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Modeling Atmospheric Releases of Tritium from Nuclear Installations

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Tritium source term analysis and the subsequent dispersion and consequence analyses supporting the safety documentation of Department of Energy nuclear facilities are especially sensitive to the applied software analysis methodology, input data and user assumptions. Three sequential areas in tritium accident analysis are examined in this study to illustrate where the analyst should exercise caution. Included are: (1) the development of a tritium oxide source term; (2) use of a full tritium dispersion model based on site-specific information to determine an appropriate deposition scaling factor for use in more simplified, broader modeling, and (3) derivation of a special tritium compound (STC) dose conversion factor for consequence analysis, consistent with the nature of the originating source material. It is recommended that unless supporting, defensible evidence is available to the contrary, the tritium release analyses should assume tritium oxide as the species released (or chemically transformed under accident's environment). Important exceptions include STC situations and laboratory-scale releases of hydrogen gas. In the modeling of the environmental transport, a full phenomenology model suggests that a deposition velocity of 0.5 cm/s is an appropriate value for environmental features of the Savannah River Site. This value is bounding for certain situations but non-conservative compared to the full model in others. Care should be exercised in choosing other factors such as the exposure time and the resuspension factor.

I. INTRODUCTION

There are numerous U.S. Department of Energy (DOE) nuclear installations that produce, store, or process inventories of the only radioactive isotope of hydrogen, tritium. Still other facilities contain other radionuclides, but include non-negligible quantities of tritium. The safety analyses for these nuclear reactor and nonreactor facilities must be sufficiently rigorous to properly identify the appropriate safety controls needed to ensure that operation poses no undue risks to workers, the general public, and the environment. Due to its unique radiological properties, physiological behavior in the human body, and ubiquitous nature as part of the hydrogen pool in the environment, tritium poses distinct challenges in consequence modeling associated with atmospheric releases.

One aspect of safety analysis is accident analysis, i.e., postulating accident conditions to identify the controls needed to protect workers and the public. To model tritium atmospheric releases under acute (short-duration) accident conditions, computer codes are often applied to model the atmospheric release, dispersion, and ultimately quantify the consequences to downwind receptors following the guidance in DOE-STD-3009-94, Appendix A,[1] and related implementation documents.[2,3] In modeling tritium dispersion and consequence phenomena for these cases, several key factors arise with respect to tritium that are unique and can impact the validity of subsequent safety documentation if not taken into account.

This paper reviews several key aspects of tritium source term and dispersion phenomenology from short-term (acute) releases and identifies several considerations for modeling tritium releases to quantify sufficiently bounding dose estimates for safety basis applications. In particular, the following issues are addressed:

- Source term estimation for oxide and gas forms of tritium, damage ratio, and cases where tritiated oil is part of the material-at-risk (MAR)
- Modeling parameters consistent with characteristics of the region of transport
- Evaluation of exposure to a receptor that accounts for the available pathways and species identity.

For purposes of the remainder of the discussion, atmospheric releases are limited to the condensable form of tritium, or tritium oxide (HTO, T_2O). Where environment dependencies and assumptions are required, those characteristic of the Savannah River Site (SRS) are applied.

II. TRITIUM SOURCE TERM, RELEASE AND DISPERSION PHENOMENOLOGY

Under hypothetical accident conditions, three phases are defined that are important for modeling tritium: (1) source term and release characteristics, (2) atmospheric dispersion, and (3) uptake by the body. In-facility source term development should treat in-facility environments that may cause chemical species transformation. As a tritium plume is released into the atmosphere, it is subject to environmental mixing and dilution effects primarily driven by diffusion and advection. A final phase is intake by the human body. The unique features of tritium pose issues for modeling and subsequent accident analysis for each of these phases. These phases are discussed in terms of case studies, or examples of situations where special considerations for tritium are necessary to perform the analysis correctly.

II.A. First Phase: Tritium Source Term

In-facility conditions from major accident types are often conducive to transforming tritium gas (HT, T_2) or hydride to the more radiotoxic form, tritium oxide (HTO, T_2O). In particular, fire and deflagration releases will likely lead to high percentages of conversion to oxide. While source term partitioning between the oxide and the gas form is critical for actual release management and emergency actions, for accident analysis purposes, these source terms are conservatively assumed to be entirely oxide. An exception to this conservative assumption is laboratory-scale storage of tritium gas where the energetics of the accident event are insufficient to cause oxidation before the tritium is released into the environment.

An example is tritium waste that is immobilized in a concrete matrix. Under normal conditions, this is little off-gassing potential and normal release of tritium is insignificant. However, during an energetic release, such as fire event, the same concrete matrix may be compromised and a release of much of the inventory is conceivable.

