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Estimated Tritium Dose in the Target Drive Room of the Second Target Station following Water Leakage

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Division Name

ESTIMATED TRITIUM DOSE IN THE TARGET DRIVE ROOM OF THE SECOND TARGET STATION FOLLOWING WATER LEAKAGE

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1. INTRODUCTION

In an incident where tritiated water is leaked from the target cooling water loop (Loop 1) in the target drive room area, the tritiated water vapor could pose a risk of radiation exposure to workers via tritium inhalation and skin absorption. This report presents analyses of the leak water evaporation rate and associated tritium dose to workers in the target drive room when such incident happens.

2. WATER EVAPORATION AND VAPOR BUILD UP IN TARGET DRIVE ROOM

2.1 WATER EVAPORATION RATE

Consider water spilled on flat floor in target drive room (TDR) covering a surface area A_{leak}. The evaporation of water from a water surface, as an open tank, a swimming pool or similar, depends essentially on the saturation vapor pressure at the water surface temperature, the air temperature and humidity (i.e. the saturation pressure at room air dew point), and velocity of the air above the surface. In order to estimate the water evaporation rate, the 2015 ASHRAE Handbook – HVAC application [American Society of Heating and Engineers 2015], suggests the use of the following relation:

$$\begin{aligned} \dot{w}_p &= \frac{A_{\text{leak}}}{Q_{\text{latent}}}(p_w - p_a)\cdot(0.089\ [\text{m}\cdot\text{s}^{-1}] + 0.0782 v_{\text{air}}), && (1)\\ &= \alpha_{\text{conv}}(p_w - p_a), && (2)\\ \alpha_{\text{conv}} &\equiv \frac{A_{\text{leak}}}{Q_{\text{latent}}}\cdot(0.089\ [\text{m}\cdot\text{s}^{-1}] + 0.0782 v_{\text{air}}), && (3) \end{aligned}$$

where the parameters used in Eq. (1) are listed and explained in Table 1.

$\dot{w}_p$	Evaporation rate of water	$[\text{g}\cdot\text{s}^{-1}]$
A_{leak}	Surface area of leaked water	$[\text{m}^2]$
Q_{latent}	Latent heat for evaporation at surface water temperature	$[\text{kJ}\cdot\text{kg}^{-1}]$
p_w	Saturation vapor pressure at surface water temperature	[Pa]
p_a	Saturation pressure at room air dew point	[Pa]
v_{air}	Air velocity over water surface	$[\text{m}\cdot\text{s}^{-1}]$

Table 1. Parameters in Eq. (1)

The temperature dependent latent heat of water is governed by Watson equation,

$$\begin{aligned} Q_{\text{latent}} &= Q_{100\,^\circ\text{C}}\cdot\left(\frac{T_c - T}{T_c - T_{100\,^\circ\text{C}}}\right)^{0.38}, && (4)\\ Q_{100\,^\circ\text{C}} &= 2256.4\ [\text{kJ}\cdot\text{kg}^{-1}], \quad T_c = 373.95\ ^\circ\text{C}, \quad T_{100\,^\circ\text{C}} = 100.00\ ^\circ\text{C}. && (5) \end{aligned}$$

The vapor pressure in the target drive room can be obtained by solving the balance equation between the water evaporation rate and the ventilation rate,

$$\begin{aligned} \dot{p}_a &= \frac{\dot{w}_p}{V_{\text{TDR}}}\frac{RT_K}{M} - p_a\frac{\dot{V}_{\text{TDR}}}{V_{\text{TDR}}}, && (6)\\ &= \dot{w}_p\beta_{\text{gas}} - p_a\dot{\xi}_{\text{TDR}}, && (7)\\ \beta_{\text{gas}} &\equiv \frac{RT_K}{V_{\text{TDR}}M}, \quad \dot{\xi} \equiv \frac{\dot{V}_{\text{TDR}}}{V_{\text{TDR}}}, && (8) \end{aligned}$$

the parameters used in Eq. (6) are listed and explained in Table 2.

