Development of Dose Assessment Code for Accidental Tritium Releases — ACUTRI —

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(Received on September 15, 2005)

(Accepted on November 18, 2005)

A computer code named ACUTRI has been developed to assess tritium doses due to inhalation to the general public. The ACUTRI code can calculate the radiological impact of tritium gas (HT) and tritiated water (HTO) released accidentally to the atmosphere. The models in this code consist of a tritium transfer model including the oxidation of HT to HTO and the re-emission of HTO from soil to the atmosphere and a dose calculation model. The atmospheric dispersion of the primary HT and HTO plumes and secondary HTO plume, which is reemitted from soil to the atmosphere, is calculated by using the Gaussian plume model. In this calculation, it is possible to analyze the meteorological data statistically, in the same way as a conventional dose assessment method according to the meteorological guideline of the Nuclear Safety Commission of Japan. Tritium concentrations in air and their resultant doses were calculated using the ACUTRI code under several conditions. In order to validate the model, calculations were compared with experimental results.

KEY WORDS: computer code, ACUTRI, dose assessment, tritium gas, tritiated water, accidental release, general public, inhalation.

I INTRODUCTION

Tritium, which is used as a fuel of the D-T burning fusion reactor, is the most important radioactive nuclide for the safety assessment of a nuclear fusion experimental reactor. Tritium has characteristic behavior in the environment as follows. In the case of tritiated water (hereafter, referred to as HTO) release, after the dispersion in the atmosphere, a fraction of HTO deposits to soil and then part of the HTO is reemitted from soil to the atmosphere. In the case of a tritium gas (hereafter, referred to as HT) release, a fraction of HT diffuses in soil and is oxidized to HTO by microorganisms in soil.¹⁾ The oxidized HTO can be also reemitted to the atmosphere. Since a dose coefficient of HTO is 10,000 times as high as that of HT,²⁾ the oxidation of HT to HTO followed by the reemission of HTO is a very important process in a dose assessment for HT release.

Several tritium dose calculation codes have been devel-

oped, such as UFOTRI,³⁾ ETMOD,⁴⁾ ETDOS⁵⁾ TRIDOSE⁶⁾ and NORMTRI.⁷⁾ These codes can calculate atmospheric tritium concentrations for the HTO and HT releases and doses by the inhalation and/or ingestion. Environmental tritium transfer models in the codes include the oxidation of HT to HTO on soil surfaces, the migration of HTO into soil, the uptake of HTO to vegetation, the reemission of HTO to the atmosphere, and so on.

In Japan, the general method to calculate the concentrations of radioactive materials in the atmosphere after the accidental release from a nuclear power plant is given in the meteorological guideline of the Nuclear Safety Commission (NSC) of Japan for the environmental safety evaluation. However, there is no detailed tritium dose assessment code to assess doses to the general public for the accidental releases of tritium from nuclear fusion facilities in accordance with the guideline of NSC in Japan. Therefore, a new calculation code for the ACUTE TRITium releases (ACUTRI) has been developed. This code can calculate the atmospheric concentrations of HT and HTO accidentally released from facilities and the doses due to the inhalation of HT and HTO and the skin absorption of HTO in the atmosphere.

This report describes tritium transfer models used in the ACUTRI code and the impact of input parameters on the calculated doses. Among input parameters are chemical forms of released tritium, dry and wet deposition velocities, reemission rates and so on. Furthermore, in order to validate the model,

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the model calculations of ACUTRI are compared with the results of a short-term HT release experiment carried out in Canada.

II MODEL DESCRIPTION

Environmental pathways incorporated in the code are shown in **Fig. 1**. The ACUTRI code is designed to simulate the environmental transfer of HT and HTO released from the facilities to the atmosphere, since most of tritium released from fusion facilities would be in HT and HTO forms. In Joint European Torus and Tokamak Fusion Test Reactor, the organic tritium was found to be less than 1% of total tritium releases.^{8,9)} The transfer model consists of the dispersion of a primary plume released as HT, HTO or both HT and HTO from the facilities, the deposition of tritium including the oxidation of HT to HTO, and the reemission of a secondary plume as HTO from the ground. In the dose model, the inhalation of HT and HTO and the skin absorption of HTO are taking into account. However, the exposure due to intake of drinking water and foods is not considered in this code because it is not included in the model of the NSC guideline for the safety assessment of nuclear power reactors. The physical and mathematical basis of ACUTRI is described in detail elsewhere.¹⁰⁾