As additional example, often laboratory and waste facilities are considered with inventories of oil-based media containing fission products, activation products, and other radioactive species including tritium. Examples include laboratory cloth refuse, wipes, drain-off from stored waste, personal protection equipment (PPE) waste, and contaminated pump oils, etc. If tritium is present under these circumstances, it is often in special tritium compounds (STC).[4] Source terms prepared for the facility in question will normally need to partition the source term into tritium oxide and STC components.

II.B. Second Phase: Environmental Dispersion

As a plume of tritium oxide material is released into the atmosphere, it is subject to environmental conditions including diffusion (acts to decrease concentration due to local mixing conditions) and advection (transports the bulk of material downwind). In this regard, condensable species of tritium (HTO and T_2O) are no different from other radionuclides when released under accidental release conditions. Due to interaction with the hydrogen throughout the ambient environment, the behavior of tritium released into the atmosphere is predicted through the use of neutrally buoyant models, with the most common model being the Gaussian plume model. For relatively flat regions of transport such as SRS (and many other DOE sites), Gaussian descriptions of plume concentration are found to be appropriate bases for prediction, especially in the first 10 km – 15 km of transport.

Similar to the transport of other radioactive species, atmospheric tritium plumes are depleted via wet and dry deposition mechanisms. For accident analysis purposes using conservative, bounding assumptions, wet deposition, or precipitation, is normally not considered. However, dry deposition is often credited, and many computer codes used for DOE accident analysis incorporate relatively simple algorithms that deplete plumes as a function of downwind travel. A common approach of this type is termed a source depletion model, and was originally attributed to Chamberlain.[5] More recent modifications have allowed incorporation of particle size distribution based on chemical-physical characteristics of the radionuclide species in the source term.[6]

While dry deposition behavior is observed for most non-noble gas radioactive species and results in diminished plume concentrations as a function of downwind transport, the full set of mechanisms governing dry deposition and uptake by soil and vegetation are especially unique to tritium. The major biophysical processes shown in Figure 1 (Ref. 7) are

1. Initial settling and deposition to ground and surface elements (vegetation, buildings, etc.)
2. HT conversion to HTO by soil
3. HTO uptake by plants (and partial conversion to organically-bound tritium, (OBT))
4. HTO re-emission from soil and plant
5. Uptake by vegetation root systems, and
6. Transport into deeper soil regions.

Only the first (deposition) and fourth (re-emission) processes have approximate parallels with particulate non-tritium particulate radionuclides. In the non-tritium case, these processes are termed deposition and resuspension.

Some generalized computer models such as MACCS2 (Ref. 8) can model deposition and resuspension but unable to track the other four phenomena. As a consequence, any tritium component to the source term is treated artificially as a particulate using a conservative value of the deposition value. It is therefore incumbent on the user to pick deposition velocity values that will not over-deplete the plume and thereby yield non-conservative dose estimates.

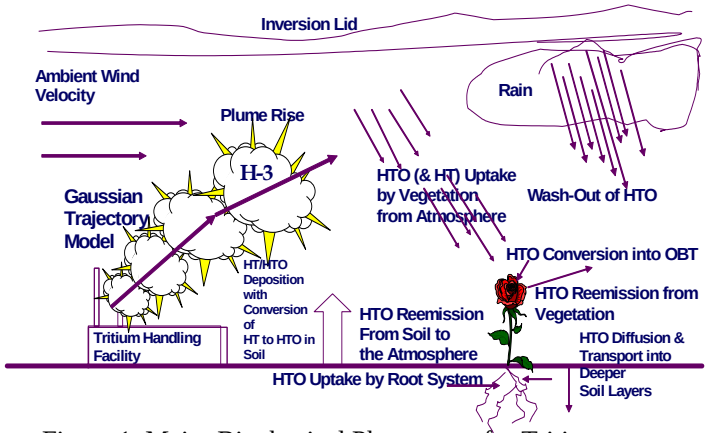

Figure 1. Major Biophysical Phenomena for Tritium During Plume Passage. (Based on Ref. 7).

The concept of a generalized deposition velocity for tritium can be viewed in a different manner. The overall effect of the above processes can be generalized as the quotient of the net tritium flux to the ground and vegetation, and the tritium air concentration at the same location. This parameter is normally termed a deposition velocity, v_{dep}, since the flux-to-concentration quotient has units of [tritium/cm^2-s]/[tritium/cm^3], or [cm/s]. For HT and T_2, v_{dep} is largely a function of soil oxidation and ambient windspeed and stability conditions. For HTO and T_2O, v_{dep} is controlled by uptake by vegetation (thus subject to diurnal fluctuations), deposition to soil, and, as in the case of molecular tritium, and the existing meteorological conditions.[9,7, 10]

Later in this paper, we will introduce an explicit computer model that describes the phenomena important for tritium dispersion processes. Use of the explicit model will allow derivation of a deposition parameter value for tritium oxide that approximately models depletion in a more simplified model.