Equations (1) and (6) forms a coupled differential equations:

$$\begin{aligned} \dot{p}_a &= \dot{w}_p\beta_{\text{gas}} - p_a\dot{\xi}_{\text{TDR}}, && (9)\\ \dot{w}_p &= \alpha_{\text{conv}}(p_w - p_a), && (10) \end{aligned}$$

R	Universal gas constant	8.314 [J·mol^{-1}·K^{-1}]
T_{K}	Water temperature in Kelvin	[K]
M	Molar mass of water	18.015 [g·mol^{-1}]
V_{TDR}	Volume of target drive room	219.17 [m^3]
$\dot{V}_{\mathrm{TDR}}$	Ventilation rate	0.189 [m^3·s^{-1}]
$\dot{\xi}_{\mathrm{TDR}}$	Fractional ventilation rate	8.613·10^{-4} [s^{-1}]
A_{TDR}	Floor area of target drive room	59.92 [m^2]

Table 2. Parameters in Eq. (6)

which reduces to an ordinary differential equation for the vapor pressure in TDR,

$$\dot{p}_a = \alpha_{\mathrm{conv}} \cdot \beta_{\mathrm{gas}} \cdot (p_w - p_a) - p_a \dot{\xi}_{\mathrm{TDR}}, \tag{11}$$

$$\frac{d}{dt} p_a = -(\alpha_{\mathrm{conv}} \cdot \beta_{\mathrm{gas}} + \dot{\xi}_{\mathrm{TDR}}) \cdot p_a + \alpha_{\mathrm{conv}} \cdot \beta_{\mathrm{gas}} \cdot p_w, \tag{12}$$

$$p_a(t=0) = p_{a:0}. \tag{13}$$

The solution of the ordinary differential equation (12) with the initial vapor pressure given by Eq. (13) at $t = 0$ is given by

$$p_a(t) = p_{a:0} \exp\left[-(\alpha_{\mathrm{conv}} \cdot \beta_{\mathrm{gas}} + \dot{\xi}_{\mathrm{TDR}})t\right] + \frac{\alpha_{\mathrm{conv}} \cdot \beta_{\mathrm{gas}} \cdot p_w}{\alpha_{\mathrm{conv}} \cdot \beta_{\mathrm{gas}} + \dot{\xi}_{\mathrm{TDR}}} \left[1 - \exp\left[-(\alpha_{\mathrm{conv}} \cdot \beta_{\mathrm{gas}} + \dot{\xi}_{\mathrm{TDR}})t\right]\right]. \tag{14}$$

The total water mass evaporated at time t is obtained by integrating Eq. (1) over time,

$$w_p(t) = \int_0^t d\tau \dot{w}_p(\tau), \tag{15}$$

which results in

$$w_p(t) = \alpha_{\mathrm{conv}} p_w t - \frac{\alpha_{\mathrm{conv}}^2 \beta_{\mathrm{gas}} p_w}{\alpha_{\mathrm{conv}}\beta_{\mathrm{gas}} + \dot{\xi}_{\mathrm{TDR}}} t - \frac{\alpha_{\mathrm{conv}} p_{a:0}}{\alpha_{\mathrm{conv}}\beta_{\mathrm{gas}} + \dot{\xi}_{\mathrm{TDR}}} \left[1 - \exp\left[-(\alpha_{\mathrm{conv}}\beta_{\mathrm{gas}} + \dot{\xi}_{\mathrm{TDR}})t\right]\right] \tag{16}$$

$$+ \frac{\alpha_{\mathrm{conv}}^2 \beta_{\mathrm{gas}} p_w}{(\alpha_{\mathrm{conv}}\beta_{\mathrm{gas}} + \dot{\xi}_{\mathrm{TDR}})^2} \left[1 - \exp\left[-(\alpha_{\mathrm{conv}}\beta_{\mathrm{gas}} + \dot{\xi}_{\mathrm{TDR}})t\right]\right], \tag{17}$$

$$= \alpha_{\mathrm{conv}} p_w \left(1 - \frac{\alpha_{\mathrm{conv}}\beta_{\mathrm{gas}}}{\alpha_{\mathrm{conv}}\beta_{\mathrm{gas}} + \dot{\xi}_{\mathrm{TDR}}}\right) t \tag{18}$$

$$- \frac{\alpha_{\mathrm{conv}}}{\alpha_{\mathrm{conv}}\beta_{\mathrm{gas}} + \dot{\xi}_{\mathrm{TDR}}} \left(p_{a:0} - \frac{\alpha_{\mathrm{conv}}\beta_{\mathrm{gas}} p_w}{\alpha_{\mathrm{conv}}\beta_{\mathrm{gas}} + \dot{\xi}_{\mathrm{TDR}}}\right) \left[1 - \exp\left[-(\alpha_{\mathrm{conv}}\beta_{\mathrm{gas}} + \dot{\xi}_{\mathrm{TDR}})t\right]\right]. \tag{19}$$

