8. The present status and recent applications of the accidental tritium assessment code UFOTRI

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Abstract:
The computer program UFOTRI can be used for assessing the impact of accidental released tritium in the two chemical forms tritiated water vapour and tritium gas. By applying UFOTRI to potential European sites for ITER, it could be demonstrated that the main goal, the non-evacuation criteria, is fulfilled for the present release limits. Contributions in international studies together with the re-evaluation of experimental data showed that the plant sub-model as well as the soil sub-model are areas for further improvement.

Keywords: UFOTRI, ITER, SEAFP, tritium, modelling, dose assessment, experiment, comparison study

1. INTRODUCTION

To estimate the spectrum of consequences after accidental releases of tritium from nuclear installations, processes such as dispersion, deposition, reemission, conversion of tritium gas (HT) into tritiated water vapour (HTO) and conversion of HTO into organically bound tritium (OBT), had to be considered time-dependently. To that purpose, an atmospheric dispersion module has been developed which allows for reemission after HT/HTO deposition and which considers all relevant transfer processes in the environment (soil, plant and animal) up to approximately 100 hours after the release event (during which atmospheric transport plays the dominant role). It was coupled to a first order compartment module, which describes dynamically the longer-term behaviour of the two different chemical forms of tritium in the food chains. The physical and mathematical basis of the new model called UFOTRI is described in detail in (1), (2) .

UFOTRI was applied in the BIOMOVS II (Biological Model Validation Study phase II) study with the aim to test and validate environmental tritium models. Based on the experiences gained within this study and during the applications of UFOTRI, two areas have been identified where model improvement seems to be necessary. This comprises the OBT build up during the night and the reemission of HTO from soil directly after deposition. However, further experimental work seems to be necessary to better understand at least the OBT formation process.

UFOTRI has been widely applied in fusion related safety studies. Among others assessments have been carried out within the SEAFP (Safety and Environmental Aspects of Fusion Power) and in the frame of the ITER (International Thermonuclear Experimental Reactor) project. The SEAFP study described the potential design of future fusion power reactors. Within the ITER programme, probabilistic dose assessments for accidental atmospheric releases of various ITER source terms which contain tritium and/or activation products were performed for the - at this time - potential European ITER sites Greifswald, Germany, and Cadarache, France.

2. MODEL DESCRIPTION

The present version is based on the Gaussian trajectory model MUSEMET(3). The importance of the reemission process necessitates two level modelling of the atmospheric dispersion. Primarily, MUSEMET calculates the dispersion after a single release event and the subsequent deposition on soil and plants. In a second step, the reemission of tritium after deposition from soil (evaporation) and plants (transpiration) is taken into account by an area source model specially developed for that purpose and combined with the original model. Hereby the area source is simulated by a single source point in the centre of the area, with a given initial widening of the plume(4).

All processes which may modify the total balance of the available HT or HTO such as the conversion of tritium gas into tritiated water (HT into HTO), the transport of tritium into deeper soil layers, the uptake of tritium by the plant root system, and the conversion of HTO into OBT are taken into account in the atmospheric dispersion module, together with the foodchain pathways such as the production of milk, milk products and beef.

2.1 Plant/atmosphere exchange processes

The exchange reaction of the plant with the atmospheric tritium takes place via the water circulation in the leaves. The mechanisms of the plant/atmosphere exchange are described according to 'big leaf' approach(5), (6). There the aerodynamic, boundary layer and stomata resistance determine the sensible and latent heat fluxes at the earth's surface. To determine the HTO exchange between the atmosphere and the vegetation, the model of Belot(7) has been used in UFOTRI. There the temperature, the inorganic content of plant matter and the transfer resistances determine the uptake of tritium in the vegetation as well as the loss of tritium from the vegetation.

$$C = X\frac{\alpha}{\rho}\left(1 - e^{-kt}\right) \qquad (1)$$

with

$$k = \frac{\rho}{\alpha \mu r_G} \qquad (2)$$

where C is the tritium concentration in tissue water in pBq g^{-1}, X is the concentration of tritium in air in pBq ml $^{-1}$, k is the time constant until equilibrium, μ is the water content per unit area of leaf in g cm^{-2}, r_G is the total resistance in cm s^{-1}, t is the time in s, ρ is the weight of water vapour in saturated air in g ml^{-1}, and α is the H/T isotope ratio (set to 1.1).

The loss from the vegetation can be determined by using the same time constant k:

$$\delta C = C_0 e^{-kt} \tag{3}$$

The dominating factor however, controlling the flux of tritium is the total resistance r_G which can be subdivided into its three components atmospheric resistance r_{av}, boundary layer resistance r_{bv} and stomata resistance r_s:

$$r_G = r_{av} + r_{bv} + r_s \tag{4}$$

The aerodynamic resistance r_{av} characterises the transfer from the free atmosphere to the surroundings of the leaf, whereas the boundary layer resistance r_{bv} describes the mass transfer through the quasi laminar air layer directly connected to the surface$^{(8)}$:

$$r_{av} = \frac{u(z)}{u_x^2} \tag{5}$$

and

$$r_{bv} = \frac{1}{u_x} B^{-1} \tag{6}$$

where u(z) is the wind speed in m/s in a given height (10m),: u_x is the friction velocity, and B is the Stanton number. Since r_{av} and r_{bv} depend on the atmospheric stability and the surface properties, the commonly used Dyer-Businger equations are used in calculating u_x $^{(8)}$.