II.C. Third Phase: Radiological Dose Conversion Factor (DCF)

Situations are often encountered in nuclear installation accident analysis for tritium where previous knowledge of the MAR is then used to infer the appropriate dose conversion factor (DCF) to downwind receptors. A second area where care should be exercised is accounting for all active pathways for tritium uptake, to include inhalation and absorption through the skin. The two factors are linked and cannot be evaluated independently.

As a case in point, Special Tritium Compounds (STCs) are typically found in oil-based inventories in many laboratory and solid waste installations. STCs have higher radiotoxicity in the body due to chemical composition characteristics indicating a large percentage of organically bound tritium (OBT). The Methodology section of this paper provides guidance on estimating the exposure to a plume that is rich in the OBT component. The implicit assumption in accident analysis involving a STC source term is that the accident event does not alter the physicochemical nature of the STC molecules.

Tritium released as part of an atmospheric plume may be incorporated into organic materials such as plants and animals. A tritium oxide release is especially important in the production of OBT through photosynthesis in green leaves with HTO as a precursor species.[11] Ref. 11 indicates tritium is bound organically either in exchange reactions or in enzymatically catalyzed reactions in which it replaces hydrogen. Tritiated organic material is usually designated based on the fractions of exchangeable and nonexchangeable it contains, with OBT being normally affiliated with the nonexchangeable fraction, It is usually bound to carbon and considered tightly bound in a nonexchangeable position in terms of molecular chemistry. The main pathway for OBT would normally be uptake through food ingestion of foodstuffs that have been exposed to HTO-dominated plumes. OBT could also be inhaled directly if organically molecules are made airborne and are part of the source term. Regardless of the mechanism and pathway, it will be shown that dose conversion factors considering the presence or formation of OBT are larger than those for HTO.

A second effect is that of uptake through the skin. Usually this effect is significant relative to inhalation. Skin absorption of tritiated water vapor has long been recognized as a contributor to the dose from tritium. Most tritium computer models account for this pathway by scaling the inhalation dose conversion factor by 1.5. This implies fifty percent as much dose is incurred through the skin absorption mechanism.

An example of where both the OBT exposure and the skin absorption pathway are important is discussed later in this report.

III. METHODOLOGY AND APPLICATION

Several methodologies are discussed in this section that provide guidance for analyzing the three areas outlined for treating tritium oxide release and consequence assessment: (1) source term estimation; (2) environmental dispersion; and (3) radiological dose to receptors.

III.A. Tritium Source Term

For most DOE nuclear facilities containing tritium, the most prevalent method for evaluating the source term is to apply the five-factor methodology, based on DOE-HDBK-3010-94.[12] This methodology considers the tritium source term based on five parameters determined in serial fashion for the accident of interest. The overall source term is quantified by specifying a point value for each of the terms in applying the five parameters in the equation:

$$\text{Tritium Source Term} = \text{MAR} \times \text{DR} \times \text{ARF} \times \text{RF} \times \text{LPF} \quad (1)$$

where:

- MAR = Material at Risk, amount of tritiated material available to be acted upon by a given physical stress initiated under the postulated accident condition;
- DR = Damage Ratio, fraction of MAR actually affected by the postulated stress from the accident;
- ARF = Airborne Release Fraction, fraction of material subject to a given stress that eventually becomes airborne;
- RF = Respirable Fraction, fraction of airborne material with Aerodynamic Equivalent Diameter (AED) of 10 microns or less; and
- LPF = Leak Path Factor, fraction of tritium in the air transported through some confinement, deposition or filtration mechanism. For unmitigated accident analysis and for outdoor releases, LPF = 1.

Generally, the tritium source term is calculated by estimating each of these factors. For most radionuclides, for a given assumed accident condition, each of the factors in the equation depends on the physical form of the material proximity to the accident stressor. However in tritium accident analysis, for all practical purposes, the fractional factors, ARF, RF, and LPF are conservatively chosen to be unity (1.0). The implicit assumption is that all tritium is converted to the oxide form regardless of chemistry and whether it is a solid, liquid or gas. For tritium, the only factors that are practical to consider are the MAR and DR.

Often it can be established that the material-at-risk (MAR) is only partially in the oxide form, and it is advantageous to evaluate source terms as partially oxide, especially if there is a possibility that the facility can be categorized below Hazard Category 2 (Ref. 13). But for most facilities, the tritium source terms should be assumed to be entirely oxide to minimize project risk, especially with respect to schedule. For the two cases introduced earlier, with concrete and STC wastes, both would be treated with the five-factor formalism to yield

$$\text{Tritium source term} = \text{MAR} \times \text{DR} \times 1 \times 1 \times 1, \quad (2)$$

and the accident under scrutiny used to determine the extent of inventory involvement. Unless inventory segmentation can be used to justify separation of the inventory with only partial exposure to accident conditions, the MAR x DR product will be conservatively estimated as the number of containers or volume involvement (MAR), since DR $\approx$ 1.

