APPENDIX C.
METHODS OF DOSE CALCULATIONS

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Introduction

Lawrence Livermore National Laboratory (LLNL) calculates doses to the public for radiation protection purposes using the U.S. Environmental Protection Agency's (EPA's) model, CAP88-PC (Parks 1992, 1997). Modeled doses are discussed in detail in Chapter 13. Emission rates of radionuclides from stacks and diffuse sources are used as input to CAP88-PC. Alternatively, doses may be calculated from concentrations in air, vegetation, water, and wine measured during routine monitoring. Because CAP88-PC generally overestimates doses to the public in the direction towards which the prevailing wind blows, doses calculated from environmental measurements for these wind directions should be lower, even when assumptions about intake rates are conservative. Regardless of wind direction, doses calculated from measured environmental concentrations will be more accurate and have less uncertainty than doses calculated using a dispersion model.

Although various radionuclides are released to the environment in small quantities by LLNL activities, tritium is the only radionuclide that can be measured in the local food chain. Furthermore, tritium is the radionuclide primarily responsible for the low dose received by the public. Thus, although some of the equations presented in this chapter can be applied to any radionuclide, only the dose from tritium will be calculated and discussed here.

In this appendix, two different models that may be used to calculate dose from measured environmental concentrations are presented. One model, the Nuclear Regulatory Commission's (NRC) Regulatory Guide 1.109 (U.S. NRC 1977), has been used by LLNL since 1979 (Silver et al. 1980) to calculate ingestion doses from measured environmental concentrations of tritiated water (HTO). Doses have been based on the assumption of maximum annual intake of water, leafy vegetables, milk and meat. Inhalation doses have also been calculated based on measured air concentrations.

Equations that derive bulk transfer parameter values used in Chapters 5, 7, and 11 to calculate doses from inhalation and ingestion of water and locally produced foodstuffs based on measured concentrations in the various media are presented here. Similarly, bulk transfer parameter values are derived to calculate the inhalation dose from predicted air concentrations of tritiated hydrogen gas (HT) and the immersion dose from swimming. In addition, for comparison, bulk transfer parameter values based on the NRC 1.109 equations with different assumptions about intake rates are presented.

Doses that account for the contribution of organically bound tritium (OBT) are also calculated using NRC 1.109 HTO concentrations and consumption rates. These doses are compared with those predicted for 2002 by NEWTRIT, the other model used to calculate doses from environmental measurements in this appendix. NEWTRIT (Peterson and Davis 2002), an improved tritium model to calculate dose contributions from OBT and doses from releases of both HTO and HT, has recently been coded into

GENII-NESHAPs by the EPA. GENII-NESHAPs is a version of GENII (Napier et al. 1988) developed for compliance with the National Emissions Standards for Hazardous Air Pollutants ((NESHAPs; 40 CFR Part 61, Subpart H). GENII-NESHAPs is undergoing peer review in 2003.

Overview of CAP88-PC, NRC 1.109, and NEWTRIT

The annual whole-body dose rate from ingestion of a particular food or drink is expressible as a product of three factors, regardless of model. These three factors are (1) the rate at which the food or drink is consumed (e.g., kg/y), (2) the radionuclide concentration in the food or drink (e.g., Bq/kg), and (3) the dose coefficient for the radionuclide (e.g., µSv/Bq). Calculating the dose contribution from inhalation will be similar (e.g., $m^3/y \times Bq/m^3 \times \mu Sv/Bq$).

Each of the three models, CAP88-PC, NRC 1.109, and NEWTRIT, approaches this calculation of dose from exposure to environmental tritium in a somewhat different way. CAP88-PC and NRC 1.109 only calculate doses from HTO inhalation and ingestion, while NEWTRIT calculates doses from inhalation of HTO and HT and ingestion of HTO and OBT.

Given a source term (Ci/y), CAP88-PC calculates the air concentration (pCi/m^3) at a particular location using a Gaussian dispersion model. Assuming a default annual absolute humidity of 8 g/m^3, CAP88-PC calculates the concentration of HTO in air moisture. The HTO in vegetables, milk and meat is assumed in equilibrium with the HTO in air moisture. The daily diet is assumed to consist of 1560 g of water obtained from food and 1440 g of drinking water (Moore et al. 1979). The fractions of daily water obtained from food that represent vegetables, milk, and meat are 0.505, 0.310, and 0.185 respectively. For an atmospheric release of HTO, drinking water is assumed to have only 1% the tritium concentration of the air moisture because drinking water is assumed to be groundwater.

Measured concentrations of HTO in air (for inhalation dose), water (for drinking water dose), and vegetation (for food ingestion dose) can be used in NRC 1.109 to calculate doses from exposure to tritium. The equations are shown in detail in the next section. Historically at LLNL, concentrations in milk and meat have been calculated based on the assumption that pasture ingested by animals has the same tritium concentration as the measured concentration of HTO in vegetation. Ingestion dose to man was then calculated based on maximum annual intake rates of leafy vegetables, milk, and meat.