Note that $w_p(t)$ cannot exceed the mass of water present in the target drive room,

$$m_{\mathrm{water}} = \rho_{\mathrm{water}} A_{\mathrm{leak}} \cdot \delta h_{\mathrm{leak}}, \tag{20}$$

where $\rho_{\mathrm{water}} = 1.0$ g·cm^{-3} is the density of water and δh_{leak} is the thickness of the leak water film. For simplicity of analysis, we assume A_{leak} is constant throughout the evaporation process. This describes cases for a relatively large water leak with $\sqrt{A_{\mathrm{leak}}} \gg \delta h_{\mathrm{leak}}$.

The implicit inequality equation,

$$w_p(t) \leq m_{\mathrm{water}} \tag{21}$$

can be solved for $t \leq t_{\max}$. Note that $\dot{w}_p = 0$ for $t \geq t_{\max}$.

Table 3. Saturated water vapor mass density for different temperatures for $p_{a:0} = 0$

Temperature [°C]	Mass density of evaporated water molecules at saturation [$g_{vapor} \cdot m_{air}^{-3}$]	Mass of vapor in TDR [kg]
20.0	17.28	3.79
30.0	30.34	5.05
40.0	51.08	11.2
50.0	82.81	18.2
60.0	129.7	28.4
70.0	197.0	43.2
80.0	290.9	63.8
90.0	418.6	91.7
100.0	588.3	128.9

2.2 VAPOR BUILD UP

2.2.1 Conservative Bounding Case

A conservative bounding case is provided by no ventilation, leak water covering the whole floor area of the TDR and continued leak,

$$\dot{\xi}_{\text{TDR}} = 0, \quad A_{\text{leak}} = A_{\text{TDR}}, \quad m_{\text{water}} \gg 1, \quad \text{and} \quad t = \infty. \tag{22}$$

For these bounding case parameters, Eqs. (14) and (19) simplify to

$$p_{a:\infty} = p_w, \quad \text{and} \quad w_{p:\infty} = \frac{1}{\beta_{\text{gas}}} \left(p_w - p_{a:0}\right). \tag{23}$$

Note that both β_{gas} and p_w are dependent on water temperature. Here, we assume the water temperature is in equilibrium with the air temperature in TDR. This assumption is justified because the water volume and mass are much smaller than the those of water-contacting structure and air in the TDR. Therefore, leak water spilled on the floor will reach thermal equilibrium with ambient temperature in a short time scale compared to the one for the evaporation process. The saturation vapor pressure p_w is analytically written as a function of temperature T [Buck Research Instruments, LLC 2010],

$$p_w(T) = 6.1121 \cdot 10^2 \exp\left[\left(18.678 - \frac{T}{234.5\ [°\text{C}]}\right)\left(\frac{T}{257.14\ [°\text{C}] + T}\right)\right] \quad [\text{Pa}], \tag{24}$$

$$\beta_{\text{gas}} \equiv \frac{R(T + 273.15\ [°\text{C}])}{V_{\text{TDR}} M}, \tag{25}$$

where T = T [° C].

Mass density of evaporated water molecules is defined by

$$\rho_{\text{vapor}} \equiv \frac{w_{p:\infty}}{V_{\text{TDR}}}. \tag{26}$$

Figure 1 shows the mass density of evaporated water molecules at saturation for $p_{a:0} = 0$. Table 3 lists the saturated water vapor mass density for different temperatures, showing its sensitivity to temperature.