III.B. Environmental Dispersion

Current tritium dispersion and consequence analysis software used for support of facility authorization basis documentation at DOE laboratories and sites may be categorized as either a *full*, or a *simplified* model. In this context, a full deposition model directly accounts for many of the processes summarized in the previous section with detailed biophysics algorithms. A simplified model employs empirical relationships to describe and quantify the same collective effects, but simplifies treatment of the underlying processes. UFOTRI (Ref. 7 and 10) and MACCS2 (Ref. 8) are examples of full and simplified models, respectively.

III.B.1. UFOTRI Model for Tritium Release

The UFOTRI (Unfallfolgenmodell fur Tritiumfreisetzungen) computer model was developed by the German national laboratory, Karlsruhe (Kernforschungszentrum Karlsruhe Gmbh, or KfK) to assess the radiological consequences due to postulated accidental atmospheric releases from nuclear installations.[9,7,10] Specifically, UFOTRI describes the behavior of tritium in the biosphere and calculates the radiological impact on individual receptors and populations due to inhalation, skin absorption and consumption of contaminated foodstuffs. Time-dependent processes modeled include dispersion, deposition, reemission, conversion of tritium gas (HT) into tritiated water vapor (HTO) by the soil, and conversion of HTO into organically bound tritium (OBT). The source term model accounts for release duration, release height, tritium species being released, and thermal energy released. A Gaussian trajectory model is applied for the initial release of HT/HTO and reemission up to seven days after the

release event. The reemission model addresses evaporation from soil and transpiration from vegetation. As shown earlier in Figure 1, UFOTRI considers all relevant transfer processes in the environment (atmosphere, soil, plant, and animal), and is unique in that the initial plume passage model is integrated with the reemission (area source) model.

The atmospheric model is coupled to a first-order compartment module, which describes dynamically the longer-term behavior of the two different chemical forms of tritium in the food chain. The long-term model accounts for food ingestion doses from contaminated foodstuffs, but does not include ingestion doses from potable water consumption. Typically, for individual dose calculations for safety basis documentation, food ingestion doses are not calculated.

The first version of UFOTRI was released in mid-1991 (Ref. 9). Version 4.0 was released in late 1993 incorporating several significant improvements to plant/exchange, soil/atmosphere exchange, plant, and photosynthesis (OBT formation) models (Refs. 7 and 10). UFOTRI for multiple plumes was released in 2001, and is the basis for the calculations reported in this paper.

The code can be executed in a deterministic manner, using prescribed meteorological conditions, or it can be run in a probabilistic manner, using a stratified random sampling algorithm. In the latter method, a set of "start times" is selected from consequence bins (sampled from meteorological data representative of the site). The consequences for the respective source terms are weighed by the probability of the consequence category, such that the output is in the form of a complementary cumulative distribution function (CCDF) table, providing median, 95th percentile, and other consequence levels.

UFOTRI has been applied primarily for fusion safety and design projects. The major applications have been for fusion studies such as the Next European Tokamak (NET) and the International Thermonuclear Experimental Reactor (ITER). Experimental studies in Canada indicate good agreement for use of UFOTRI for tritiated water vapor release.[14] Testing with HT species in Canada has shown good agreement despite data collection uncertainties and modeling interpretations.[9] Similar results were obtained when applied to HTO and HT accidental releases at SRS.[15]

III.B.2. Comparison of Full and Simplified Models

A series of probabilistic and deterministic (persistent meteorological conditions) calculations were executed with the UFOTRI 4.2 model to evaluate the consequences of unit activity releases of HTO under varying assumptions for deposition. The environmental input parameters for the calculations are those consistent with SRS, including use of site meteorological data, surface roughness length, vegetation coverage, soil type and other regional input data.

The calculations are run with full environmental factor input (full model), and with a constant deposition velocity for HTO of 0.5 cm/s (simplified model), and evaluate the initial plume passage component to dose as well as approximately the total inhalation dose incurred for one week after plume passage. The dose accounts for uptake through the inhalation pathway and through skin absorption. The full model runs are considered more near a "true" estimate of the dose in light of the meteorological sampling, since these runs account for the full range of environmental transfer of HTO while the simplified calculations artificially maintain a constant deposition velocity.

Figure 2 compares 95th percentile and mean TEDE dose results from 65 m to nearly hundred kilometers, for both the full and simplified model with an assumed deposition velocity of 0.5 cm/s in the latter model. An artifact of the code is the increase in dose with distance (to approximately 200 m) for the ground level release. No building wake effect is modeled but the code restricts to release to the meteorological data set 10-m reference height for source heights below 10 m. The ground-level release is thus modeled as essentially an elevated release and the plume reaches a maximum with a touch down effect beyond 200 m.