This approach, although still used for calculations in Chapter 11 and demonstrated in the equations presented here, ignored the important contribution of tritium in the animal's drinking water to the concentration in the animal product. It also ignored the potential contribution to dose from vegetables other than leafy ones. For comparison with doses based on the highly unrealistic assumption of maximum annual intake that are reported in Chapters 5, 7, and 11, dose calculations using NRC 1.109 will be presented that are based on an average annual intake of a fairly complete diet. The milk and meat concentrations that comprise that diet include the contributions from HTO in both ingested vegetation and drinking water.

NEWTRIT calculates doses from releases of HT and HTO based on predicted or measured air concentrations. The default absolute humidity, like that in CAP88-PC, is 8 g/m^3, but a site-specific absolute humidity may be substituted. The model is formulated in terms of the tritium-to-hydrogen ratio in each environmental compartment. However, with each transfer, a small reduction in the ratio is introduced to reflect dilution observed in nature. Drinking water for animals is assumed to have half the concentration of air moisture because small bodies of water exhibit that level of contamination near an atmospheric source of tritium. Drinking water for people is assumed to have 10% the HTO concentration of air moisture, which is the concentration of tritium expected in a large body of water near an atmospheric source of tritium. NEWTRIT accounts for dose from ingested OBT, as well as HTO. Based on experimental data, NEWTRIT accounts for the conversion of HT to HTO in soil and the consequent emission of HTO to the atmosphere from soil. Doses calculated from a release of HT include inhalation of HT, inhalation and skin-absorption of HTO, ingestion of HTO from drinking water and foods, and ingestion of OBT from foods. Doses from a unit release of HT are expected to be about 10% those from a unit release of HTO, given the default absolute humidity. The diet in NEWTRIT is the same as that in GENII (Napier et al. 1988), and it is assumed that all food ingested has been grown at the location at which air concentrations have been estimated.

Each model recommends different consumption rates (see **Table C-1**). In Appendix E of the NRC Regulatory Guide 1.109, two annual diets are recommended, one for maximum intake and one for average intake. The diet shown for CAP88-PC is derived from water equivalent annual ingestion rates (kg/y) of vegetables, milk, and meat based on values for fresh weight, protein, carbohydrate, and fat fractions (Ciba-Geigy Ltd. 1981). Assumptions about the fractions of fruit, grain, root crops, and fruit vegetables that make up “plant products” come from NRC Regulatory Guide 1.109. Clearly, based on consumption alone (see **Table C-1**), doses from these models will be different.

Table C-1. Examples of annual inhalation and ingestion rates

	NRC 1.109 maximum	NRC 1.109 average	CAP88-PC	NEWTRIT
Leafy vegetables/other plant products (kg)	64/520	—[a]/190	—[a]/333	15/276
Milk (L)	310	110	183	230
Meat (kg)	110	95	113	98.5
Drinking water (L)	730	370	526	440
Inhalation (m^3)	8000	8000	8038	8521

a Leafy vegetables are included with the other plant products.

Each of the three models uses different dose coefficients. The dose coefficients used in the calculations of HTO dose from NRC 1.109 were obtained from the committed dose equivalent tables for DOE dose calculations (U.S. DOE 1988). They are similar to those specified in ICRP 72, *Age dependent doses to* *members of the public from intake of radionuclides* (ICRP 1996), which are used in NEWTRIT. The dose calculation for inhalation of tritiated hydrogen (HT) gas uses a dose coefficient from ICRP 71, (ICRP 1995). A comparison of dose coefficients is shown in **Table C-2**.

Table C-2. Comparison of dose coefficients for tritium (μSv/Bq)

	DOE	CAP88-PC[a]	ICRP
HTO (inhalation, skin absorption)[b]	1.73×10^{-5}	3.41×10^{-5}	1.8×10^{-5}
HT (inhalation)	3.31×10^{-13}[c]	—[d]	1.8×10^{-9}
HTO (ingestion)	1.73×10^{-5}	2.43×10^{-5}	1.8×10^{-5}
OBT (ingestion)	—[d]	—[d]	4.2×10^{-5}

a Computer code required by the EPA for modeling air emissions of radionuclides

b CAP88-PC's dose coefficient includes skin absorption. Because skin absorption and inhalation have the same dose conversion factor, and the uptake of the body by skin absorption is 0.5 times the uptake by inhalation, DOE and ICRP account for skin absorption dose by multiplying the inhalation dose by a factor of 1.5.

c Units are μSv/Bq × s/m^3 because dose is considered external from air submersion.

d Not taken into account

Assumptions play such a very important part in predicting dose that assumptions must be clearly elucidated, so that the apparent differences in dose predictions may be understood.