The stomata resistance r_{st} describes the transfer of tritiated water vapour via the leaf surface into the plant. As this transfer depends on the environmental conditions, correction functions according to $^{(5)}$ have been introduced:

$$r_{st} = r_{st,min}\left(1 + \frac{c}{I_p}\right)\frac{1}{f_l f_w f_t} \tag{7}$$

with the weighting function humidity $f_l = 1 - b_v \Delta e$,

the weighting function for the temperature $f_t = \left(\frac{T - T_e}{T_0 - T_e}\right) \cdot \left(\frac{T_h - T}{T_h - T_0}\right)^{b_t}$

with $B_t = \cdot\left(\frac{T_h - T_0}{T_0 - T_e}\right)$

and the weighting function for soil water content which is a linear function ranging from 1 (if the water content > 5% above wilting point) down to 0.07, if the water content is less than the wilting point. In this set of equations, $r_{st,min}$ is the minimum stomata resistance, Δe is the vapour pressure deficit, b_v is a plant specific constant, T is the actual temperature, T_0 is the optimal temperature for photosynthesis, T_h is the upper limit of photosynthesis and T_e is the lower limit for photosynthesis.

At night, when the stomata are closed, r_s will be replaced by epidermial resistance which is a factor of 15 higher than the minimum stomata resistance.

Because vegetation occurs always as a plant population (fields, forests, etc.), an effective stomata resistance (now canopy resistance r_c) has to be calculated, by dividing the stomata resistance of a single plant by the leaf area index L, which describes the area of all leaves of the vegetation normalised to one square meter.

$$r_c = \frac{r_{st}}{L} \tag{8}$$

UFOTRI considers four different plant species, namely nutriment plants (leafy vegetables, potatoes and winter wheat) and pasture grass.

2.2 Soil/atmosphere exchange processes and transport in soil

The deposition process of HT and HTO to the soil is expressed in the form of a deposition velocity. The HT deposition rate $v_{d,HT}$ depends on the type of soil and on the free pore space in the first soil layer (5 cm).

$$v_{d,HT} = \frac{D_{eff}}{z_{ref}} \tag{9}$$

with

$$D_{eff} = 0.7 \cdot D_0 \cdot \left(\frac{T_a}{273}\right)^{1.75} \cdot \frac{\Theta_S - \Theta}{tort}$$

where D_{eff} is the effective diffusion coefficient, D_0 is the diffusion coefficient of HT in air (0.634 E-04 $m^2\ s^{-1}$), z_{ref} is the reference depth in m (r = 23 mm), Θ_S is the maximum water content, Θ is the actual water content and tort is the soil torture factor.

Once deposited, HT is transformed into HTO very quickly as a result of micro-organism activity. Only the transformed part of HT remains in the soil.

The dry deposition rate of HTO to soil $v_{d,HTO}$ is calculated dependent on the status of soil and atmospheric turbulence. It will be expressed as the inverse of the atmospheric- and soil- exchange resistances.

$$v_{d,HTO} = \frac{1}{r_{av} + r_{bv} + r_{soil}} \tag{10}$$

with the soil resistance r_{soil}

$$r_{soil} = \frac{z}{D_{eff}}$$

1

The effective diffusivity D_{eff} can be expressed as:

$$D_{eff} = D_0 \times \left(\frac{T_a}{273}\right)^{1.75} \times \frac{1}{\left(\frac{\Theta_S - \Theta}{\Theta}\right)} \times tort$$

where D_0 is the diffusion coefficient of HTO in water (0.23 E-04 $m^2\ s^{-1}$). The depth of the dry layer is assumed to be variable and depends on the soil water content:

$$z = \frac{z_0}{\Theta}$$

where z0 is the initial depth of the dry soil layer (4 mm).

In addition, based on comparison with experimental data, a residual resistance r_{sm} has been added to prevent the appearance of a zero surface resistance(9). This leads to the following equation for the soil resistance:

$$r_{soil} = \frac{z}{D_{eff}} + r_{sm} \tag{11}$$

The process of wet deposition of HTO to soil is considered in the model as washout from the whole plume. The washout coefficients depend on the intensity of precipitation. They are very small for HT, i.e. wet deposition is neglected.