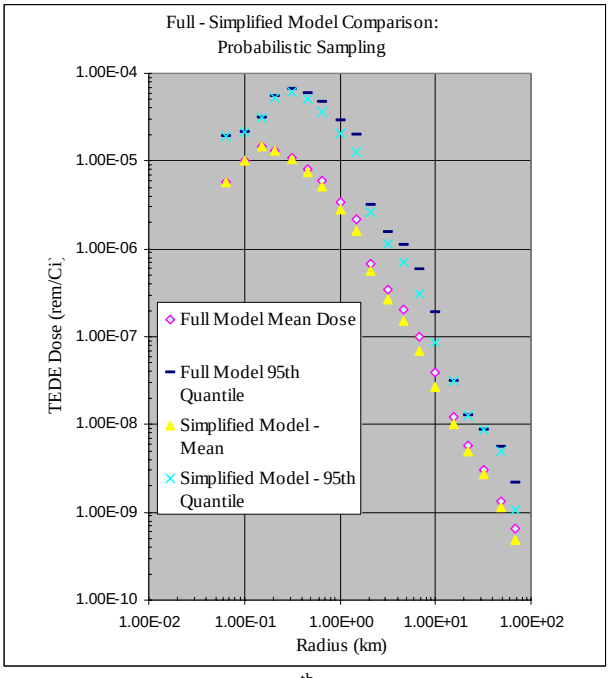

Figure 2. Comparison of 95th Quantile and Mean Doses for Full and Simplified Models.

Figure 3 illustrates the same unit activity release of one curie of HTO with the mean level of consequences shown. The curves show the full model, the simplified model assuming 0.5 cm/s deposition velocity, and the simplified model assuming 1 cm/s deposition velocity. The three curves are indistinguishable up until a distance of about 600 m to 800 m. For distance greater than 1 km, the full model is always bounding, but with very little difference compared to the simplified model with a constant deposition of 0.5 cm/s until approximately 8 km to 10 km. The use of a simplified model using a constant value of 1 cm/s would tend to over-deplete the plume and therefore under-estimate doses at all distances.

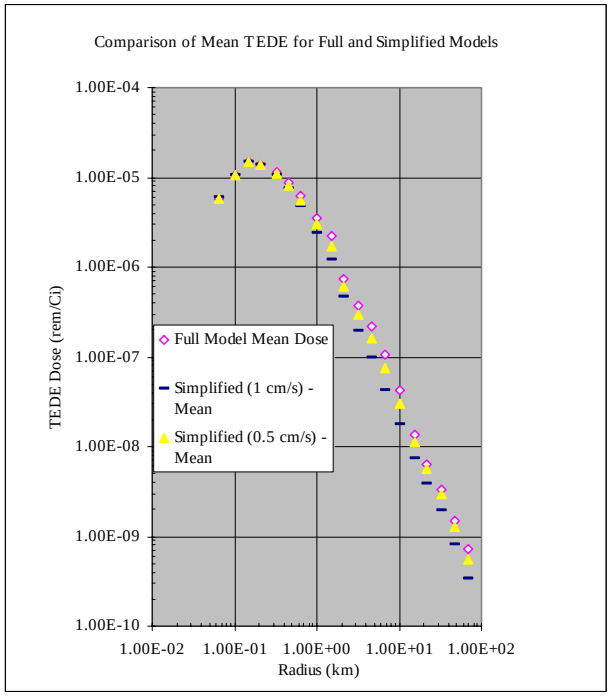

Figure 3. Mean TEDE Dose vs. Distance for Full Model and Simplified Models (0.5 cm/s and 1.0 cm/s deposition velocities).

Other values of the deposition velocity in the range 0.1 cm/s to 1 cm/s were tested in the simplified but are not reproduced here. For SRS characteristics, the best approximation to the full model was concluded to be the point value of 0.5 cm/s. Other values either under-predicted the dose or were overly conservative, especially for distances in the 5-mile to 8-mile range that are important to the maximally exposed offsite individual (MOI) dose calculated for documented safety analysis (DSA) applications.

To illustrate the agreement of the full model with the simplified model (with the 0.5 cm/s value implemented in the latter), Table 1 compares the two models for three sets of persistent meteorological conditions:

- F stability and 1 m/s wind speed
- E and 1.7 m/s, and
- D and 4.5 m/s.

For the most stable conditions (F and 1 m/s), the simplified model is within a few percent of the full model for distances as far as 1 km from the source. Beyond this distance, the simplistic model predicts smaller doses from approximately one kilometer until the most distant radii. The comparison with less stable conditions of E and 1.7 m/s are shown next, and indicate good agreement for the full range of distances. Review of the Savannah River Site meteorology has shown that E stability and 1.7 m/s wind speed closely approximates a 95th percentile consequence condition for release heights between 0 m to 10 m and for MOI-characteristic distances to the boundary.[16] A final comparison of the full and simplified model is made with D stability and 4.5 m/s wind speed. This condition is representative of mean or average conditions for many sites, and shows that the simplified model is the same or bounding compared to the full model at all distances of interest.