1. Atmospheric Dispersion

For the calculation of the atmospheric tritium dispersion, the Gaussian plume dispersion model described in the meteorological guideline of NSC is used. For a short-term release (< 8 hours), an air concentration per unit amount of release, $(\chi/Q)_{lhr}$ (s/m³), for an hour from the hour $lhr-1$ to lhr is given by **Equation (1)**. This concentration is hereafter referred to as relative concentration.

$$(\chi/Q)_{lhr} = \frac{1}{2\pi \cdot \sigma_y \cdot \sigma_z \cdot U} \times \exp\left[-\frac{y^2}{2 \cdot \sigma_y^2}\right] \times \left\{ \exp\left[-\frac{(H-z)^2}{2 \cdot \sigma_z^2}\right] + \exp\left[-\frac{(H+z)^2}{2 \cdot \sigma_z^2}\right] \right\} \times F_{dcy} \quad (1)$$

where χ is the tritium concentration in the atmosphere (Bq/m³), Q is the release rate (Bq/s), σ_y and σ_z are the standard deviations in y and z directions, respectively, U is the wind speed (m/s) at the release height, H (m), and F_{dcy} is the plume attenuation correction factor due to dry and wet deposition. The standard deviations σ_y and σ_z representing the width of plume are functions of downwind distance and atmospheric

stability. In the dose calculation, the effective release height, which includes the stack height plus plume rise, is used as the release height. However, it is difficult to estimate the plume rise for the accidental releases. Thus special consideration would be necessary if the relative concentrations are calculated using the effective release height.

For a long-term release (>8 hours), the relative concentration is expressed as **Equation (2)**.

$$(\chi/Q)_{lhr} = \frac{2.032}{2 \cdot \sigma_z \cdot U \cdot x} \times \left\{ \exp\left[-\frac{(H-z)^2}{2 \cdot \sigma_z^2}\right] + \exp\left[-\frac{(H+z)^2}{2 \cdot \sigma_z^2}\right] \right\} \times F_{dcy}$$

$$2.032 = \sqrt{\frac{2}{\pi}} \times \frac{16}{2\pi} \quad (2)$$

2. Deposition of HT and HTO to the ground

After the dispersion of HTO in the atmosphere, HTO deposited to soil is partly reemitted from soil to the atmosphere. In the case of HT release, since a fraction of HT diffused into soil is oxidized to HTO, the secondary plume contains HTO reemitted from soil. Schematics of deposition of HT and HTO released from facilities and HTO reemission from soil are shown in **Fig. 2**. The downwind terrestrial surface is divided into the fan-shape regions, which are called elements, by the concentric circles centered on the evaluation point and by the 16 radial lines drawn from the evaluation point. The element area can be reduced by separating sub-concentric circles. The advantages of this method are as follows. One is ability to make the elements smaller as they get closer to the evaluation point as shown in **Fig. 2(a)**. This should improve the accuracy of the calculation of HTO concentrations in the secondary plume, because HTO reemitted from the nearer elements to the evaluation point is likely to contribute to dose more than that from the far elements. Another advantage is ability to deal with the changes of wind direction during the reemission period. In the previous dividing method that usually uses rectangular elements it is very difficult to incorporate the wind direction change into the reemission model.

The relative amount of deposition of HTO per unit area on the element k from the hour $lhr-1$ to lhr , DP_{k-lhr} (s/m²), is represented by **Equation (3)** using a deposition velocity of HT

Fig. 1 Environmental pathways in ACUTRI.

Fig. 2 Schematics of dispersion of HT and HTO and reemission of HTO. (a) Dispersion and deposition of HT and HTO released from facilities and (b) Reemission of HTO from a soil surface.

or HTO, $V_{g,k}$ (m/s).

$$DP_{k,Jhr} = (\chi_k/Q)_{Jhr} \times V_{g,k} \times t_{dp} \quad (3)$$

where t_{dp} is the deposition period (3,600 s). Various deposition velocities of HT or HTO can be assumed for each terrestrial element.