The reemission processes from soil are modelled by coupling the reemission of HTO to the evaporation of water from soil. There, only the water content in the top five centimetres of soil is taken into account(10). To describe the water flux and thus the coupled flux of tritium, Monteith's bulk resistance formula for the actual transpiration is used(8).

$$\lambda E_a = \frac{\delta I_a + \varsigma c_p (e_s - e_a)/r_{av}}{\delta + \gamma(1 + r_x / r_{AV})} \tag{12}$$

where λ is the latent heat of evaporation in J kg^{-1} , c_p is the specific heat of air at constant pressure in J kg^{-1} K^{-1}, E_a is the actual evapotranspiration, I_a is the incoming solar radiation in W m^{-2}, e_s is the actual saturation vapour pressure of air in N m^{-2}, e_a is the actual vapour pressure of air in N m^{-2}, δ is the gradient of the vapour pressure curve at ambient temperature in J m^{-3} K^{-1}, γ is the psychrometer constant in J m^{-3} K^{-1}, r_{AV} is the sum of the atmospheric and the boundary resistance and rx is the resistance of the surface.

Derived for vegetated surfaces, it can be also used for the soil by replacing the incoming solar radiation with the fraction reaching the soil $I_{a,S} = I_a \cdot e^{-0.398L}$ and the surface resistance r_x with that of the soil resistance r_s (11). The water vapour flux finally is linked with the specific tritium content in the upper soil to obtain the reemission of HTO.

Even if the reemission of tritium from vegetation is expressed by equation 3, the transpiration of plants has to be taken into account for the replacement of the transpiring plant water by soil water. This uptake of HTO by the plant root system compensate the transpiration loss. Again, Monteith's bulk resistance formula for the actual transpiration is used; now by replacing the incoming solar radiation with the fraction reaching the canopy $I_{a,L} = I_a \cdot (1 - e^{-0.398L})$ and the surface resistance r_x with that of the canopy resistance r_c.

As often used in UFOTRI, the movement of tritium in soil is coupled to the movement of water. The water movement $v_{a,b}$ from layer a to layer b is calculated by using a simplified version of Darcy's law(12) :

$$V_{1,2} = K_{1,2} \cdot \frac{S_1 - S_2}{\left(\Delta z_1 + \Delta z_2\right)/2} - 1 \tag{13}$$

where Δz_1 and Δz_2 are the thickness of layer one and two, respectively, S_1 and S_2 are the pressure head of layer one and layer two, respectively and $K_{1,2}$ is the mean conductivity of the two layers.

To solve the above equation, the hydraulic conductivity K and the pressure head S of the soil have to be calculated.

$$S = 1.5 \cdot 10^5 \Psi^{a + b\Psi + c\Psi^n} \tag{14}$$

with the relative water content of the soil layer $\Psi = \frac{\left(\Theta_S - \Theta\right)}{\left(\Theta_S - \Theta_W\right)}$

and the conductivity function $K = \frac{\alpha}{S^m + \beta}$ (15)

where Θ_S is the maximum water content, Θ_W is the water content at wilting point, Θ is the actual water content, and a, b, c, n, α, m and β are soil specific constants.

The tritium movement in soil is simply coupled to the water movement. Diffusion of tritium however, is not considered explicitly.

2.3 Exchangeable/non-exchangeable tritium

Plants exposed to a tritium atmosphere contain tritium not only in the plant water (HTO), but tritium atoms are also incorporated in the organic matter of the plant (OBT). A photosynthesis sub model calculates the hourly built-up of organic material. The photosynthesis rate is based on the amount of CO_2 assimilation within a time step. A commonly used approach including respiration can be found in(13) :

$$P_{pot} = \frac{P_m \cdot \varepsilon H}{P_m + \varepsilon H} - R \tag{16}$$

where P_{pot} is the potential CO_2 assimilation rate in g CO_2 m^{-2} h^{-1}, P_m is the maximum CO_2 assimilation rate in CO_2 m^{-2} h^{-1}, H is the absorbed photosynthetically active radiation in W m^{-2}, ε is the initial light use efficiency in g CO_2 W^{-1} m^{-2} h^{-1} and R is the respiration rate in g CO_2 m^{-2} h^{-1}. Integrating this equation over the whole canopy which means over the present leaf area index L, the following equation for the total canopy assimilation P_c can be derived:

$$P_c = \frac{P_m}{k} \cdot \ln\left(\frac{P_m \cdot \varepsilon k I_{n0}}{P_m + \varepsilon k I_{abs}}\right) - R \tag{17}$$

with

$$I_{abs} = I_{n0} \cdot k e^{-kL}$$

where: I_{abs} is the radiation flux absorbed by the canopy, I_{n0} is the incoming photosynthetically active radiation, L is the leaf area in m^2/m^2, ranging from zero to the total leaf area index and k is the extinction coefficient (0.69).

