) is maintained below a depth of 1.2 m from the top of the reactor pool in order to reduce the radiation level of the reactor pool top area.

After a normal operation of the HWL, the pool top radiation level is safely maintained below the limit of the pool top radiation level. For studying more the characteristics of the HWL under a reactor coolant downward flow condition, The HWL heat loss is calculated based on the HANARO HWL calculation model. The HWL heat loss characteristics were reviewed by variations of the HWL temperature, reactor core coolant flow direction, and reactor power.

It was confirmed through the results that the HWL heat loss under a reactor coolant downward flow condition was increased by about 20% to 60% over that under a reactor coolant upward flow condition, as per the HWL temperature variation. It was the reason that the HWL bottom convection heat loss was increased by the higher flow rate under a reactor coolant downward flow condition than that under a reactor coolant in an upward flow condition.

INTRODUCTION

HANARO[1], a 30 MW research reactor, was installed at the depth of about 13 m of an open pool. The primary coolant is an upward flow to cool the heat generated by the reactor. 90% of the primary coolant was designed to pass through the core to remove the reaction heat of the core in HANARO. The remaining 10% of the primary coolant was designed to bypass the core to cool the heat of the reactor outside.

Through the two reactor coolant outlets installed at top of the reactor chimney, the primary coolant through and bypassing the core is inhaled by the coolant pumps. But, a part of the core bypass coolant was not inhaled by the primary coolant pumps and reached the top of the reactor pool by natural convection. And it increased the radiation level at the top of the reactor pool[2]. To protect a natural convection of the core bypass flow, a hot water layer was installed in the top of the reactor pool[2].

When the primary coolant flows downward to cool the heat generated by the reactor, the total coolant including the core bypass flow supplies to the reactor pool. By the suction force of the primary coolant pumps, the reactor pool water is inhaled through the reactor chimney, core, and outlet plenum to remove the heat generated by the reactor and to protect the radiated gas lifting to the top of the reactor pool.

Same as the upward flow, a part of the coolant will not be inhaled by the primary coolant pumps, reach the top of the reactor pool by a natural convection, and which will increase the radiation level at the top of the reactor pool. To reduce the radiation level, HWL will be installed the top of the reactor pool. This paper describes HWL heat loss characteristic including heat loss evaluation for heat loss trend of reactor coolant down flow, each reactor coolant flow direction, HWL temperature increment, and reactor power increment based on the calculation model of HANARO for reducing the pool top radiation level.

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NOMENCLATURE

A_b: Hot water layer bottom area
A_h: Surface area of hot water layer
A_S: Straight wall area
C: Unit conversion factor
P_a: Dew point air vapor pressure above hot water layer
P_h: Vapor pressure of hot water layer
H_b: Heat transfer coefficient of hot water layer bottom
H_h: Heat transfer coefficient of convection heat loss
k : Wall heat transfer ratio
k_b : Hot water layer bottom heat transfer ratio
L_b : Hydraulic radius
P_r: Prandtl's number
R_e: Reynolds number
R_1: Cylindrical wall heat resistance
R_2 : Straight wall heat resistance
r_o : Reactor pool outside radius
r_i : Reactor pool inside radius
Q_b: Bottom convection heat loss
Q_c: Surface convection heat loss
Q_e: Evaporation heat loss
Q_h: Heating load of heater
Q_w: Wall conduction heat loss
T_a: Reactor hall air temperature
T_b: Water temperature below hot water layer
T_h: Hot water layer temperature
V_a: Air velocity above hot water layer surface
ΔT : Wall temperature difference
$\sum R$: Sum of heat resistance
Δx : Straight wall thickness

HWL OF HANARO

In HANARO, when the HWL is maintained at the pool top, the heat losses of the HWL are induced by an evaporation loss, a surface convection loss, a bottom convection loss and a wall conduction loss[3]. To compensate the heat loss, the HWL