The deposition of tritium due to washout of rain is calculated for a primary HTO release only. The relative amount of wet deposition per unit area on the element k from $Jhr-1$ to Jhr , $DW_{k,Jhr}$ (s/m²), is described by **Equation (4)**.¹¹⁾

$$DW_{k,Jhr} = \Lambda_{Jhr} \times \int_0^\infty (\chi_k(x,y,z)/Q)_{Jhr} dz \times t_{rain} \quad (4)$$

$$\Lambda_{Jhr} = a \times I_{Jhr}^b$$

where Λ_{Jhr} is the washout coefficient (s⁻¹) and t_{rain} is the precipitation period (s). The coefficient Λ_{Jhr} is modeled as a function of rainfall rate, I_{Jhr} (mm/h), from $Jhr-1$ to Jhr . Constants a and b used in the analysis of the wet deposition described later¹⁰⁾ are assumed to be 1.2×10^{-4} and 0.5, respectively. These constants are selected to evaluate the wet HTO deposition realistically and conservatively.

To shorten the calculation time, it is assumed that the deposition of primary HT and HTO on terrestrial elements and the reemission of HTO take place only once. In other words, a secondary HTO plume is assumed as not to be deposited on

the ground.

3. Reemission of HTO from terrestrial surface

Deposited HTO on a terrestrial surface is reemitted continuously even after the release of primary HT and HTO is stopped. Thus ACUTRI simulates the tritium transfer according to hourly changes of the meteorological conditions, such as wind speed, wind direction and atmospheric stability class during the reemission process of HTO. The proportion of reemitted HTO to deposited HTO, $RE_{k,Jhr}$, on the element k during the period from the hour $Jhr-1$ to Jhr is given by,

$$RE_{k,Jhr} = (DP_{k,Jhr} + DW_{k,Jhr}) \times A_k \frac{\phi_{Jhr} \times \rho_{Jhr}}{\sum_{j=0}^{T_{2nd}} (\phi_{Jhr+j} \times \rho_{Jhr})} \times \frac{1}{3600} \times f_{rain,Jhr} \times F_{re} \quad (5)$$

where A_k is the area of element k (m²), T_{2nd} is the reemission period (h), ϕ_{Jhr} is the hourly reemission rate in the daytime or nighttime (h⁻¹), ρ_{Jhr} is the factor that reflects decrease in reemission rate with time (-), $f_{rain,Jhr}$ is the correction factor with precipitation for the reemission period (-) and F_{re} is the ratio of HTO reemitted during a total reemission period to total deposited HTO. The ratio F_{re} is equal to 1, if all HTO deposited on terrestrial elements is reemitted to the atmosphere.

For a long-term reemission period ($T_{2nd} > 8$ hours), the total relative concentration due to reemitted HTO from the elements around the evaluation point is expressed as **Equation (6)**.

$$(\chi_{re}/Q)_{Jhr,Jhr} = \sum_{k=1}^m (\chi_{re,k}/Q)_{Jhr,Jhr} \quad (6)$$

$$(\chi_{re,k}/Q)_{Jhr,Jhr} = 2.032 \times RE_{k,Jhr} / (\sigma_{z,Jhr} \times U_{Jhr} \times x_k)$$

where m is the number of elements, $(\chi_{re}/Q)_{Jhr,Jhr}$ is the relative concentration due to reemitted HTO from the element k (s/m³), $\sigma_{z,Jhr}$ is the standard deviations in z direction (m), U_{Jhr} is the wind speed (m/s) at the hour Jhr and x_k is the distance between the element k and the evaluation point (m).

Tritium deposited on a terrestrial element including the evaluation point (hereafter, called self-element) and the surrounding elements would greatly contribute to the HTO concentration in the secondary plume. In the ACUTRI code, a hypothetical space is set up on the self-element as shown in **Fig. 2(b)**. The deposited HTO on the self-element is supposed to be reemitted into the hypothetical space. The reemitted HTO is assumed to be distributed uniformly in the space and to be diluted by wind. The relative HTO concentration due to reemitted HTO is given by,

$$(\chi_{self}/Q)_{Jhr,Jhr} = RE_{k,Jhr} / (U_{Jhr} \times H_{self} \times A_{self}^{0.5}) \quad (7)$$

where H_{self} is the height of hypothetical space over the self-element (m) and A_{self} is the area of self-element (m²).