Dose Calculation Methods

Although the analytical laboratories report concentrations in pCi and CAP88-PC's dose coefficients have units of mrem/pCi, LLNL uses Système Internationale (SI) units of becquerel (Bq) for concentration and millisievert (mSv), microsievert (μSv), or nanosievert (nSv) for dose in compliance with Presidential Executive Order 12770, Metric Usage in Federal Government Programs (July 25, 1991). The conversion factors are as follows:

1 Bq = 27 pCi
1 mSv = 100 mrem; 1 μSv = 0.1 mrem; 1 nSv = 0.1 μrem

All units have been converted to SI units throughout this appendix.

Note: In some of the following equations, the dimensions associated with a multiplicative factor are not shown explicitly; the dimensions of the dependent variable and measured quantity are shown explicitly.

In the past, median or maximum concentrations in environmental media were used to calculate doses. The median is used as the default average for the Site Environmental Annual Report for a variety of reasons. However, for calculations of dose from inhalation and ingestion, the mean, not the median, should be used. For example, if a cow ingests equal quantities of vegetation quarterly, the cow's exposure is properly assessed by the mean. Thus, for dose calculations, the use of the mean is justified and will be used henceforth.

Dose Calculation Methods for Chapters 5, 7, and 11 Using NRC 1.109

In the following subsections, equations from NRC 1.109 provide guidance to estimate the annual dose from inhalation and from tritium ingested from water (or wine) and food (e.g., leafy vegetables, milk, and meat) based on mean or maximum observed values for 2002.

Calculating Annual Dose from Potable Water (Chapter 7)

The effective dose equivalent for tritium in drinking water (D_{water}) in µSv/y is calculated using the following equation:

$$D_{\text{water}}\ (\mu\text{Sv/y}) = U_{\text{w}} \times DC_{\text{HTO}} \times C_{\text{w}} \qquad \text{(C-1)}$$

where

U_{w} = water consumption rate (L/y)

DC_{HTO} = dose coefficient for HTO (µSv/Bq) (U.S. DOE 1988)

C_{w} = mean or maximum concentration of tritium measured in drinking water (Bq/L)

The tritium dose from ingestion of potable water, assuming maximum intake of water, is then

$$\text{D}_{\text{water}}\ (\mu\text{Sv/y}) = 730\ (\text{L/y}) \times 1.73 \times 10^{-5}\ (\mu\text{Sv/Bq}) \times C_{\text{w}}\ (\text{Bq/L})$$

$$= 1.3 \times 10^{-2} \times C_{\text{w}}\ (\text{Bq/L})$$

In Chapter 7, this equation is used to estimate doses from drinking water. Assuming different quantities are consumed, this equation can also be used to calculate the effective dose equivalent from wine (see Chapter 11).

Calculating Annual Dose from Food Ingestion (Chapter 11)

The effective dose equivalent from ingestion of food (D_{food}) is calculated by summing the dose contributions from leafy vegetables, meat, and milk to the diet. The concentrations in these foodstuffs are calculated from measured concentrations in annual grasses or weeds (see Chapter 11) using the equations from NRC Regulatory Guide 1.109.

Leafy Vegetables: For dose calculations, the assumption is that the leafy vegetables are 100% water; therefore, Bq/L = Bq/kg fresh weight.

$$D_{\text{veg}}\ (\mu\text{Sv/y}) = U_{\text{veg}} \times DC_{\text{HTO}} \times C_{\text{veg}} \qquad \text{(C-2)}$$

where

U_{veg} = intake rate of leafy vegetables (kg/y)

DC_{HTO} = dose coefficient for HTO (µSv/Bq) (U.S. DOE 1988)

C_{veg} = mean or maximum concentration measured in annual grasses and weeds (Bq/L)

The tritium dose from ingestion of leafy vegetables, assuming maximum intake, is then

$$\begin{aligned} D_{\mathrm{veg}}\,(\mu\mathrm{Sv/y}) &= 64\ (\mathrm{kg/y}) \times 1.73 \times 10^{-5}\ (\mu\mathrm{Sv/Bq}) \times C_{\mathrm{veg}}\,(\mathrm{Bq/kg}) \\ &= 1.1 \times 10^{-3} \times C_{\mathrm{veg}}\,(\mathrm{Bq/L}) \end{aligned}$$

Meat (Beef): To calculate dose from ingestion of meat, first the concentration of tritium in the meat must be calculated from the measured mean or maximum concentration of tritium in vegetation.

$$C_{\mathrm{meat\_veg}} = F_{\mathrm{f}}\,(\mathrm{d/kg}) \times Q_{\mathrm{f}}\,(\mathrm{kg/d}) \times C_{\mathrm{veg}}\,(\mathrm{Bq/kg}) \times \exp(-\lambda_{\mathrm{i}} t_{\mathrm{s}}) \qquad \text{(C-3)}$$

where

F_{f} = average fraction of an animal's daily intake of radionuclide appearing in each kilogram of animal flesh [(Bq/kg) in meat per (Bq/d) ingested by the animal] = 1.2×10^{-2} d/kg

Q_{f} = amount of feed consumed = 50 kg/d

C_{veg} = mean or maximum concentration measured in vegetation (Bq/kg)