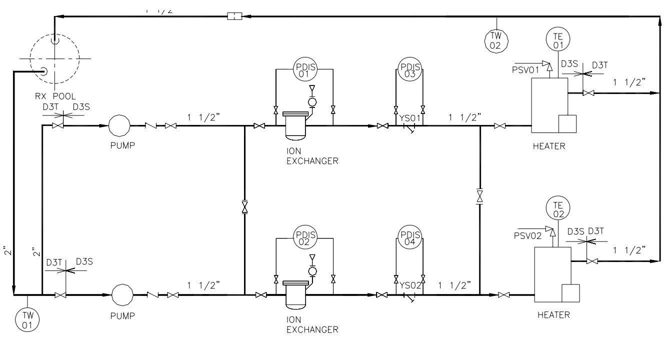

Fig. 1 Schematic diagram of HWL system

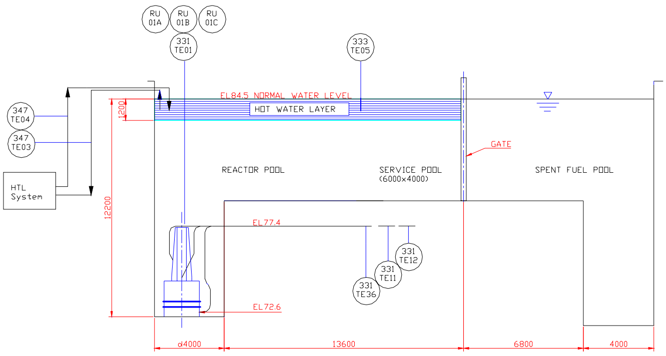

Fig. 2 Temperature control of HWL system

system was composed of two 100% capacity pumps, ion exchangers, heaters and strainers in parallel. The two heaters were automatically operated by two temperature detectors (347-TE03 and 347- TE04) that were installed in the suction and the discharge pipe of the heater as shown in Fig. 1[4,5].

As shown in Fig. 2, a service pool water temperature detector (333-TE05) was installed at the top of a service pool to measure the temperature of the HWL. A chimney water temperature detector (331-TE01) was installed to measure the reactor chimney top water temperature, at just above the reactor chimney. Pool top radiation detectors (RU-10A, RU-10B and RU-10C) were installed to measure the pool top radiation level.

Each detector was composed of an ion chamber, a measuring unit, a connection box, a recorder, a signal unit and a test source[6]. The ion chamber was installed at the height of fifty centimeter (50 ㎝) from the top of the reactor pool and the space of one hundred and twenty degree (120^o).

HEAT LOSS CALCULATION OF HWL

Operation conditions

The HWL of HANARO adopted as the calculation model of the reactor coolant downward flow. Under a normal operation, to maintain the HWL of the pool top with above 5℃ temperature difference higher than the reactor chimney top water temperature, the reactor chimney water and the HWL temperatures are 34℃ and 39℃ respectively as listed in Table 1. The reactor pool top air flow velocity, and the reactor hall temperature and relative humidity are 1.5 m/s, 27℃, and 60 % respectively.

When the primary coolant pumps are normally operated, the pumps suck core coolant including 10% pool water under a reactor coolant upward flow condition (UFC, hereinafter). But, under a reactor coolant downward flow condition (DFC, hereinafter), the pumps suck one hundred percent suction flow of reactor pool through the reactor chimney as different from that of the reactor coolant UFC.

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Table 1 Operation conditions

Reactor coolant flow direction	UFC	DFC
HWL temperature (℃)	39	
Reactor chimney water temp. (℃)	34	
HWL surface air velocity (m/s (ft/s))	1.5 (5)	
Reactor hall relative humidity (%)	60	
Reactor hall air temperature (℃)	27	
Bypass flow (kg/s)	10% of FF	100% of FF
Coolant full flow (kg/s)	780	
Surface area of HWL (㎡ (ft^2))	48.27 (520)	
Thickness of HWL (m)	1.2	