4. Relative concentration and dose corresponding to 97%

The ACUTRI code can calculate a relative tritium concen-

tration in the atmosphere and dose corresponding to 97% of annual accumulative frequency, which are hereafter referred to as 97% concentration and 97% dose, respectively, using a similar way to the meteorological guideline of NSC.

In the case of HTO release, relative HTO concentrations for the primary and secondary plumes are firstly summed up as shown in **Equation (8)**.

$$\chi_{\text{HTO}}/Q = \sum_{I_{\text{hr}}=1}^{T_{1\text{st}}} \left[(\chi/Q)_{I_{\text{hr}}} + \sum_{J_{\text{hr}}=1}^{T_{2\text{nd}}} \left\{ (\chi_{\text{re}}/Q)_{I_{\text{hr}} \cdot J_{\text{hr}}} + (\chi_{\text{self}}/Q)_{I_{\text{hr}} \cdot J_{\text{hr}}} \right\} \right] T_{1\text{st}} \quad (8)$$

where $T_{1\text{st}}$ is the release period of the primary plume (h). The total relative concentrations for all 16 directions are calculated using the annual hourly meteorological data whose number is 8,760. These 8,760 total relative concentrations are then sorted according to the increasing concentration. A value equal to 97% of annual accumulative frequency is chosen as a 97% concentration in each direction and the highest one is selected from among the 16 concentrations. A 97% dose is calculated by using this selected concentration. In the case of HT release, the primary HT plume dose and secondary HTO plume dose are calculated separately in each direction. The calculated primary and secondary plume doses are summed up to obtain a 97% total dose in each direction. Then the highest 97% dose is selected from the 16 doses as in the case of HTO release. In addition to the above mentioned statistical analysis, ACUTRI can calculate the maximum concentrations and doses for primary and secondary plumes and their total doses, as well as the doses using specific meteorological data.

5. Calculation of individual dose

An effective dose by inhalation at an evaluation point is calculated using HT and/or HTO concentrations in the air at 1m height, a breathing rate and age-dependent dose coefficients of HT and HTO given in ICRP Publication 72.²⁾ The HTO inhalation dose is multiplied by 1.5 to take into account

the dose due to absorption of HTO from the skin.

III RESULTS OF ANALYSIS

It is expected that the chemical form of tritium released from facilities, the deposition velocities, the reemission rates and the element size have an effect on the doses. Thus the effect of these parameters on estimated doses were examined. **Table 1** shows the basic analysis condition for the calculation. The release and reemission period are set to 1 hour and 24 hours, respectively. The release amount of HT or HTO from the facility is 3.58×10^{14} Bq, which is equivalent to 1 g of tritium. The HT and HTO deposition velocities are 0.0005 and 0.01 m/s respectively that are the average values of experimental results¹²⁻¹⁵⁾. A terrestrial surface is divided into 8 main circles of which radii are 50, 100, 200, 500, 1,000, 2,000, 5,000 and 10,000m, respectively. In addition, main concentric circles of radii 50, 100 and 200m are divided into 9, 10 and 20 sub-concentric circles, respectively. Main concentric circles of which radii are from 500 to 10,000m are separated into 30 sub-concentric circles each. The factors of decrease in reemission rate, $\rho_{J_{\text{hr}}}$, are 0.34, 0.074 and 0.008875 per hour for 0-1, 1-8 and 8-24 hours, respectively. These factors are selected according to our previous experimental results.¹⁶⁾ The annual meteorological data on 1988 at Tokaimura, Ibaraki, is used in the calculation.¹⁷⁾

1. Effect of chemical form of tritium released from facilities

Figures 3, 4 and 5 indicate the 97% dose for primary plume and 97% total dose as a function of distance from the release point for the HT and HTO releases at 0, 40 and 100 m heights, respectively. The primary plume dose is the same as that calculated by a conventional calculation method provided by the guideline of NSC. The total and primary plume doses show similar variations for each of HT and HTO releases both

Table 1 Code input parameters for calculations.