To express P_m, an approach has been adopted$^{(14)}$, taking into account for the dependency on the temperature also.

$$P_m = \frac{0.158 \cdot C_0 \cdot 10^9 \cdot T \cdot \exp\left(-\frac{\Delta H_1}{RT}\right)}{1 + \exp\left(-\frac{\Delta H_2}{RT}\right) \cdot \exp\left(\frac{\Delta S}{R}\right)} \qquad (18)$$

where $\Delta H1$, $\Delta H2$ are the activation and denaturation energies for the electron transport, respectively, in cal, C_0 is the value for the formation of organic matter in mg CO_2 m^{-2} h^{-1}, R is the gas constant in cal/Kelvin per mol, ΔS is the entropy change on denaturation of the electron transport system in cal/Kelvin per mol and T is the air/leaf temperature in Kelvin

The total respiration R can be split up into two fractions.

$$R = C1_p \cdot P_c + C2_m \cdot W_d \qquad (19)$$

where $C1_p$ P_c is the photorespiration, dependent on the photosynthesis rate, $C2_m$ W_d is the maintenance respiration, dependent on the plant weight and $C1_p$ and $C2_m$ are constants.

Applying equations 17 to 19, and taking into account the conversion factor CO_2 to dry matter as well as the weighting functions for the responses of the stomata to the environmental conditions, the actual photosynthesis rate can be expressed as:

$$P_{act} = P_c \cdot COA \cdot 1 / f(sr) \qquad (20)$$

where COA is the conversion factor CO_2 to dry matter and f(sr) is the weighting function for the stomata opening which is identical to those used for calculating the actual stomata resistance (radiation, temperature, humidity and soil water content).

The specific concentration of the built-up HTO is connected to the actual specific tritium concentration in the water compartment of the plant. Until now the OBT transfer model is only physically based for the hours with solar insolation. During the night it is assumed, that the transfer rate is a quarter of the daily mean.

2.4 Foodchain compartments

For all crops, in particular grass, leafy vegetables, winter wheat and potatoes, the above mentioned dynamic transfer rates are applied starting with the beginning of the release. In addition, in the atmospheric part of UFOTRI, all exchange processes cow/atmosphere, cow/plant and cow/soil, which are important for the ingestion pathways via milk, beef and dairy products, are also considered. The transfer rates are in general the same as for the long term ingestion module of UFOTRI (see below), which were derived on the basis of a constant daily rate, but now converted to an hourly value.

2.5 Long term ingestion module of UFOTRI

In this part of the model, the long term behaviour of tritium in the environment and the assessment of the long term doses of the population from the consumption of tritium contaminated foodstuffs are described. To that purpose, the model calculates the time integrated tritium concentrations in vegetables, meat and milk products. To describe the transport processes mathematically, the areas in the environment where tritium may appear are divided into different compartments. The transfer rates which quantify the transfer processes are averaged values valid for longer periods and calculated by assuming equilibrium conditions. The exchange processes between the individual compartments are treated by first order differential equations which describe linear dependencies of tritium concentrations or concentration differences(15).

3. Areas for model improvements

Within the BIOMASS exercise it was demonstrated that the present tritium models differ mostly in assessing the concentration in the foodstuffs and the reemission of HTO from soil(16). From the recent applications of UFOTRI it was also obvious, that the contamination of the agricultural products may be one of the important tasks in defending the ITER source terms(17). Therefore, experimental work has been carried out at FZK in the years 1995 and 1996 to get a better understanding of the reemission from bare soil and the formation and translocation of OBT in wheat plants.

3.1 Plant experiments

3.1.1 Experimental design

Winter wheat (*Triticum aestivum L.*, cv. Contra) was cultivated on a small field (3m x 3m) in 1995 and 1996 within the area of the Forschungszentrum Karlsruhe (FZK) from sowing in October to harvest in July of the next year. The plants were provided with fertiliser as required and additionally with water in extremely dry periods because the soil (sandy soil) had a low water capacity. Before exposure to HTO, the plot was covered with a layer of Parabraunerde (3-4 cm) which was removed after the exposure. This procedure was necessary to reduce the influence of HTO reemission from soil. The exposure box was made of plexiglas (ground area 30 x 30 cm, height 100 cm). Inside were sensors for temperature and relative humidity and a fan to prevent gradient build-up and to minimise the boundary layer resistance of leaves. All necessary environmental data to operate tritium models were either measured directly at the field or taken from the meteorological tower of the centre.

Winter wheat plants on the experimental field were exposed to HTO vapour between the 12th and the 28th day after the beginning of anthesis which is in the period of grain filling. Experiments were performed at different times of the day under conditions of sunrise, morning, afternoon, sunset and night. At high light intensity (morning and afternoon), the temperature in the box was up to 10°C higher than outside. The difference was very low under conditions of low light intensity and during the night indicating that the influence of the heating unit for vaporisation of HTO was low.