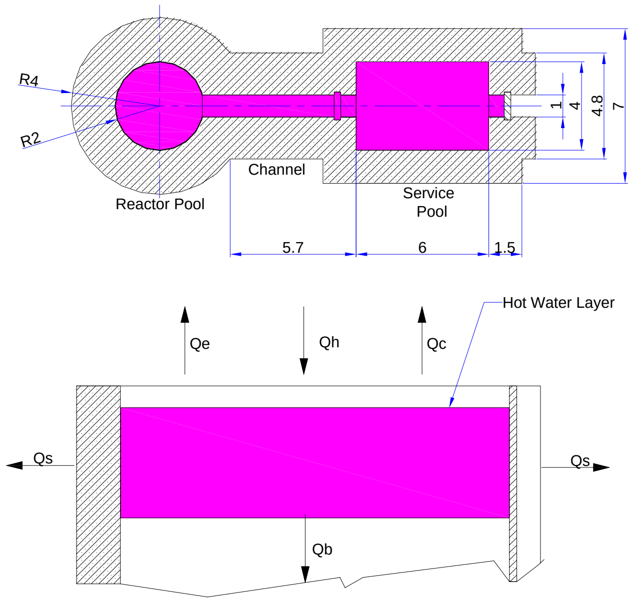

Fig. 3 Configuration of HWL heat balance

Heat loss calculation under a reactor coolant DFC

When HWL is normally maintained at the pool top as shown in Fig. 3, the heater capacity is equalized to the sum of heat loss as shown in formula (1) to compensate the loss of HWL.

$$Q_h=Q_e+Q_c+Q_w+Q_b \qquad (1)$$

The evaporation loss of HWL surface occurs by the surface air velocity and pressure difference between the vapor pressure of HWL and the reactor hall air dew point in according to each temperature as shown in formula (2)[3,7].

$$Q_e=A_h \cdot (95+0.425V_a)(P_h-P_a) \cdot C \qquad (2)$$

Here, each vapor pressure is 55.3 mmHg (2.178 inch-Hg) for hot water layer at 39℃ and 16.0 mmHg (0.631 inch-Hg) for the reactor hall air dew point and 60 % of the relative humidity at 27 ℃ of the reactor hall. The unit convert factor of C is 0.293 $\frac{W}{Btu/hr}$. The heat loss was calculated at 21.2 kW. It was the same as the reactor coolant UFC.

The HWL surface convection loss[3,7] occurs by the te mperature difference between HWL and that of the reactor hall as shown in formula (3)[3,7].

$$Q_c=H_h \cdot A_h \cdot (T_h-T_a) \qquad (3)$$

The range of a natural convection heat transfer coefficient[8] is 5.68 to 28.40 $\frac{W}{m^2 \cdot {}^oC}\left(1 \text{ to } 5 \frac{Btu}{hr \cdot ft^2 \cdot {}^oF}\right)$. The minimum value is adopted to calculate the heat loss by an engineering experience. The heat loss was calculated at 3.3kW. It was the same as the reactor coolant UFC. The HWL bottom convection loss occurs by the temperature difference between the HWL and the reactor hall air as shown in formula (4)[3,7]

$$Q_b=H_b \cdot A_b \cdot (T_h-T_b) \qquad (4)$$

The water temperature below the HWL is the same as the reactor chimney water. In this formula, the heat transfer coefficient of the HWL bottom is governed by the pool water suction flow rate of the coolant pumps. In this case, as shown in formula (5)[3,7]), the heat transfer coefficient is governed by a hydraulic radius, a Reynolds number and a Prandtl's number.

$$H_b \times \frac{L_b}{k_b} = 0.644 Re^{1/2} \cdot Pr^{1/3} \qquad (5)$$

Each value is 0.782m of the hydraulic radius, 4.666 of the Prantl's number, 721,775 of the Reynolds number, 0.628 $\frac{W}{m^2 \cdot {}^oC}$ of the ratio of heat transfer and 233.1 $\frac{W}{m^2 \cdot {}^oC}$ of the heat transfer coefficient[9]. The heat loss was calculated at 13.9 kW. This value was higher than 3.1 kW of the reactor coolant UFC because the pool water pumps' suction flow rate was 100% of full flow for reactor coolant DFC and 10% of full flow for reactor coolant UFC.

The wall conduction loss is governed by the heat resistant coefficient as shown in formula (6). The coefficient is governed by the wall configuration as shown in Fig. 2. Each coefficient is adopted to formula (7) for the cylindrical wall and to formula

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$$Qb = \frac{\Delta T}{\sum R} \tag{6}$$

$$R_1 = \frac{\ln(r_0/r_i)}{k_s/2\pi 2} \tag{7}$$

$$R_2 = \frac{\Delta x}{k_s A_s} \tag{8}$$

(8) for the straight wall[3,7]. Each ratio of heat transfer is 0.012 $\frac{W}{m^2 \cdot {}^oC}$ for cylindrical wall, 0.167 $\frac{W}{m^2 \cdot {}^oC}$ for straight wall[9]. The heat loss of wall penetrated conduction was calculated at 2.4 kW. It was the same as reactor coolant UFC.