Parameter	Value															
Release period (h)	1															
Reemission period (h)	24															
Release of HT or HTO (Bq)	3.58×10^{14} (1g)															
HT deposition velocity (m/s)	0.0005															
HTO deposition velocity (m/s)	0.01															
Factor of variation of reemission (-)	0-1 h: 0.34, 1-8 h: 0.074, 8-24 h: 0.008875															
Reemission rate (h^{-1})	Daytime: 0.1, Nighttime: 0.05															
	<table><tr><th>Month</th><th>Daytime</th><th>Nighttime</th></tr><tr><td>April - May</td><td>: 7:00 - 18:00</td><td>18:00 - 7:00</td></tr><tr><td>June</td><td>: 7:00 - 19:00</td><td>19:00 - 7:00</td></tr><tr><td>July - September</td><td>: 7:00 - 18:00</td><td>18:00 - 7:00</td></tr><tr><td>September - March</td><td>: 8:00 - 17:00</td><td>17:00 - 8:00</td></tr></table>	Month	Daytime	Nighttime	April - May	: 7:00 - 18:00	18:00 - 7:00	June	: 7:00 - 19:00	19:00 - 7:00	July - September	: 7:00 - 18:00	18:00 - 7:00	September - March	: 8:00 - 17:00	17:00 - 8:00
Month	Daytime	Nighttime														
April - May	: 7:00 - 18:00	18:00 - 7:00														
June	: 7:00 - 19:00	19:00 - 7:00														
July - September	: 7:00 - 18:00	18:00 - 7:00														
September - March	: 8:00 - 17:00	17:00 - 8:00														
Meteorological data	1988 at Tokai, JAERI															
Age	Adult															
Dose coefficient for HT inhalation (Sv/ Bq)	1.8×10^{-15} (ICRP Publ. 72)															
Dose coefficient for HTO inhalation (Sv/Bq)	1.8×10^{-11} (ICRP Publ. 72)															
Evaluation height (m)	1															
Radius of self-element (m)	5															
Height of self-element (m)	1															
Washout coefficient (s^{-1})	$\Lambda_{I_{hr}} = 1.2 \times 10^{-4} \times I_{I_{hr}}^{0.5}$

Fig. 3 Effective dose for HT and HTO released at 0 m height as a function of distance from the release point.

Fig. 4 Effective dose for HT and HTO released at 40 m height as a function of distance from the release point. Arrows indicate points where the maximum primary plume and total doses appear at.

Fig. 5 Effective dose for HT and HTO released at 100 m height as a function of distance from the release point. Arrows indicate points where the maximum primary plume and total doses appear at.

in Figs. 3 and 4. The total doses for HTO release at 0, 40 and 100 m heights are about 25, 30–70 and 40–160 times respectively higher than those for HT release at those heights. For the HT releases at 0 and 40 m heights, the total doses are two or three orders of magnitude as high as the primary plume doses. On the other hand, for the HTO releases at 0 and 40 m heights, the total doses are a few times as high as the primary plume doses. As shown in Fig. 5, while the primary plume doses for both HT and HTO releases rapidly decrease with decreasing the distance less than several hundreds meter, the total doses have no large variation with distance. This is due to the effect of secondary HTO plume. In Fig. 4, the maximum total doses appear at 3,600 m from the release point, which is about 5 times as distant as a point for the maximum primary plume doses at 720 m. The similar tendency is observed in Fig. 5. These are also caused by the addition of secondary HTO doses to primary plume doses. These results show that it is important to evaluate the dose due to the secondary plume of HTO because the current model of NSC guideline is most likely to underestimate doses to the general

Fig. 6 Effective dose calculated using different HT deposition velocities. Release of HT: 1 g, release height: 100 m and evaluation point: 1,000 m.

public for an accidental tritium release, in particular for an HT release.