3.1.2 Results

Besides the uptake of tritiated water during daytime and night-time conditions, the formation and translocation of OBT was measured intensively. Detailed records on the OBT formation allowed to compare measurements with model calculations. To evaluate the data, a special model named Plant-OBT was developed for describing all the relevant transfer processes in detail which are both dependent and independent on solar insolation. Especially the consideration of light independent processes was a considerable improvement of the existing tritium models(18). As this work was also aimed to improve the present OBT modelling in UFOTRI, comparison calculations have been performed for both the Plant-OBT and the UFOTRI model. In its newest version UFOTRI is modified in its photosynthesis submodule, in particular the daytime/night-time factor of 1.75 was deleted for the improved photosynthesis option. In addition, a reduction in the OBT production rate was introduced at those times when water stress due to solar insolation occurs. This modified version was applied for the comparison calculations, however, the changes will be made only official, if further experimental data support the revision.

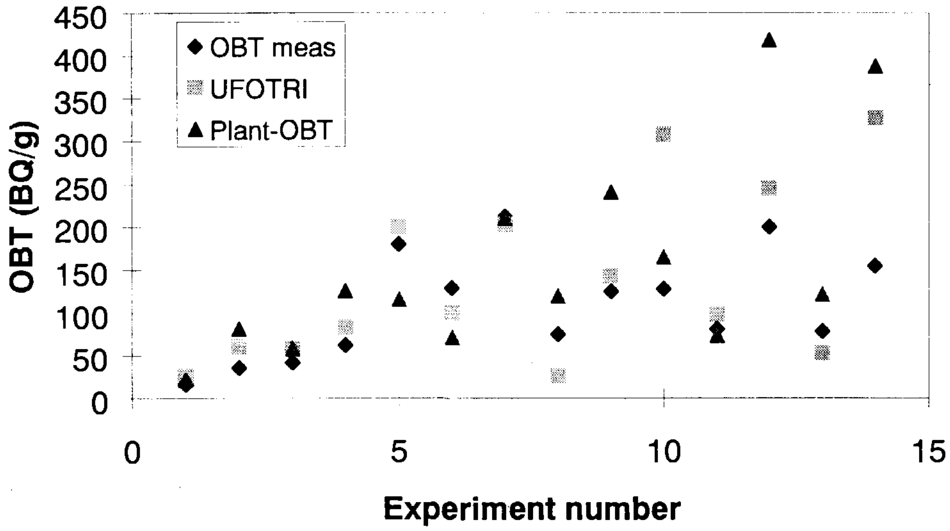


Figure 1: Comparison of the measured and calculated OBT at harvest time

Comparing the measurements with both the Plant-OBT model and UFOTRI it becomes obvious that both computer codes overestimate the OBT formation in most cases. However, the general agreement between model and experiment was within a range of two. Only in few cases, this difference was exceeded. Another effect could not be predicted by both computer programs. Within the measurements, in particular during the night-time, OBT was formed rapidly at exposure time and within the first hour after the end of exposure. In the following hours, however, the OBT formation rate was nearly zero even if the TWT concentration in the plants remained nearly constant. There was no explanation found and the assumption of a linear production rate at night, which simply depends on the specific TWT concentration in the plant, could not be verified. Even if the final OBT results - at harvest time - could be reproduced sufficiently, further work seems to be necessary at least to improve the understanding of the process. Without the understanding, it might be not appropriate to apply the same approach to other nutrient plants.

3.2 Reemission from soil

As described in$^{(19)}$, two HTO deposition/reemission experiments were performed at FZK in 1995 by scientists from the Zentrum für Strahlenschutz und Radiobiologie (ZSR) of Hannover. One took place at 09.00 a.m. (sunrise) whereas the other was conducted at 07.00 p.m. (sunset). After a deposition phase of one hour, the reemission from the bare soil was observed over a period of 12 hours. In both cases, the wind speed was very low and the daytime period can be characterised as a typical mid summer day.