λ_{i} = radiological decay constant = 1.5×10^{-4} /d

t_{s} = time from slaughter to consumption = 20 d

Therefore

$$\begin{aligned} C_{\mathrm{meat\_veg}} &= 1.2 \times 10^{-2}\ (\mathrm{d/kg}) \times 50\ (\mathrm{kg/d}) \times C_{\mathrm{veg}}\,(\mathrm{Bq/kg}) \times \exp[(-1.5 \times 10^{-4}) \times 20] \\ &= 0.6 \times C_{\mathrm{veg}}\,(\mathrm{Bq/kg}) \end{aligned}$$

The dose from ingestion of meat is calculated:

$$D_{\mathrm{meat}}\,(\mu\mathrm{Sv/y}) = U_{\mathrm{meat}} \times C_{\mathrm{meat}} \times DC_{\mathrm{HTO}} \qquad \text{(C-4)}$$

where

U_{meat} = maximum intake rate (kg/y)

C_{meat} = predicted concentration in meat at time of consumption from the contribution of vegetation = C_{meat_veg} (Bq/kg)

DC_{HTO} = dose coefficient for HTO (µSv/Bq) (U.S. DOE 1988)

The tritium dose rate from meat consumption is then

$$D_{meat}\ (\mu Sv/y) = 110\ (kg/y) \times [0.6 \times C_{veg}\ (Bq/kg)] \times 1.73 \times 10^{-5}\ (\mu Sv/Bq)$$

$$= 1.1 \times 10^{-3} \times C_{veg}\ (Bq/L)$$

Cow Milk: To calculate dose from ingestion of milk, first the concentration of tritium in the milk must be calculated from the measured mean or maximum tritium concentration in vegetation.

$$C_{milk\_veg} = F_m\ (d/L) \times Q_f\ (kg/d) \times C_{veg}\ (Bq/kg) \times \exp(-\lambda_i t_f) \qquad (C\text{-}5)$$

where

F_m = average fraction of an animal's daily intake of radionuclide appearing in each kilogram of milk [(Bq/L) in milk per (Bq/d) ingested by the animal] = 1.0×10^{-2} d/L

Q_f = amount of feed consumed by the milk cow = 50 kg/d

C_{veg} = mean or maximum concentration measured in vegetation (Bq/kg)

λ_i = radiological decay constant = 1.5×10^{-4} /d

t_f = time from milking to milk consumption = 2 d

Therefore

$$C_{milk\_veg} = 1.0 \times 10^{-2}\ (d/L) \times 50\ (kg/d) \times C_{veg}\ (Bq/kg) \times \exp[(-1.5 \times 10^{-4}) \times 2]$$

$$= 0.5 \times C_{veg}\ (Bq/L)$$

The dose from consumption of milk is calculated:

$$D_{milk}\ (\mu Sv/y) = U_{milk} \times C_{milk} \times DC_{HTO} \qquad (C\text{-}6)$$

where

U_{milk} = maximum intake rate (L/y)

C_{milk} = predicted concentration in milk at time of consumption from the contribution of vegetation = C_{milk_veg} (Bq/kg)

DC_{HTO} = dose coefficient for HTO (µSv/Bq)

The tritium dose rate from directly consumed milk is then

$$D_{milk}\ (\mu Sv/y) = 310\ (L/y) \times [0.5 \times C_{veg}\ (Bq/kg)] \times 1.73 \times 10^{-5}\ (\mu Sv/Bq)$$

$$= 2.7 \times 10^{-3} \times C_{veg}\ (Bq/L)$$

Total Food Ingestion: The annual dose from food ingestion as calculated in Chapter 11 based on measured HTO in vegetation is then:

$$D_{food}\ (\mu Sv/y) = D_{veg} + D_{meat} + D_{milk} \qquad (C\text{-}7)$$

where

D_{veg} = dose from ingestion of leafy vegetables (µSv/y)

D_{meat} = dose from ingestion of meat (µSv/y)

D_{milk} = dose from ingestion of milk (µSv/y)

Therefore

$$D_{food}\ (\mu Sv/y) = 1.1 \times 10^{-3} \times C_{veg}\ (Bq/L) \qquad \text{(dose from leafy vegetables)}$$

$$+\ 1.1 \times 10^{-3} \times C_{veg}\ (Bq/L) \qquad \text{(dose from meat)}$$

$$+\ 2.7 \times 10^{-3} \times C_{veg}\ (Bq/L) \qquad \text{(dose from milk)}$$

$$= 4.9 \times 10^{-3} \times C_{veg}\ (Bq/L)$$

Calculating Annual Inhalation and Skin Absorption Doses of HTO (Chapter 5)

Doses caused by inhalation of tritium-contaminated air can be estimated in a way analogous to the preceding treatment of ingestion doses. The starting point is to evaluate the tritium concentration in air, χ (Bq/m^3), at the location of interest. Measurements of tritium in air are found in Chapter 5.