2. Effect of dry and wet deposition

The dry deposition velocities of HT and HTO to soil respectively range from 10^{-5} to 10^{-3} m/s and from 5×10^{-3} to 2×10^{-2} m/s depending on the soil condition.^{12–15} For an HTO release, the washout of HTO in the atmosphere may increase the deposition of HTO on a terrestrial surface, unless the surface HTO moves into a deeper soil layer by heavy rain. Therefore the effects of dry and wet deposition on the doses have been examined.

Figures 6 and 7 illustrate 97 % doses calculated using different dry deposition velocities for HT and HTO releases, respectively. The doses were calculated at a distance of 1,000 m using the calculation condition shown in Table 1. The release height is assumed to be 100 m. The HT and HTO deposition velocities are assumed to range from 1×10^{-5} to 1×10^{-3} m/s

Fig. 7 Effective dose calculated using different HTO deposition velocities. Release of HTO: 1 g, release height: 100 m and evaluation point: 1,000 m.

and from 1×10^{-3} to 1×10^{-2} m/s, respectively. In **Fig. 6**, the doses due to the secondary plumes are predominant in all cases for the HT release. Thus the total doses approximately increase proportionally to the HT deposition velocity. In **Fig. 7**, the doses due to the secondary plumes for Cases 2-1 and 2-2 account for about 2 and 30% respectively of the total doses. The total doses for Case 2-2 is 1.2 times as high as that for Case 2-1. It was found that the total dose does not significantly change in the case of HTO release, even if the HTO deposition velocity becomes one order of magnitude lower.

Figure 8 shows 97% doses and the maximum doses with or without HTO wet deposition for HTO release. The primary HTO is assumed to be released at 100 m height during one hour. The default input data shown in **Table 1** are applied in the calculation. The maximum doses with wet deposition vary from 5 to 50 times of those without wet deposition depending on distance from the release point. The great differences within several hundred meters from the release point are attributable to the large wet deposition of high concentration HTO that does not yet sufficiently disperse in the atmosphere.

As for the 97% doses, there are small differences between with and without wet deposition over 1,000 m. On the other hand, within several hundreds meters from the release point, the 97% doses with wet deposition are several times as high as those without wet deposition. The primary plume concentration in the atmosphere near the release point under Class A or B is several orders of magnitude higher than that under Class D or F. Thus, when the wet deposition is not taken into account, the total doses under Class A and B are predominant in an upper part of the annual accumulative frequency distribution. When the wet deposition is taken into consideration, the doses near the release point for hourly periods of rain, which mostly appear under Class D or F, are added to the upper part of the annual accumulative frequency distribution. Therefore, the 97% doses with wet deposition in the vicinity of the

Fig. 8 Effect of wet deposition on effective dose for 1 g HTO released at 100 m height. Parameter for washout coefficient: $a = 1.2 \times 10^{-4}$, $b = 0.5$ and $I = 3.0$.

release point would shift to the higher dose side.

Over 1,000 m from the release point, there is no significant difference between the 97% doses with and without wet deposition. Since the primary plume concentration at these distances becomes higher under Class D or F, the upper part of the annual accumulative frequency distribution is considerably occupied by the concentrations in Class D or F. The annual precipitation frequency in each direction is 2.8% at the maximum with respect to the present meteorological data. Therefore, doses exceeding 97% in the annual accumulative frequency distribution are mainly affected by wet deposition. Consequently, the 97% doses at big distances from the release point would be little influenced by wet deposition.

3. Effect of reemission rate

The effect of time-variation of reemission on the 97% total dose has been examined. The following two time-variations were chosen: one was the variable rate shown in **Table 1**,

Table 2 Effect of time-variation of reemission on the 97% total dose.

		Release height (m)	Reemission factor	97% total dose (mSv)
HT release	Case 3-1	100	Variable*	1.8×10^{-4}
	Case 3-2		Constant**	2.8×10^{-4}
	Case 3-3	0	Variable*	1.4×10^{-1}
	Case 3-4		Constant**	7.4×10^{-2}
HTO release	Case 4-1	100	Variable*	1.1×10^{-2}
	Case 4-2		Constant**	1.4×10^{-2}
	Case 4-3	0	Variable*	3.5
	Case 4-4		Constant**	2.3

*The factors of variation of reemission are 0.34, 0.074, and 0.008875 for 0–1 h, 1–8 h and 8–24 h, respectively.