DISCUSSION

HWL heat loss by reactor coolant flow direction

Fig. 4 shows the heat loss calculation results under each reactor coolant flow conditions listed in Table 1. The other heat loss except from the bottom heat convection loss of the DFC was the same as the UFC. The evaporation loss was about fifty two percent (52%) of the total heat loss in DFC. This loss occurs by the vapor pressure difference between the HWL and the reactor hall air according to the temperature difference. As the reactor hall temperature was lower than that of the HWL, which also increased the evaporation loss.

As shown in the figure, the total heat loss of a DFC had a higher increase than that of a UFC for about 1.4 times due to the increment of bottom surface heat convection loss. From the reactor pool, 100% of core full flow was sucked by the coolant pumps, the heat loss of the bottom surface heat convection of a DFC showed about 4.5 times increase over that of the UFC. As the bottom cold flow of HWL in DFC had increased, it was found through the calculation results that the bottom convection heat loss of DFC had also increased than those of UFC.

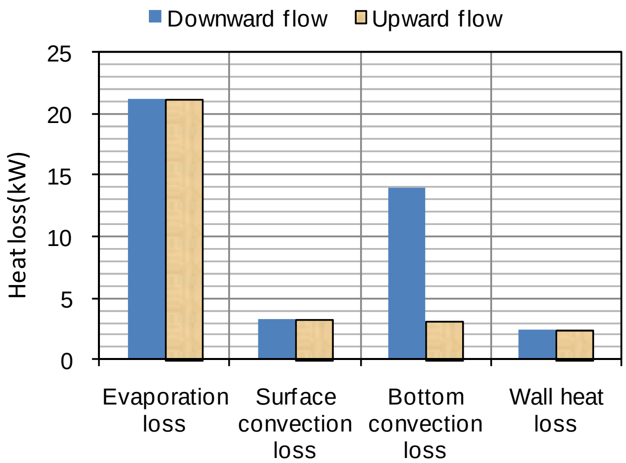

Fig. 4 HWL heat loss under each flow condition

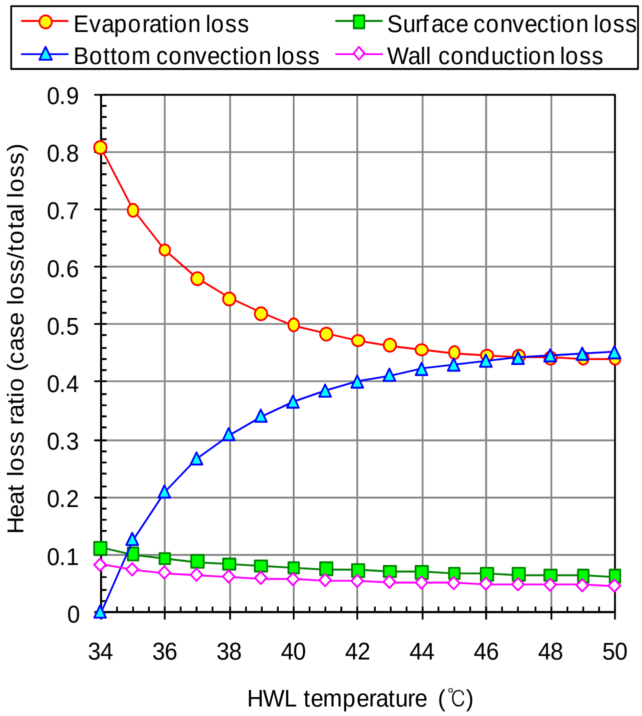

Fig. 5 Heat loss trend of the DFC BY the HWL temperature increment

Heat loss trend of the DFC

Fig. 5 shows the HWL heat loss trend of the DFO as per the HWL temperature increment. At 34℃ of the HWL temperature, the major loss was evaporation loss due to nothing of the bottom convection loss. After 34℃ of the HWL temperature, as the bottom convection loss had increased until 48℃ of the HWL temperature, the ratio of the evaporation loss had decreased relatively with a litter decrement of the evaporation loss. After 48℃ of the HWL temperature, the ratio of the evaporation loss was more decreasing than that of the bottom convection loss.