The dose from HTO arises from the processes of inhalation and skin absorption. For inhalation/skin absorption dose, the known concentration of tritium in the air is multiplied by the inhalation rate of a human to obtain the number of becquerels of tritium inhaled. Dose coefficients provided by the DOE (U.S. DOE 1988) are used to relate the intake of radioactive material into the body to dose commitment. The dose coefficient for inhalation is the same as for ingestion. However, to account for skin absorption, the inhalation factor must be multiplied by 1.5. These dose factors provide estimates of the 50-year dose from a one-year intake of radioactivity.

The inhalation/skin absorption dose is expressible as

$$D_{\mathrm{inh/sa}}\,(\mu\mathrm{Sv/y}) = 1.5 \times U_{\mathrm{air}} \times C_{\mathrm{air}} \times DC_{\mathrm{HTO\_inh}} \qquad \text{(C-8)}$$

where

1.5 = factor that accounts for skin absorption

U_{air} = air intake rate ($\mathrm{m^3/y}$)

C_{air} = mean HTO concentration measured in air at the receptor ($\mathrm{Bq/m^3}$)

$DC_{\mathrm{HTO\_inh}}$ = dose coefficient for inhalation (µSv/Bq) (U.S. DOE 1988)

The whole-body inhalation/skin-absorption dose rate from HTO is then

$$D_{\mathrm{inh/sa}}\,(\mu\mathrm{Sv/y}) = 1.5 \times 8000\ \mathrm{m^3/y} \times C_{\mathrm{air}} \times 1.73 \times 10^{-5}\ \mu\mathrm{Sv/Bq}$$

$$= 0.21 \times C_{\mathrm{air}}\,(\mathrm{Bq/m^3})$$

Doses in Chapter 5 are calculated as shown here. The breathing rate of 8000 $\mathrm{m^3/y}$ is that of NRC 1.109.

Guidance to Calculate Annual Ingestion Dose with NRC 1.109 Using Modified Assumptions: Drinking Water for Animals and Annual Average Ingestion Rates for People

The calculations shown above of ingestion dose for Chapter 11, historically used to calculate doses from measurements at LLNL, do not account for ingestion of tritiated drinking water by animals, and yet drinking water is an important pathway. In 1998, in this appendix, a new approach to calculating the ingestion dose using NRC 1.109 was introduced that included drinking water for animals. In 1999, two further changes were introduced: (1) the annual ingestion rate for an individual was changed to include produce as well as leafy vegetables and (2) average ingestion rates replaced maximum ingestion rates (see **Table C-1**).

To calculate concentrations of tritium in meat and milk resulting from ingestion of water, the contribution of drinking water must be calculated using eqs C-3 and C-5 with two substitutions: (1) the daily intake of water (50 L/d for beef cattle and 60 L/d for milk cows) must replace daily intake of pasture and (2) the measured concentration in potable water must replace the measured concentration in vegetation. When dose is calculated using eqs C-4 and C-6, the tritium contributed by drinking water must be added to the tritium contributed by the vegetation to obtain the concentration in meat or milk from both ingestion sources.

To calculate dose from average rather than maximum ingestion rates, the average NRC 1.109 consumption rates from **Table C-1** are substituted into eqs C-1, C-2, C-4, and C-6.

Complete equations that account for these assumptions may be found in Larson et al. (2000). Bulk transfer factor parameter values based on these assumptions have been calculated using eqs C-1 through C-6. They are summarized and compared in **Table C-3** with the values used for the calculations in Chapters 5, 7, and 11.

Table C-3. Comparison of the two sets of bulk transfer factors based on different assumptions to calculate doses using NRC 1.109

Doses	Assumptions for SAER	Alternate assumptions: tritium in milk and meat comes from pasture and drinking water; average annual diet		
Inhalation and skin absorption: $D_{inh/sa}$	See Chapter 5 $0.21 \times C_{air}$ (Bq/m^3)	$0.21 \times C_{air}$ (Bq/m^3)		
Drinking water: D_{water}	See Chapter 7 $1.3 \times 10^{-2} \times C_w$	$6.4 \times 10^{-3} \times C_w$		
Food Ingestion:	See Chapter 11 Factor x C_{veg} (Bq/kg)	Factor x C_{veg} (Bq/kg)		Factor x C_w (Bq/L)
D_{veg}	1.1×10^{-3}	3.3×10^{-3}	+	NA
D_{meat}	1.1×10^{-3}	9.9×10^{-4}	+	9.9×10^{-4}
D_{milk}	2.7×10^{-3}	9.5×10^{-4}	+	1.1×10^{-3}

Method to calculate dose from ingestion of OBT

Models that account only for dose from HTO have come under attack in recent years. As shown in **Table C-2**, the dose coefficient for OBT is 2.3 times greater than that of HTO. When it is assumed (as in CAP88-PC and NRC 1.109) that all ingested tritium is HTO, there is a possibility, depending on other assumptions in the models, that dose may be underestimated. It is easy enough to calculate the probable contribution of OBT to dose, even from a model that only calculates concentrations of HTO and dose from HTO.