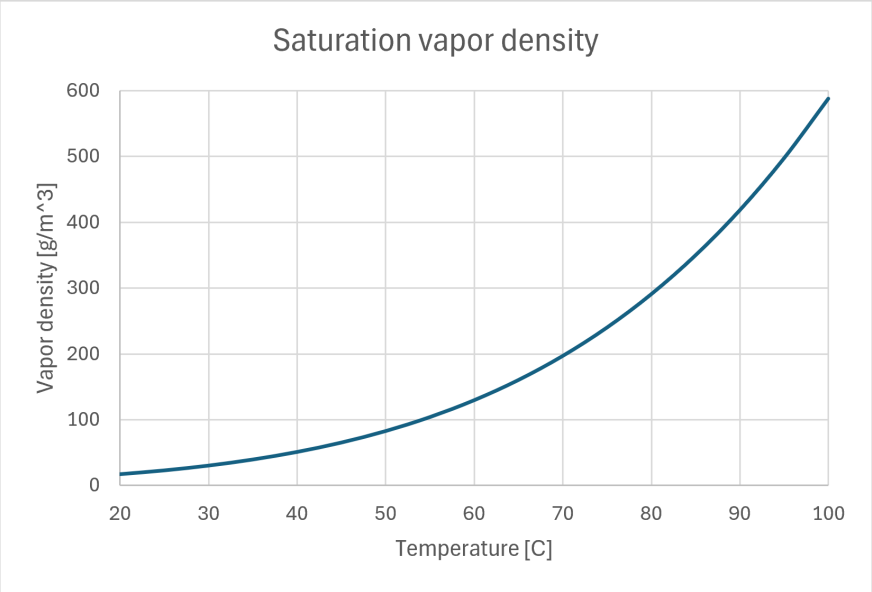

Figure 1. Mass density of evaporated water molecules at saturation in [$g_{vapor} \cdot m_{air}^{-3}$].

Table 4. Time t_{max} it takes for complete evaporation of the 120 kg mass leak water quantity

Temperature	t_{max} [s]
20.0	59885.4
30.0	33205.7
40.0	19091.9

2.2.2 Vapor Build Ups for a Large Water Leak Case

We consider a large leak case where $A_{leak} = A_{TDR}$. We assume that the water area is kept constant during evaporation to make the analyses simpler while not losing too much of generality. An initial film height of $\delta h_{leak} = 2.0$ mm is chosen for the study case presented in this section. The water mass present on the floor at $t = 0$ is 120 kg. For the analyses presented in the following, the TDR operation parameters listed in Table 2 are used.

Table 4 lists the time t_{max} it takes for complete evaporation of the 120 kg mass leak water quantity, as described in Eq. (21) for the selected temperatures, 20, 30 and 40 °C.

Figure 2 shows the transient build up of vapor partial pressure at 20 °C with initially dry air condition $p_{a:0} = 0$. Note that the maximum vapor partial pressure reached is 1415.9 Pa, which is 60.6% of the saturation vapor pressure of $p_w = 2338.3$ Pa. This is due to the flow balance with the ventilation in the TDR at the rate of 0.189 [$m^3 \cdot s^{-1}$]. The pressure of evaporated water exponentially decays for $t \geq t_{max} = 59885.4$ s as initial water mass is fully evaporated and ventilation transport vapor molecules out from the TDR.

Figure 3 shows the transient build up of vapor mass density in the TDR for chosen temperatures. The maximum vapor mass density reached after 3 hours of leak water exposure to air in the TDR is listed in Table 5. Note that it takes about less than an hour that the vapor level in the TDR reaches a steady maximum level.

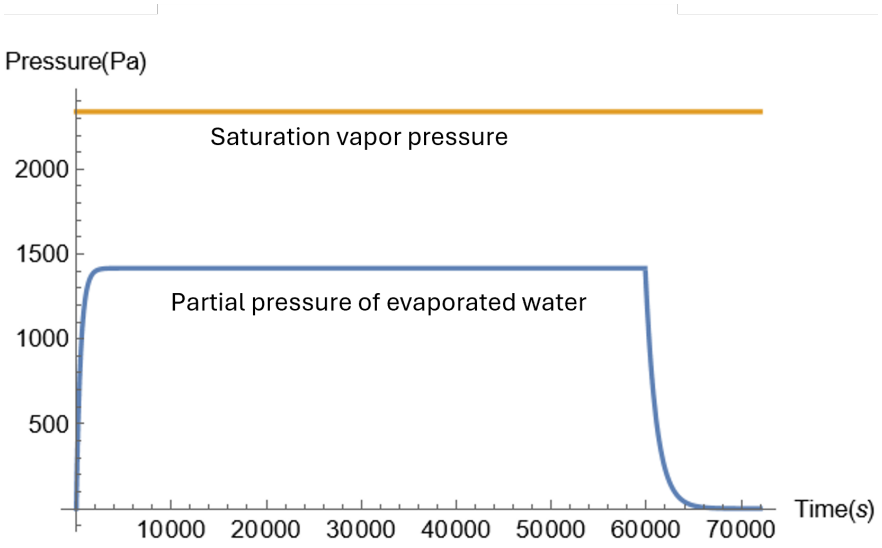

Figure 2. Transient build up of vapor partial pressure at 20 °C with initially dry air condition $p_{a:0} = 0$.