The other losses showed a litter decrement as per the HWL temperature increment, but the ratio of the other heat loss decreased due to the much increment of the HWL bottom convection loss. In case of the UFC, the bottom loss was litter because the pool flow sucked by cooling pumps was 10% of the DFC and the ratio of the bottom convection loss did not impact to the ratio of the evaporation loss.

Heat loss by HWL temperature increment

As the HWL temperature increased, the pool top radiation level decreased. To reduce the pool top radiation level, the heat losses were calculated by the HWL temperature increment under each flow condition. When the HWL temperature had increased, the HWL heat losses under each flow condition were calculated as shown in Fig. 6.

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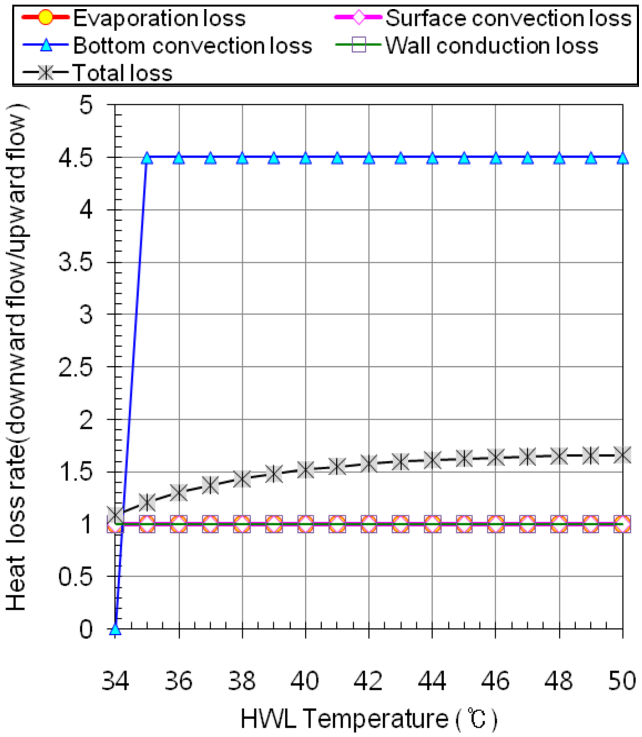

Fig. 6 Heat loss by HWL temperature increment for each flow condition

The total heat loss of the DFC showed a 1.6 times increase over that of the UFC until 41℃ of the HWL temperature. After 41℃ of the HWL, the increment was smooth. The reason was that the bottom convection loss of DFC was 4.5 times more increased than that of the UFC. The other loss of the DFC indicated as one (1). This means that the heat loss of the DFC was the same as the UFC.

In figure 6, the loss of bottom convection loss indicated zero at 34℃ of HWL temperature. This means a convection heat loss did not occur due to the same temperature between the HWL and the reactor chimney water. The other losses occur due to temperature differences between the HWL and the reactor hall.

DFC heat loss as reactor power increment

When a research reactor power is increased, it is necessary to increase the coolant flow rate or the coolant temperature difference. In case of DFC, when the coolant temperature difference increases, the coolant outlet temperature will also increase. But the coolant inlet temperature will not be changed, hence it will not be affected in the HWL heat loss. When the coolant flow rate is increased, the HWL heat loss is increased due to the bottom convection loss increment. To predict the HWL heat loss under a DFC, the heat loss was calculated as shown in Fig. 7. As the reactor power is increased, the HWL heat loss is increased as the HWL temperature increment.