At LLNL, the HTO concentration of the plant water is measured in Bq/L. The concentration of tritium in fresh weight plant is the sum of the tritium in the water fraction (HTO) plus the tritium in the dry matter fraction (OBT):

$$\text{Bq/kg fresh weight plant} = (\text{Bq/ L (measured HTO)} \times F_{fw}) + (\text{Bq/ L (measured HTO)} \times F_{dm} \times W_{eq}) \qquad \text{(C-9)}$$

where

F_{fw} = water fraction of the plant (L/kg)

F_{dm} = dry matter fraction of the plant (kg/kg)

W_{eq} = water equivalent factor (L/kg) = amount of water generated through the combustion of the dry material in the sample = [(percent protein × 0.07) + (percent fat × 0.12) + (percent carbohydrate × 0.062)]/ 100 × (1/fraction of mass of water that is hydrogen)

where

0.07 = fraction of hydrogen in proteins

0.12 = fraction of hydrogen in fats

0.062 = fraction of hydrogen in carbohydrates

2/18 = fraction of mass of water that is hydrogen

Values of water fractions and fractions of protein, fat, carbohydrate, and fiber for a wide variety of foodstuffs can be found in Ciba-Geigy Ltd. (1981). The W_{eq} varies with the type of food and can be calculated from these data. A median value of W_{eq} for a normal array of vegetables is about 0.6 L/kg.

Similarly, concentrations of HTO and OBT per kilogram milk or meat can be estimated based on the total concentrations of milk and meat calculated using eqs C-3 and C-5, including the contribution of drinking water. A median value of W_{eq} for animal products is about 0.8 L/kg.

Examples of concentrations of various foodstuffs based on the 2002 mean tritium concentrations in plant water (4.7 Bq/L) and rainwater (2.3 Bq/L) at VIS (**Table C-4**) are shown below. These equations follow the format of eq C-9, where the total concentration of tritium per kilogram edible food is the sum of the HTO and OBT contributions, respectively.

Lettuce $(4.7 \times 0.948) + (4.7 \times 0.052 \times 0.602) = 4.46 + 0.15 = 4.61$ Bq/kg fresh weight

Potato $(4.7 \times 0.798) + (4.7 \times 0.202 \times 0.568) = 3.75 + 0.54 = 4.29$ Bq/kg fresh weight

Whole milk $(3.73 \times 0.885) + (3.73 \times 0.115 \times 0.746) = 3.30 + 0.32 = 3.62$ Bq/kg fresh weight

Lean sirloin $(4.20 \times 0.718) + (4.20 \times 0.282 \times 0.724) = 3.02 + 0.86 = 3.88$ Bq/kg fresh weight

To calculate dose that accounts for OBT, the concentration of HTO or OBT in each foodstuff must be multiplied by the appropriate dose coefficient (**Table C-2**) and by the quantity consumed. The total food ingestion dose is then the sum of the HTO and OBT dose contributions.

Method to calculate dose from inhalation of HT

In the recent past, HT doses were treated as immersion doses (Eckermann and Ryman 1993) because HT has a low-energy beta particle and behaves similarly to ^{41}Ar. However, the dose from HT is dominated by the small fraction that is metabolized. HT is therefore treated as a soluble gas (ICRP 1995), and an inhalation dose is calculated.

For tritium gas (HT), an inhalation dose is expressible as

$$D_{inh\_HT}\ (\mu Sv/y) = C_{air\_HT} \times U_{air} \times DC_{HT} \qquad \text{(C-10)}$$

where

C_{air_HT} = concentration of HT in air at location X; estimated by dispersion modeling (Bq/m^3)

U_{air} = air intake rate (m^3/y)

DC_{HT} = effective dose per unit intake (µSv/Bq) (ICRP 1995)

Therefore

$$D_{inh\_HT}\ (\mu Sv/y) = C_{air\_HT}\ (Bq/m^3) \times 8000\ m^3/y \times 1.8 \times 10^{-9}\ \mu Sv/Bq$$

The tritium dose rate from inhalation of HT is then (based on predicted HT in air):

$$D_{inh\_HT}\ (\mu Sv/y) = 1.4 \times 10^{-5} \times C_{air\_HT}\ (Bq/m^3)$$

Method to calculate dose from swimming

Immersion in water is another pathway to dose from tritium because tritium can be absorbed through the skin. The intake of water by skin diffusion is 0.4 mL/min (Osborne 1968). A high estimate of time spent swimming in the LLNL pool would be 250 hours a year. The amount of water absorbed through the skin in this period would be 6 L.