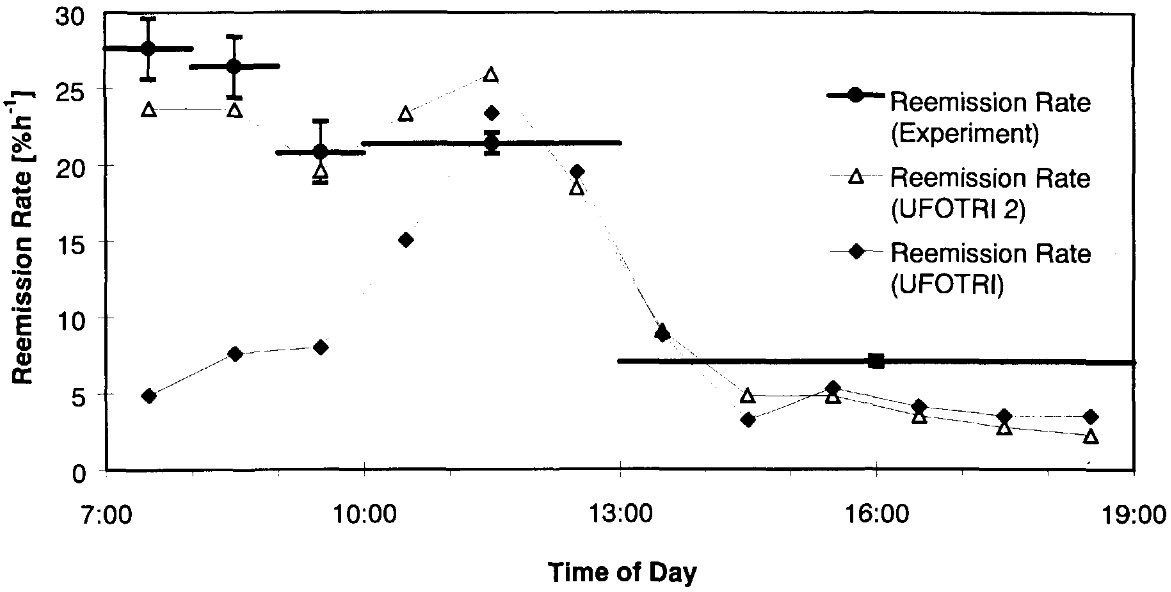
Comparing the measurements with calculations from UFOTRI by using the default parameter values, differences can be easily identified. The high reemission rate in the first hour found in both experiments could not be reproduced by UFOTRI. The further course of the concentration pattern of the sunrise experiment was at least partially covered by the model. At the end of the experiment, the measured and predicted concentration differed by a factor of about 2. This relative good agreement was never reached for the sunset experiment. The initial as well as the following reemission rates were drastically underestimated by UFOTRI. The main reason for this discrepancy seemed to be the steep concentration profile in the top soil which might be not well represented in UFOTRI. This steep concentration profile in the top soil of the HTO is different from that following a deposition of HT-gas$^{(20)}$. But most of the data which were used to test the reemission part of UFOTRI were taken from the HT-release experiments.

As described before, the reemission rate from soil is linked to the water vapour evaporation. But as the gradient of tritium and water vapour differ in general shortly after deposition of tritium, scaling parameters were introduced in the tritium reemission formula of UFOTRI.

$$F_{re} = \frac{E_a}{\Theta} \cdot C_1 \exp\left(-\frac{t}{T}\right) + k_b \exp\left(-\frac{t}{T}\right) \qquad (21)$$

where F_{re} is the reemission rate per time step, E_a the actual evaporated water per time step, Θ is the actual water content, and C_l, k_b, and T are scaling constants. K_b is assumed to be constant and determines the reemission rate at night. The time function t/T is introduced to simulate the movement of the tritium into deeper parts of the upper soil layer and the constant C_l determines the basic relationship between the flux of water and HTO. Changing the basic values ($C_l = 500$, $k_b = 1$ and $T = 50$) to the new ones ($C_l = 1200$, $k_b = 23$ and $T = 5$) resulted in a rather good agreement with the observations (see Figure 2). However, the initial high reemission rate can not be fully simulated by the model. Nevertheless, the agreement between the data and the simulations is sufficient to that extent, that further investigations about the dose relevance can be performed.

A: Sunrise Experiment



B: Sunset Experiment

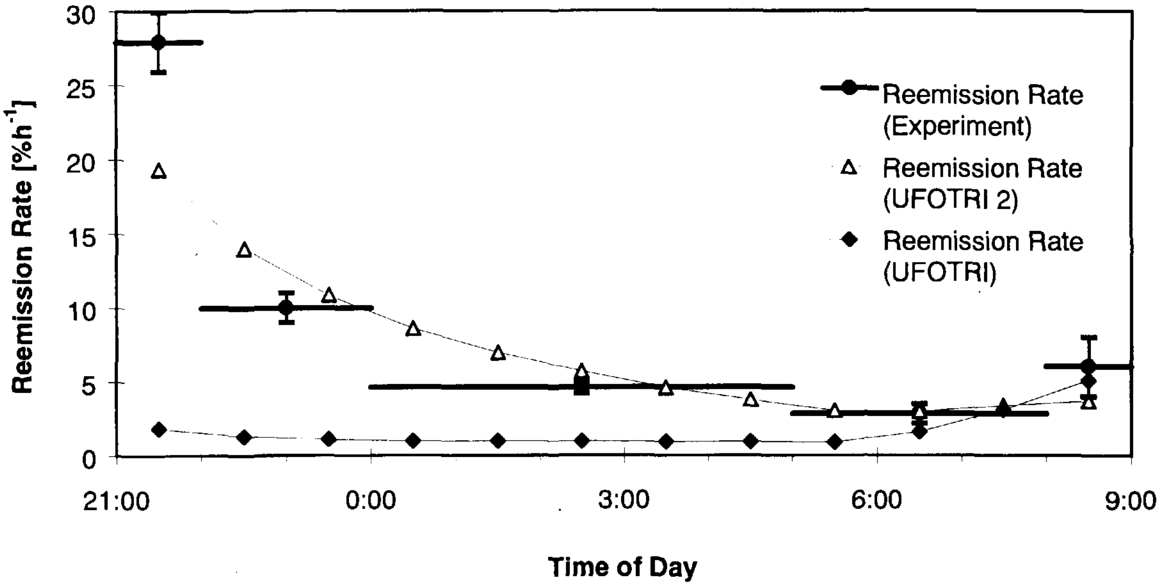


Figure 2: Time courses of reemission rates measured in the field and modelled with the original (UFOTRI) and the modified default values (UFOTRI 2) after 1-hour HTO depositions at sunrise (A) and at sunset (B). Vertical bars indicate the total experimental error (Figure according to Ref. 19)