**The factors of variation of reemission is a constant of 0.04167.

Fig. 9 Relationship between numbers of sub-concentric circles and total doses. Release height: 100 m, Evaluation point: 1,000 m, Release start time: 1:00 p.m. June 07, 1988, Radii of main concentric circles: 500 m (first circle) and 1000 m (second circle) of Case 5-1 to 5-5. The numbers in the parentheses on the x-axis show the number of sub-concentric circles in the first and second main circles. The number of main circles of Case 5-6 is 8. Main concentric circles of radii 50, 100 and 200 m are divided into 9, 10 and 20 sub-concentric circles, respectively. Main concentric circles of which radii are from 500 to 10,000 m are separated into 30 sub-concentric circles each. The primary plume dose is 9.3×10^{-7} mSv in all cases.

which reflected a realistic variation of reemission, and the other was a simple, constant rate. **Table 2** shows calculated results at 1,000 m from the release point. The release heights of HT and HTO are assumed to be 0 and 100 m. In Cases 3-1, 3-3, 4-1 and 4-3, the factors of decrease in reemission rate, ρ_{Jhr} , in **Equation (5)** are set to 0.34, 0.074 and 0.008875 for the first one-hour, 1–8 hours and 8–24 hours, respectively. In Cases 3-2, 3-4, 4-2 and 4-4, this factor is kept at a constant of 0.04167 for a 24-hour reemission period. These variations have an impact on the total doses by a factor of maximum two. However, there is no correlation between the dose and reemission variation. It is desirable to use a realistic reemission pattern for the precise evaluation of doses, though the time-variation of reemission is not a critical factor in order to decide the total dose.

4. Effect of segmentation of terrestrial element

The contribution of HTO reemitted from terrestrial elements to doses may depend on the size of elements. Although dividing the terrestrial area into small elements would enhance the precision of calculation, it will pose a long calculation time. To ascertain that the sizes of elements used in the above calculations are sufficiently small, the effect of the element size on doses was studied.

Figure 9 shows the relationship between numbers of sub-concentric circles and total doses. The doses are calculated under a specific meteorological condition. The release of HT is supposed to start at 1:00 p.m. June 7, 1988, at 100 m height. The doses at 1,000 m are calculated using the input data in

Table 1, except for the meteorological data. During the release and reemission periods, the wind speed ranges between 1.1 and 5.0 m/s and the atmospheric stability changes from B to F. There is no precipitation during these periods. The secondary plume doses are predominant in the total doses because the primary plume dose, which is 9.3×10^{-7} mSv in all cases, is two orders of magnitude lower than the secondary plume doses. The numbers in the parentheses in **Fig. 9** represent the number of sub-concentric circles in a main circle. Two main circles of which radii are 500 m and 1,000 m are set in Case 5-1 to 5-5. The first number in each parenthesis corresponds to the number of sub-concentric circles in the first main circle, which varies from 1 to 9. The second main circle is partitioned into 5 sub-concentric circles, which is shown as the last number in each parenthesis. In Case 5-6, the number of main concentric circles is 8 and the numbers of sub-concentric circles are 9, 10, 20 and 30, which are the same segmentation mentioned above.

The total doses in Cases 5-1, 5-2, 5-3 and 5-4 decrease by 47, 12, 4 and 1.5% respectively compared with that in Case 5-6. The dose in Case 5-5 is nearly equal to that in Case 5-6. The results show that the element size has little effect on the total dose, if the element sizes are smaller than those of Case 5-4. Thus the element sizes in Case 5-6 are sufficiently small under the present calculation conditions.

IV MODEL VALIDATION

In order to validate the model of ACUTRI, calculations were compared with experimental results obtained in Canada in 1987^{12–15}. In this experiment, 3.5 TBq of HT was released into the atmosphere at 1 m height and HT and HTO concentrations in air were continuously measured for a week. **Table 3** shows input parameters for the calculation aiming to compare our results. The meteorological data measured during the experimental period was used for the calculation. The deposition velocity of HT was set to 8×10^{-4} m/s in the experimental area from the HT release point to 200 m on the leeward

Table 3 Code input parameters for the calculation to compare the experiment.