Dose from immersion in water can be expressed as:

$$D_{imm\_HTO}\ (\mu Sv/y) = C_{pool}\ (Bq/L) \times U_{pool}\ (L/y) \times DC_{HTO}\ (\mu Sv/Bq) \qquad \text{(C-11)}$$

where

C_{pool} = mean annual concentration of HTO in the LLNL swimming pool (Bq/L)

U_{pool} = intake rate of water through the skin (L/y)

DC_{HTO} = effective dose per unit intake HTO (µSv/Bq) (ICRP 1996)

The whole-body skin absorption dose from swimming is:

$$D_{imm\_HTO}\ (\mu Sv/y) = C_{pool}\ (Bq/L) \times 6\ L/y \times 1.8 \times 10^{-5}\ \mu Sv/Bq$$

$$= 1.1 \times 10^{-4}\ C_{pool}\ (Bq/L)$$

Dose Predictions

Regulatory Dose Predictions

Observed and Predicted Input to Models

Concentrations of tritium in air (Chapter 5) are monitored at eight perimeter locations, including the Visitors Center (VIS), which is a convenient location for comparing doses from different modeling approaches because measurements of tritium in vegetation and rainfall are also taken at VIS. Furthermore, VIS is close to the location of the site-wide maximally exposed individual.

Mean concentrations measured in the air, vegetation (Chapter 11) and rainwater (Chapter 7) for VIS are shown in **Table C-4** along with air concentrations at VIS predicted for releases from the Tritium Facility and the Building 612 yard by CAP88-PC. If the contribution of all LLNL sources of tritium had been estimated at VIS, the predicted concentrations of tritium in air would be somewhat higher. The concentrations of tritium in wine (Chapter 11) and the LLNL swimming pool (Chapter 7) are also shown in **Table C-4**.

CAP88-PC doses are calculated based on measured or estimated source terms. Doses using NEWTRIT can be estimated using either observed or predicted air concentrations. Measured concentrations in vegetation, air, and rainfall can be used as input to NRC 1.109 to calculate doses. The assumption for all calculations is that the exposed person never leaves the Visitors Center and is entirely self-sufficient in that all vegetables (including grain) ingested are grown at the Visitors Center. Furthermore, all animals used for food live there too and consume pasture grown there.

Table C-4. Observed tritium concentrations in various environmental media at VIS and in the vicinity of Livermore, and concentrations of HTO and HT in the air at VIS predicted by CAP88-PC from releases from the Tritium Facility and the Building 612 yard. All data are for 2002.

	Mean Observed HTO Concentrations	Predicted Tritium Concentrations
Air concentration (Bq/m^3) at VIS		
HTO	0.064	0.094
HT	n/a[(a)]	0.0048
Vegetation (Bq/L) at VIS	4.7	n/a[(a)]
Rain (Bq/L) at VIS	2.3[(b)]	n/a[(a)]
Livermore Valley Wine (Bq/L)	1.4	n/a[(a)]
LLNL Swimming Pool (Bq/L)	0.47[(b)]	n/a[(a)]

a n/a = not applicable

b = Below the normal limit of detection

Drinking water for both animals and people (in NRC 1.109) is rainwater at the mean concentration for the entire year. The assumption that drinking water has the concentration of rainwater is usually conservative and should result in a higher estimated dose than the true probable dose in the Livermore Valley because Livermore Valley drinking water for people comes primarily from distant sources or from groundwater, neither of which is affected by locally emitted tritium. Drinking water for animals may come from small basins that receive some tritium from rainwater, although the drinking water for animals is expected to have a much lower concentration of tritium than rainwater. The use of different models and different assumptions will result in very different dose predictions (**Table C-5** and **Table C-6**). Because the protection of the public is paramount, it should be shown by more than one model and more than one set of assumptions that the dose to the public is acceptably low.

Comparison of Model Predictions for inhalation and ingestion of HTO: CAP88-PC and NRC 1.109

Results in **Table C-5** compare doses predicted by CAP88-PC and the NRC 1.109 model with two different sets of assumptions. Results for NRC 1.109 in the middle column of **Table C-5** were calculated using the historical assumptions that have been used in the SAER for dose calculations in the appropriate chapters (i.e., no drinking water for animals and maximum annual ingestion rates of leafy vegetables, milk and meat). Numbers for NRC 1.109 in the right-hand column were calculated based on the assumption of drinking water for animals and an annual average diet. All results are based on the assumption that ingested tritium is only HTO.

The CAP88-PC predictions are all higher than either set of NRC results except for drinking water. The default assumption in CAP88-PC is that drinking water is only 1% as contaminated as air moisture (or 0.12 Bq/L in 2002); in NRC 1.109, the assumption has been made that the individual is drinking water with a concentration of 2.3 Bq/L (equal to rainwater). Thus, for 2002, the dose from drinking water in

NRC 1.109 can be as much as nearly 45% of the total dose, depending upon other assumptions, while in CAP88-PC, the drinking water contribution is about 1% of the total dose. This illustrates the importance of tritium concentrations in drinking water to total dose.