The question arises now if the reemission pathway is important with respect to the dose. Most of the dose assessments, in particular for licensing purposes, are explicitly directed to the release of HTO only and to obtain the dose for a person who is living close to the fence at the most contaminated point. As the measured reemission rates are strictly valid only for bare soil, dose assessments by using the new values can be only performed for a dose without the ingestion pathways. However it can be speculated which influence might have the new reemission model also in case of the total dose.

To answer the question if the reemission pathway is important with respect to the dose, the contribution of the resuspension exposure pathway IHR has been investigated by applying the old and the new reemission approach for an accidental release of HTO from a ground level source (10 m release height). The same weather conditions as for the two experiments were used. The wind direction was set to a constant value as no measurements were available for this period. The dose from IH and IHR was calculated for a period of 12 hours exposure. The difference between the old and the new model approach is not very high for the sunrise experiment but much more obvious for the sunset data. One reason for the relative high contribution of the reemission process can be found in the fact that the wind direction was hold constant for the 12 hours.

	old approach		new approach	
	IH (%)	IHR (%)	IH (%)	IHR(%)
sunrise	96.7	3.3	94.5	5.5
sunset	94.1	5.9	78.9	21.1

Table 1: Contribution in % to the inhalation dose after 12 hours exposure

When thinking about the transferability of these results to other conditions such as the reemission from vegetated surfaces or after rain, it is necessary to estimate the dose relevance of the reemission process in general. The inhalation dose to the most exposed individual (MEI), however, will be reduced in real assessments due to changing wind directions within the reemission phase. Coming to the ingesting pathways, the contribution to the ingestion dose of that tritium taken up by roots from the soil can be estimated to be about 20% to 30% for the MEI at 1 km distance, assuming an accidental release of HTO near ground level(21). These numbers were obtained by using the default reemission rates of UFOTRI. When applying the higher ones, and speculating that they are also valid for vegetated surfaces, one can assume, that the root uptake from soil is diminished. Together with a reduced - or at least an equivalent - contribution from the inhalation pathways, the overall dose will be lower due to the lower ingestion dose. However it is not possible in the present stage to quantify the reduction in the contribution from soil and thus in the resulting dose, but it appears to be necessary to investigate this in future. To this purpose, further reemission experiments have been carried out by ZSR to investigate the influence of vegetation cover on the reemission rate. However the evaluation of these experiments is still ongoing.

4. Application

4.1 ITER

4.1.1 Objective of the application

One of the most recent applications of UFOTRI was to perform site independent dose assessments within the ITER programme, to derive the release limits associated with proposed dose limits(17). Since a specific site for ITER has still to be defined, generic calculations have to be compared with site specific ones to complete the environmental data base. To this purpose, probabilistic dose assessments for accidental atmospheric releases of various ITER source terms which contain tritium and/or activation products were performed for the - at this time - potential European ITER sites Greifswald, Germany, and Cadarache, France. No country specific rules were applied and the input parameters were adapted as far as possible to those used within former studies to achieve a better comparability with site independent dose assessments performed in the frame of ITER. The calculations were based on source terms which, at the first time, contain a combination of tritium and activation products. This allowed a better judgement of the contribution to the total dose of the individual fusion relevant materials. The computer program UFOTRI was applied for the tritium fraction whereas calculations for the released activation products were performed with the version NL/95 of the program system COSYMA(22) (subsystem NL), including extended data sets for activation products.

Probabilistic dose assessments, based on hourly meteorological data, have been performed. 144 different weather conditions - together with their probability of occurrence - have been selected therefrom to be representative for the vegetation period of the year under consideration. Mostly potential individual doses and, if appropriate, also the need to initiate protective measures have been investigated for three types of accidents, all of them placed in the event sequence categories IV (‘extremely unlikely events’) and V (‘hypothetical sequences’). For details see Ref. 23, 24 and 17. Source terms of up to 100 g of HTO, 3000 g of HT (both elevated) and of up to 2000 g of activation products (elevated) have been considered for the CAT IV releases. The CAT V scenario comprised more than 4 kg of activation products and 42 g of HTO, both released at ground level.

Two different types of doses have been obtained. The individual early dose results from the first week exposure and a 70 years integration time but without ingestion, whereas the individual EDE is based on a chronic exposure, 70 years integration and includes also the ingestion pathways.

4.1.2 RESULTS

One of the key points for ITER is the non-evacuation criteria. This means that under no release condition evacuation has to be initiated. To this purpose the early dose as defined before should not exceed 50 mSv at the fence of the fusion installation. This value was selected to represent an average value which can be applied within all potential ITER home countries.