Parameter	Value
Release duration (h)	1
Reemission duration (h)	1 week
Chemical form of tritium	HT
Release of HT (Bq)	3.54×10^{12}
Release height (m)	1
HT deposition velocities (m/s)	0.0008 (< 200 m) 0.0003 (> 200 m)
Evaluation height (m)	1
Meteorological data	Measured data
Wet deposition	No
Age	Adult
Dose coefficient for HT inhalation (Sv/Bq)	1.8×10^{-15}
Dose coefficient for HTO inhalation (Sv/Bq)	1.8×10^{-11}
Breathing rate (m ³ /h)	1.2

Fig. 10 Comparison of ACUTRI calculations with experimental results.

axis and 3×10^{-4} m/s over 200 m.^{18, 19)} The concentration of HTO in air was calculated assuming that all HTO in soil was reemitted for 24 hours. The factor of variation of reemission was set to the same as in Table 1. Since the HT plume center during the experiment was out of the measurement point, concentrations adjusted to values on the plume center by Murata et al.²⁰⁾ were used.

Doses calculated with the ACUTRI code are illustrated in Fig. 10, along with doses calculated from the adjusted experimental concentrations. The ACUTRI calculations exceed all the experimental values. The estimated doses well correspond to the experimental results at distances less than 100 m. On the other hand, the ACUTRI results are 3 or 4 times higher than the measured ones over 100 m. These differences may be explained as follows. It has been reported that the HT deposit to the soil around a certain area at 100 m distance was extremely smaller than expected, since the oxidation activity of the soil was low in the area.¹²⁾ The present calculation does not reflect this low deposition. In addition, it may be inferred that part of HTO on the terrestrial surface was not reemitted to the atmosphere because some HTO moved to a deeper layer due to rainfall during the experiment. Considering the uncertainty of experimental results mentioned above, we concluded that the ACUTRI code can estimate the doses due to tritium releases with sufficient accuracy.

V CONCLUSIONS

A computer code named ACUTRI has been developed to assess doses for accidental HT and HTO releases from nuclear fusion facilities. The code has the following characteristics: 1) it can calculate an individual dose due to tritium using a tritium transfer model in the environment and a dose model, 2) the dose is conservatively assessed to prevent underestimation, and 3) it is possible to analyze data statistically on methodology based on the meteorological guideline of the Nuclear Safety Commission of Japan.

The effects of several parameters, such as a chemical form of tritium, a deposition velocity, a reemission rate and a terrestrial element size on the dose due to the inhalation of tri-

tium were studied. The difference of chemical form of tritium released to the atmosphere has a great influence on a total dose which is the sum of a dose due to a primary plume (HT or HTO) and a dose due to secondary HTO plumes reemitted from the ground. Although the dose coefficient of HTO is 10,000 times as high as that of HT, the ratios of total doses for HTO releases to those for HT releases range from 25 to 160 depending on the release height and downwind distance. The decreased dose ratios compared to the dose coefficient ratio are attributed to the reemission of HTO formed by the oxidation of HT in soil. The total doses depend on the dry deposition velocity in the case of HT release, because the contribution of the secondary plume dose to the total dose is extremely large. In the case of HTO release, even if the dry deposition velocity of HTO is changed by an order of magnitude, the velocity has small influence on the total doses, because these are largely dominated by primary plume doses. The wet deposition of HTO raises the maximum total doses several times. This also elevates the 97% doses near the release point. However, the 97% doses over 1,000 m are little affected by wet deposition of HTO.

To validate the ACUTRI code, the calculations were compared with the results of the Canadian field HT release experiment. There was a good agreement between these results for distances less than 100 m from the release point. The differences between ACUTRI results and experimental ones were observed over 100 m. These differences, however, may become smaller if ACUTRI takes into account a lower HT deposition velocity in a certain experimental area and transfer of HTO in soil to the deeper layer by rain. It was demonstrated from the comparison that the ACUTRI code will be able to evaluate doses to the general public due to the inhalation of tritium slightly conservatively but with sufficient accuracy.

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