Table 5. Maximum vapor mass density reached after 3 hours of leak water exposure to air in the TDR

Temperature	Maximum vapor density [g·m^{-3}]
20.0	10.5
30.0	18.7
40.0	32.0

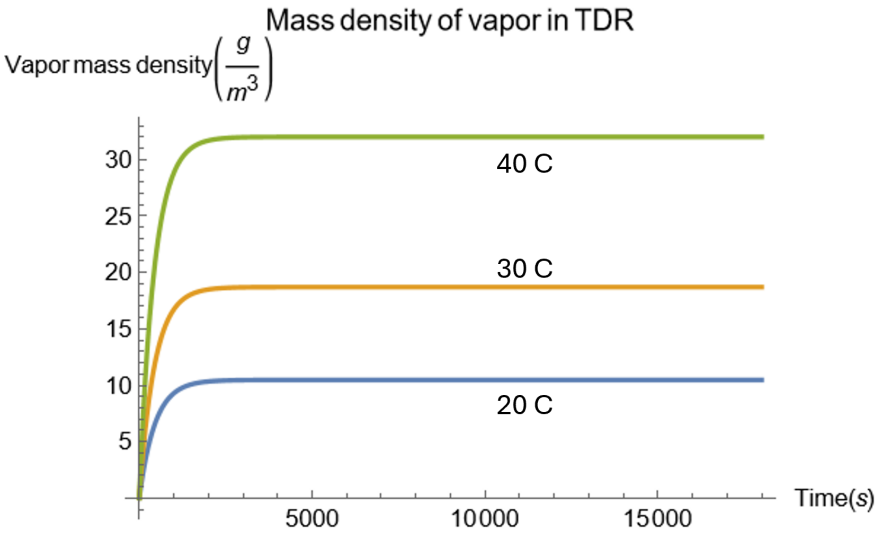

Figure 3. Transient build up of vapor mass density in [$g_{vapor} \cdot m_{air}^{-3}$] for chosen temperatures.

3. TRITIUM ACTIVITY IN TARGET DRIVE ROOM

3.1 DOSE CALCULATION METHOD

The dose calculations given here for the combined inhalation and skin absorption pathways for tritiated water (HTO) follows the methodology presented in Ref. [S. Ring Peterson 1999]. Reference [S. Ring Peterson 1999] is based on the Nuclear Regulatory Commission (NRC) Regulatory Guide 1.109, *Calculation of Annual Doses to Man from Routine Releases of Reactor Effluent* (U.S. Nuclear Regulatory Commission 1977). The dose coefficients used in Ref. [S. Ring Peterson 1999] and in this report were obtained from the committed dose equivalent tables for DOE dose calculations (U.S. Department of Energy 1988) and are consistent with those specified in ICRP 30, *Limits for Intakes of Radionuclides by Workers* (International Commission on Radiological Protection [ICRP] 1979). Specifically, we use the following dose conversion factor:

$$\mathcal{DCF} = 1.5 \cdot 1.8 \cdot 10^{-11} \quad \mathrm{Sv} \cdot \mathrm{Bq}^{-1}. \tag{27}$$

Here, the conversion factor $1.8{\cdot}10^{-11}$ Sv·Bq^{-1} is for inhalation dose of HTO. The 1.5 multiplication factor accounts for dose from HTO absorbed through the skin from air.