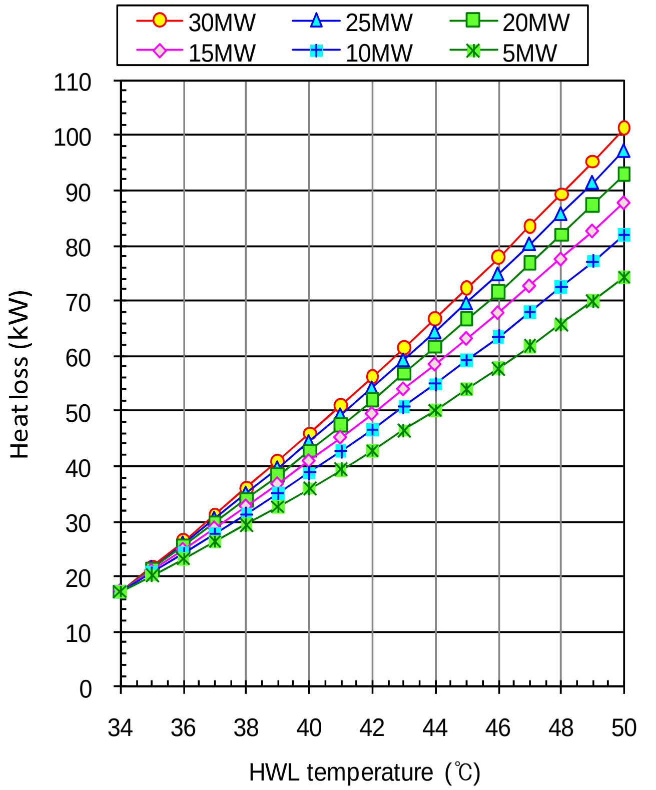

Fig. 7 Heat loss of HWL heat loss as reactor power increment under a DFC

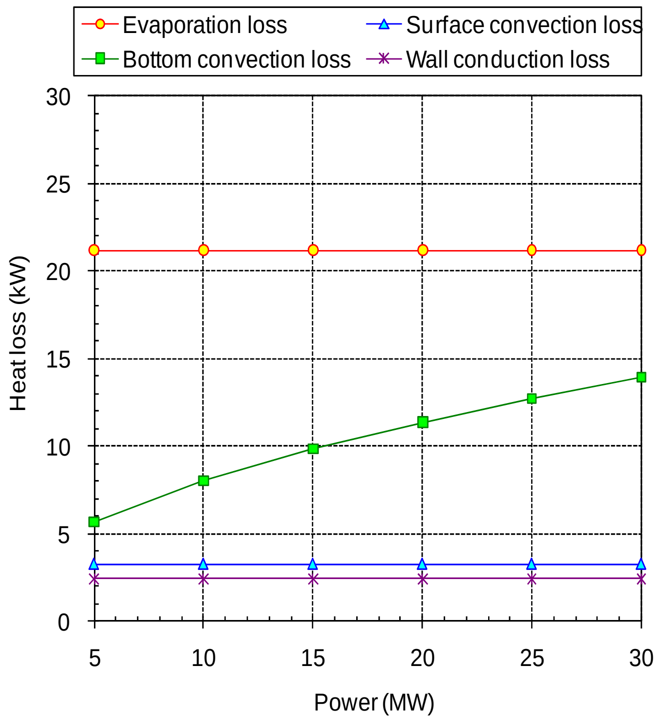

FIG. 8 Heat loss trend as reactor power increment

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Fig. 8 shows the reason for the HWL heat loss increment. The evaporation loss, the surface convection loss, and the wall conduction loss each show steady loss. But, the figure shows the bottom convection loss increased according to the reactor power increment due to the increment of HWL bottom pool water suction flow. Therefore it is confirmed through the result that the HWL heat loss is increased by the increment of the reactor power and the HWL temperature due to the increment of HWL bottom convection heat loss by the increment of HWL bottom pool water being sucked by the cooling pumps.

CONCLUSIONS

Under a reactor normal operation, a HWL is maintained at the pool top to reduce the pool top radiation level. To maintain the HWL under a DFC, the heat loss is calculated and evaluated. The conclusions are as following.

1) The other heat loss except from the bottom heat convection loss of the DFC is the same as the UFC. The evaporation loss is major as about fifty two percent (52%) of the total heat loss in DFC.
2) As the increment of HWL temperature, the heat loss of DFC shows a 1.2 to 1.6 times increase over that of UFC due to the HWL bottom convection heat loss is increased due to an increment of the pool water sucked by the cooling pumps.
3) As an increment of the pool water being sucked by the cooling pumps, the bottom convection heat loss of DFC is 4.5 times more increased than that of the UFC.
4) When the reactor power is increased, the HWL heat loss of DFC is increased due to the HWL bottom convection loss by the increment of pool water flow sucked by the cooling pumps.

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