Table I. Comparison of Full and Simplified Tritium Dispersion Models for Three Persistent Weather Conditions.

Distance (m)	F Stability/1.0 m/s		E Stability/1.7 m/s		D Stability/4.5 m/s	
	Full EDE (Sv)	Simpl. EDE (Sv)	Full EDE (Sv)	Simpl. EDE (Sv)	Full EDE (Sv)	Simpl. EDE (Sv)
6.50E+01	2.5E-09	2.6E-09	2.4E-07	2.4E-07	5.9E-08	5.9E-08
1.00E+02	4.0E-08	4.0E-08	3.4E-07	3.4E-07	9.4E-08	9.4E-08
2.10E+02	2.8E-07	2.9E-07	2.7E-07	2.7E-07	7.6E-08	7.7E-08
4.60E+02	3.2E-07	3.2E-07	1.2E-07	1.2E-07	3.3E-08	3.4E-08
6.40E+02	2.5E-07	2.5E-07	7.8E-08	7.8E-08	2.2E-08	2.2E-08
1.00E+03	1.6E-07	1.5E-07	4.2E-08	4.2E-08	1.1E-08	1.2E-08
2.10E+03	6.3E-08	5.7E-08	1.5E-08	1.5E-08	3.9E-09	4.1E-09
3.20E+03	3.3E-08	2.6E-08	7.7E-09	7.8E-09	2.1E-09	2.2E-09
4.60E+03	1.9E-08	1.3E-08	4.5E-09	4.6E-09	1.2E-09	1.3E-09
6.80E+03	9.9E-09	6.2E-09	2.5E-09	2.5E-09	6.5E-10	7.0E-10
1.00E+04	5.1E-09	2.7E-09	1.4E-09	1.4E-09	3.6E-10	3.9E-10
2.19E+04	1.2E-09	4.1E-10	4.0E-10	4.1E-10	1.1E-10	1.2E-10
3.25E+04	5.1E-10	1.4E-10	2.1E-10	2.2E-10	5.7E-11	6.4E-11
4.80E+04	2.1E-10	4.4E-11	1.2E-10	1.2E-10	3.0E-11	3.4E-11
6.88E+04	1.1E-10	2.1E-11	8.3E-11	8.4E-11	1.6E-11	1.9E-11

The comparisons discussed in this section between the full UFOTRI model and the simplified UFOTRI model with different assumed values of the deposition velocity indicate numerical differences are a function of distance, the type of meteorological conditions, and whether the meteorology is persistent or statistically sampled. The results obtained here suggest that the deposition velocity value that is technically defensible for application to most distances of interest at SRS is 0.5 cm/s. One additional

goal of this discussion is to determine whether a value of the deposition velocity is applicable to other computer models that are more limited in their treatment of tritium. Using the value of 0.5 cm/s in the MACCS2 computer code, it is found that tritium doses are conservative compared to UFOTRI at the 95th percentile level of consequence for distances characteristic of the MOI receptor. However, the degree of conservatism is a function of the receptor exposure time input by the user, as well as the value of the resuspension factor.

In the MACCS2 code analysis performed for this paper, the resuspension model[8] applied is

$$\text{Air Concentration} = \text{Ground concentration} \bullet \text{RESCON} \bullet \exp(-0.693\ t/\text{RESHAF}) \quad (3)$$

where RESCON is the initial value of the resuspension coefficient (m^{-1}) (set at 1.0E-04 in these calculations), RESHAF is the resuspension coefficient half-life (s) (set at 1.825E+05 s, or 2.11 d), and t is the time after passage of the plume. Resuspension accounts for remission of deposited radioactivity back into the atmosphere and is an appropriate model for aerosols and particulates. This factor accounts for the action of ambient wind conditions in creating an area source of radioactivity from the initial "footprint" of the deposited plume but is overly simplistic when accounting for the re-emission behavior of tritium from soil and vegetation after plume passage.

In summary, judicious selection of source term characteristics, deposition velocity, receptor exposure time, and resuspension are necessary to ensure that calculated doses are conservatively calculated with non-tritium specific computer models.

III.C. Radiological Dose Conversion Factor (DCF)

For tritium oxide source terms, the safety analyst should verify that both inhalation and skin absorption pathways are addressed correctly by either the dispersion/consequence code, or by the set of dose conversion factors (DCF, dose per unit activity inhaled) used by the code. Codes such as MACCS2 require that the DCF be scaled by 1.5 to account for the skin absorption pathway.