To estimate the tritium inhalation rate in the form of HTO, the breathing rate of

$$\mathcal{U}_{\mathrm{air}} = 3.47 \cdot 10^{-4} \quad [\mathrm{m}^3 \cdot \mathrm{s}^{-1}] \tag{28}$$

is used at the Spallation Neutron Source. Consider a worker at location where HTO concentration is

$$C_{\mathrm{HTO}} \quad [\mathrm{Bq} \cdot \mathrm{m}^{-3}]. \tag{29}$$

Then, the The whole-body inhalation dose rate from HTO is calculated by the following formula,

$$\mathcal{D}_{\mathrm{HTO}}\ [\mathrm{Sv} \cdot \mathrm{s}^{-1}] = \mathcal{DCF} \cdot \mathcal{U}_{\mathrm{air}} \cdot C_{\mathrm{HTO}}. \tag{30}$$

3.2 TRITIUM ACTIVITY OF WATER IN TARGET COOLING LOOP (LOOP 1)

In the Loop 1, the water line that cools the target, total tritium activity in water after 40 years of operation with 5000 hours of yearly beam time on the target is calculated to be 69.17 Ci. This is based on the assumption that all tritium atoms produced tritiate water to form HTO. Considering the total water volume of 5,564,552.7 cm^3, the tritium activity concentration is $1.243{\cdot}10^{-5}$ ^{3}H-Ci·cm^{-3} which is equivalent to $4.599{\cdot}10^5$ ^{3}H-Bq·cm^{-3}. For the water density $\rho_{\mathrm{water}} = 1.0$ g·cm^{-3} the tritium activity concentration in water can be equally written as $4.599{\cdot}10^5$ ^{3}H-Bq·g^{-1}.

The HTO concentration in the target drive room is calculated by

$$C_{\mathrm{HTO}} \quad [\mathrm{Bq} \cdot \mathrm{m}^{-3}] = \rho_{\mathrm{vapor}}\ [\mathrm{g} \cdot \mathrm{m}^{-3}] \cdot 4.599 \cdot 10^5\ [\mathrm{Bq} \cdot \mathrm{g}^{-1}]\ldots \tag{31}$$

3.3 TRITIUM DOSE IN TARGET DRIVE ROOM - LARGE WATER LEAK CASE

We consider a large leak case where $A_{\mathrm{leak}} = A_{\mathrm{TDR}}$.

3.3.1 No Ventilation

Assume that the target drive room is a closed volume without ventilation. Then, the vapor density in TDR is given by Table 3. Using Eqs. (30) and (31), one can calculate the dose rate to the workers. Table 6 lists the calculated dose for different temperatures. Note that the tritium dose in TDR does not exceed 100 mrem·hr^{-1} below 40 °C. which allow personnel to enter TDR for maintenance works.

Table 6. Dose calculated for saturated water vapor mass density at different temperatures with $p_{a:0} = 0$

Temperature	Dose [mSv·hr^{-1}]	Dose [mrem·hr^{-1}]
20.0	0.27	26.8
30.0	0.47	47.1
40.0	0.79	79.2
50.0	1.28	128.5
60.0	2.01	201.2
70.0	3.06	305.6
80.0	4.51	451.2
90.0	6.49	649.3
100.0	9.13	912.6

Table 7. Calculated tritium dose for water vapor mass density at different temperatures with $p_{a:0} = 0$ reached after 3 hours of leak water exposure to air in the TDR

Temperature	Dose [mSv·hr^{-1}]	Dose [mrem·hr^{-1}]
20.0	0.16	16.3
30.0	0.29	29.0
40.0	0.50	49.6

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3.3.2 With Ventilation

With ventilation on, the maximum vapor mass density reached after 3 hours of leak water exposure to air in the TDR is listed in Table 5. Using Eqs. (30) and (31), one can calculate the dose rate to the workers. Table 7 lists the calculated dose for different temperatures.

Note that the tritium dose in TDR does not exceed 100 mrem·hr^{-1} below 40 °C. which allows personnel to enter TDR for maintenance works.

4. CONCLUSIONS

The airborne tritium contamination in the target drive room originated from a large scale water leak from the target cooling loop (Loop 1) was evaluated. The leak water is considered to cover the whole of the TDR floor area for the analyses. A worst case is that evaporated leak water reaches the vapor pressure in the absence of ventilation. Calculations show that the tritium dose rate caused by inhalation and skin absorption of a personnel in that environment does not exceed 100 mrem·hr^{-1} if the temperature in TDR is kept below 40 °C. With the TDR ventilation on, the tritium dose at room temperature is below 20 mrem·hr^{-1}. This indicates that personnel will be able to enter TDR for maintenance works in case of water leak accidents. Proper person protection equipments may be required.

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