The assessments showed that early doses from all CAT-IV release scenarios do not exceed the lower reference level of 50 mSv for evacuation at 1 km distance, when compared with the 95% percentile of the probabilistic calculations. Independent from the selection of Cadarache or Greifswald as site, the new release limits fit with the proposed dose limits.

However, the dose values for Cadarache are slightly higher than for Greifswald. The dust composition steel showed the highest values for both the early dose (13 mSv) and the EDE (910 mSv) when compared to the maximum percentile. The highest early dose for the 95% percentile resulted from HTO releases (5 mSv), followed by steel (1.2 mSv) and the other two dust compositions copper (0.8 mSv) and tungsten (0.5 mSv). The early dose from the other CAT-IV scenarios is lower and reaches only up to 0.7 mSv for the 95% percentile. CAT-V releases, which are stated to be hypothetical, should be compared to the 50% percentile or the mean value of the probabilistic calculations. Early dose values of several mSv at 1 km distance were obtained when looking at the lower percentiles. The dust released as pure steel shows up to 7 mSv for the mean and up to 3 mSv for the 50% percentile of the early dose distribution. Even if recommended to use average weather conditions, a look at the upper percentiles is also interesting. In particular the 50 mSv intervention level for evacuation is almost reached at the site of Cadarache (48 mSv), up to one half of this value is found for Greifswald (26 mSv) when comparing with the 95% percentiles.

At present, release limits to avoid evacuation are key criteria for ITER. However, other protective actions such as sheltering, relocation and food banning may become important in future. None of the source terms caused evacuation beyond the proposed site boundary of 1 km. Also shelter areas were rather small and were only obtained for the CAT-V source term (up to 1.4 km^2 as maximum). Only banning of agricultural products was found to be important. Dependent on the scenario, banning affects initially areas of several hundreds of square kilometres and can be as large as 10000 km^2 and more for CAT-IV (up to 11000 km^2 for the wet bypass) and CAT-V (up to 18000 km^2) releases - when considering the 95% percentile of the concentration distribution. Most of these large areas are attributed to tritium and the fact that there exists no special intervention level for food banning for tritium. Therefore, the value of 1250 Bq/kg fresh weight was selected as this value is appropriate for Cs and other long living radionuclides. However, the radiological significance of tritium is much lower than for Cs, thus an overestimation of the ban areas cannot be precluded. It seems to be necessary to evaluate specific ban criteria for the use of tritium. Nevertheless, also when releasing the CAT-IV limits on dust (steel), initial ban areas of several thousands of square kilometres - for Cadarache (up to 2000 km^2 for the 95% fractile) - have been estimated.

4.2 SEAFP

One of the aims of the SEAFP study was to quantify the environmental impact from future fusion power reactors, in particular to demonstrate its potential in safety and environmental aspects(25). Two power plant designs were studied:

1. PM-1, using an advanced vanadium alloy structure, a lithium oxide pebble bed tritium synthesiser and pressurised helium coolant.
2. PM-2, a near-term concept with ferrous structural materials, tritium synthesis in liquid lithium/led, and pressurised water as the primary circuit coolant.

When identifying the potential accident sequences, no active safety countermeasures were considered. Mobilisation of the inventories, their transport to the external environment and finally their consequences to the public were assessed. As for the SEAFP study, the computer systems UFOTRI and COSYMA were applied for tritium and activation products, respectively. Differing from the ITER applications, the definition of the source terms within SEAFP took full credit of the transport and depletion processes inside the power plant. This led to rather small releases into the environment, even if several kilogram of activation products and up to one kilogram of tritium was mobilised initially. Also the accident sequence lasted up to several weeks which is again in contrast to the one hour duration of the ITER scenarios. A further difference was the selection of only one deterministic weather sequence which was identified as worst case for HTO releases.

The early dose for both concepts are far below the conditions where evacuation should be initiated. In no case, one mSv was exceeded. Also the EDE was found to be rather low, highest values amounted to about 40 mSv. Within all calculation, the advanced plant concept PM-1 showed lower doses than PM-2.

5. Summary

The UFOTRI is widely accepted in fusion related studies as a reference tool for assessing the impact of accidental released tritium. By coupling it to the European assessment system COSYMA it was possible to perform dose assessments for combined releases of tritium and activation products. By applying these tools to potential European sites for ITER, it could be demonstrated that the main goal, the non-evacuation criteria, is fulfilled also for specific sites in Europe. However the banning of agricultural products was identified as one potential countermeasure which might be initiated after a major fusion accident. However there exists no specific ban criteria for tritium, thus these calculations are of preliminary nature.

The assessment of food countermeasures also highlighted one of the areas where UFOTRI is still under development. Plant exposure experiments performed at FZK together with the development of a specific Plant-OBT model suggest an improved modelling of the formation and translocation of OBT in cereals. In addition, the soil model is under revision and may be also improved in the next version of UFOTRI.

6. References

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