In this section, a methodology is provided to illustrate application of the skin absorption pathway recommendation along for developing a DCF for STC-based source terms. This example thus serves to estimate the dose received through (1) uptake through inhalation and skin absorption pathways, and (2) the OBT-rich nature of the source term.

For a tritiated oil source term, the DCF is based onan approach given in the DOE Handbook for STCs.[4] Following the DOE STC Handbook, tritiated oil can be reasonably assumed to be a mixture of three components as follows: 80% insoluble large molecule OBT, 10% soluble small molecule OBT, and 10% HTO. The latter two of these three components can diffuse through the skin.[4] The inhalation DCFs for these components will be increased by a factor of 1.5 to include skin absorption effects. [17]

The component inhalation DCFs are based on ICRP Publications 68 (worker basis)[18] and 72 (general public basis)[19] as taken from the ICRP Dose Coefficient Database Compact Disc.[20] Table 2 lists component fraction, DCF, and skin absorption factor for each of the three STC components. The insoluble OBT is based on a 1-µm AMAD and lung absorption type S, consistent with the recommendation given in DOE Handbook for STCs.[4]

A tritiated oil inhalation DCF is calculated for both worker- and public-receptor applications using the ICRP-72 based component inhalation DCFs applying the general public value for the insoluble OBT for the worker case because a recommendation is not made for the DCF in the ICRP-68 set. A composite tritiated oil DCF is calculated as shown in Eqn 4.

$$\text{Tritiated oil DCF} = \sum_i (f_i \times DCF_i \times AF_i) \quad (4)$$

$$= (0.8)(2.6\text{E-}10\ \text{Sv/Bq})(1.0) + (0.1)(4.1\text{E-}11\ \text{Sv/Bq})(1.5) + (0.1)(1.8\text{E-}11\ \text{Sv/Bq})(1.5)$$

$$= 2.2\text{E+}10\ \text{Sv/Bq}$$

Table II. DCF Components for STC Airborne Species

Component	Component Fraction (f_i)	Component DCF_i (Sv/Bq) [Ref.4]		Skin Absorption Factor (AF_i)
		Worker (ICRP 68)	Public (ICRP 72)	
Insoluble OBT (Type S)	0.8	Not Specified	2.6E-10	1.0
Soluble OBT	0.1	4.1E-11	4.1E-11	1.5
HTO	0.1	1.8E-11	1.8E-11	1.5

A comparison can be made of the derived tritiated oil DCF to that of HTO to illustrate the influence of the OBT component in this species. The STC DCF for oil-based

atmospheric releases is calculated to be (2.2E+10 Sv/Bq)/ (1.8E-11 Sv/Bq)(1.5) = 8.1 times larger than the DCF for HTO.

IV. CONCLUSIONS

Tritium dispersion and consequence analyses supporting the safety documentation of a nuclear facility is especially sensitive to the methods employed, the input data applied, and the assumptions made. This paper illustrated three sequential areas in tritium accident analysis where care should be exercised. Included were: (1) the development of a tritium oxide source term; (2) use of a full tritium dispersion model based on SRS site-specific information to determine an appropriate deposition scaling factor for use in more simplified modeling, and (3) derivation of a STC dose conversion factor for resultant dose analysis and consistent with the nature of the originating source material. In lieu of complete information regarding the material-at-risk and the environment posed under accident conditions, experimental data and accidental release information from similar situations can be used to determine bounding doses for application in the DOE nuclear safety documentation.

The three phases of tritium dispersion/consequence analysis discussed in three segments, or case studies, led to the following conclusions and recommendations:

- **In-facility source terms**– Bounding estimates for tritium are obtained assuming complete oxidation of the source term. In other words, unless supporting, defensible analysis is available to the contrary, the tritium release analyses should assume tritium oxide as the species released (or chemically transformed under accident's environment). Important exceptions include the STC case noted below, and HT/T_2 gas releases.
- **Transport and dispersion based on environmental conditions specific to the site under study** – The deposition velocity depletion scaling parameter is developed using characteristics of the Savannah River Site. The full UFOTRI computer model suggests that a deposition velocity of 0.5 cm/s is an appropriate value for the soil and vegetation characteristics of SRS. Its use in simplified model applications is bounding for certain situations but non-conservative compared to the full UFORTI simulation in others. If applied to a different, non-tritium specific model such as MACCS2, care should be exercised in choosing other factors such as the exposure time and the resuspension factor.
- **Dose Conversion Factor for oil-based species** – Consideration of tritiated-oil STCs as part of some tritium source terms yields a dose conversion factor approximately a factor of eight larger than tritium oxide. This scales proportionately to larger doses and is primarily due to the organically-bound tritium (OBT) dose component to the body. This assessment is strongly dependent on the assumption that the post-event airborne STC species is the same as the pre-event STC inventory.

It is clear from the trends and results reported here that a full model application of conservatively chosen source terms and use of site-specific parameter values are preferred analysis approaches. Several tritium-specific computer models are available that allow this rigor, of which UFOTRI is the analysis method applied here. While use of implied deposition model may be expedient to a full consequence analysis, it is difficult to determine whether or not the results are bounding. In other words, the conservative outcome that is desirable in safety basis calculations may be indeterminate in applying a computer model of this nature. Finally, tritium species identity in all situations should be confirmed to ensure that uptake (dose) parameters are correctly specified.

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REFERENCES

1. U.S. DEPARTMENT OF ENERGY, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports*, DOE-STD-3009-94, Change Notice 3, , Washington, DC, March 2006.
2. U.S. DEPARTMENT OF ENERGY, *Implementation Guide for Use in Developing Documented Safety Analyses to Meet Subpart B of 10 CFR 830*, DOE G 421.1-2, Washington, DC, 10-24-01.
3 U.S. DEPARTMENT OF ENERGY, *Nonreactor Nuclear Safety Design Criteria and Explosive safety Criteria Guide for Use with DOE O 420.1, Facility Safety*, DOE G 420.1-1, Washington, DC, 3-28-00.
4. U.S. DEPARTMENT OF ENERGY, *Radiological Control Programs for Special Tritium Compounds, Facility Safety*, DOE-HDBK-1184-2004, Washington, DC, (September 2004).
5. A.C. CHAMBERLAIN, *Aspects of Travel and Deposition of Aerosol and Vapour Clouds, Atomic Energy Research Establishment*, Harwell, United Kingdom, British Report, AERE-HP/R 1261, (1953).
6. H.N. JOW, J.L. SPRUNG, J.A. ROLLSTIN, L.T. RITCHIE, AND D.I. CHANIN, *MELCOR Accident Consequence Code System (MACCS) Model Description*, Sandia National Laboratories,

NUREG/CR-4691 (SAND86-1562) Volume 2 (February 1990).
7. W. RASKOB, *Modeling of Tritium Behavior in the Environment*, Fusion Technol., 21, pp. 636-644 (March 1992).
8. D.I. CHANIN AND M.L. YOUNG, *Code Manual for MACCS2: Volume 1, User's Guide*; NUREG/CR-6613 (SAND97-0594), Sandia National Laboratories, published by the U.S. Nuclear Regulatory Commission, Washington, DC, 1998.
9. W. RASKOB, *UFOTRI: Program for Assessing the Off-Site Consequences From Accidental Tritium Releases*, Kernforschungszentrum Karlsruhe GmbH, Karlsruhe, KfK 4605, (July 1990).
10. W. RASKOB, D*escription of the New Version 4.0 of the Tritium Model UFOTRI Including User Guide*, Kernforschungszentrum Karlsruhe GmbH, Karlsruhe, KfK 5194, (August 1993).
11. S. DIABATE AND SIEGFRIED STRACK, Organically Bound Tritium, *Health Physics*, **65**(6), 698 (1993).
12. U.S. DEPARTMENT OF ENERGY, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*, DOE-HDBK-3010-94, U.S. Department of Energy, Washington, DC, Change Notice 1 (March 2000).
13. U.S. DEPARTMENT OF ENERGY, *Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports*, DOE-HDBK-3010-94, U.S. Department of Energy, Washington, DC, Change Notice 1 (March 2000).
14. BIOMOVS, Biospheric Modeling Validation Study, Technical Report No. 13, (1996).
15. K.R. O'KULA, J.M. EAST, AND D.R. MARX, *A Posteriori Verification and Validation of a Tritium Dispersion & Consequence Model*, WSRC-MS-2000-00075, 2001 EFCOG Safety Analysis Working Group Workshop, (June 2001).
16. C.H. HUNTER, *Revised Onsite Meteorological Data for Emergency Planning Hazards Assessments*, SRT-ETS-931167, Savannah River Technology Center, (November 30, 1993).
17. U.S. DEPARTMENT OF ENERGY, DOE Handbook, *Primer on Tritium Safe Handling Practices*, U. S. Department of Energy (December 1994).
18. ICRP, *Dose Coefficients for Intakes of Radionuclides by Workers: A Report of a Task Group of Committee 2 of the International Commission on Radiological Protection Replacement of ICRP Publication 61*, ICRP Publication 68, Annals of the ICRP, Volume 24, Number 2, Pergamon Press, New York, NY (1995).
19. ICRP, *Age-dependent Doses to the Members of the Public from Intake of Radionuclides: Part* 5, ICRP Publication 72, Annals of the ICRP, Volume 26, Number 1, Pergamon Press, New York, NY (1996).
20. ICRP, *The ICRP Database of Dose Coefficients: Workers and Members of the Public, Version 2.0.1*, Pergamon Press, New York, NY, (2001).