Table C-5. Comparison of hypothetical annual doses from only HTO at the Visitors Center

Dose (nSv/y)	CAP88-PC[(a)] (from predicted air concentrations)	NRC 1.109 (from observed concentrations)—SAER assumptions	NRC 1.109 (from observed concentrations)—new assumptions
Inhalation and skin absorption	26	13	13
Vegetables	82	5.2	16
Milk	[50]	13	7.0
Meat	30	5.2	6.9
Drinking water	1.5	30	15
Total ingestion dose (food and water)	114 [164]	53	44
Total dose from HTO	140 [190]	66	58

a Numbers in brackets (e.g., dose from milk) are not calculated for reported LLNL doses. See *LLNL NESHAPs 2000 Annual Report* (Gallegos et al. 2001), *Guidance for Radiological Dose Assessment* (Harrach 1999), and Chapter 13. Doses from CAP88-PC are based on predicted HTO concentrations at VIS for B331 and the B612 yard (**Table C-4**).

Comparison of Model Predictions for HTO inhalation and ingestion and OBT ingestion: NRC 1.109 and NEWTRIT

Using the assumptions of the NRC 1.109 model (animals drink rainwater and the annual diet is average) and estimated concentrations of HTO and OBT in Bq/kg fresh weight of food, doses for total tritium (HTO and OBT) can be calculated for NRC 1.109 (**Table C-6**). The contribution of OBT increases the doses over those shown for NRC 1.109 in **Table C-5** by 31%, 16% and 43% for vegetables (including grain), milk, and meat respectively.

In **Table C-6**, doses from NRC 1.109 that account for OBT are compared with doses calculated by NEWTRIT. Differences are due to different assumptions about diets (see **Table C-1**) and the fact that NEWTRIT's concentrations in vegetables, milk, and meat are higher than those of NRC 1.109. NEWTRIT's concentrations are driven by the tritium concentration in air moisture (8.0 Bq/L, the 2002 mean air concentration divided by the default absolute humidity of 8 g/m^3), which results in a higher concentration in vegetation water (6.4 – 7.2 Bq/L depending upon the type of vegetable) than was observed (4.7 Bq/L). Furthermore, the drinking water tritium contribution to milk is greater for NEWTRIT than for NRC 1.109 for 2002; the contribution of drinking water to meat is approximately the same for the two models. In spite of NEWTRIT's conservative assumption that drinking water has the concentration of 10% that of air moisture, NEWTRIT's drinking water dose is less than half that of NRC

Table C-6. Comparison of hypothetical annual doses from HTO and OBT at the Visitors Center

Dose (nSv/y)	NRC 1.109 (from observed air and vegetation concentrations)[(a)]	NEWTRIT[(b)] for HTO (from observed air concentrations)	NEWTRIT[(b)] for released HTO (from predicted air concentrations)	NEWTRIT[(b)] for released HT (from predicted air concentrations)
Inhalation	13	15	22	0.071
Vegetables[(b)]	21	38	56	0.33
Milk	8.1	24	35	0.16
Meat	9.9	12	18	0.073
Drinking water	15	6.3	9.3	0.031
Total ingestion (food and water)	54	80	118	0.59
Total dose from HTO and OBT	67	95	139	0.67

a This column corresponds to the far right column in **Table C-5** but accounts for OBT.

b The total tritium dose predicted by NEWTRIT for HT and HTO released from the Tritium Facility will be the sum of the NEWTRIT results for predicted air concentrations of HT and HTO or the sum of the HT inhalation doses for predicted air concentrations plus the HTO doses based on observed air concentrations. NEWTRIT was used in default mode.

c Includes leafy vegetables, fruit, fruit vegetables, root vegetables and grain

1.109 because the concentration in rainwater for 2002 (2.3 Bq/L) is more than twice as high as NEWTRIT's drinking water concentration (0.8 Bq/L). Note, however, that both concentrations are below the lower limits of detection and therefore the differences calculated between doses are not very meaningful.

Also shown in Table C-6 is the estimated dose from the release of HT from the Tritium Facility. A tiny contribution to total dose from inhalation (7.4×10^{-5} nSv/y, not shown explicitly) arises from air concentrations of tritiated hydrogen (HT) gas, based on an air concentration of 0.0048 Bq/m^3 estimated by the dispersion model in CAP88-PC. The inhalation dose, shown in Table C-6, from the release of HT is due to conversion of HT to HTO in the soil and the emission of HTO to air. Emitted HTO is incorporated into plants. For 2002, the release rate of HT was very small compared with the release rate of HTO from the Tritium Facility. As a result, the dose from released HT is only about 0.5% that of the dose from the released HTO. Measured HTO concentrations in air and vegetation account for the dose from any HT that has been converted to HTO in the environment.

The assumptions behind the models in Table C-5 and Table C-6 are all designed to predict highly conservative doses for regulatory purposes that will not be exceeded by any member of the public. The lowest dose from Table C-5 and Table C-6 (58 nSv/y for NRC 1.109, assumptions of animal drinking water and average diet) is about a factor of three below the highest dose, which was calculated with CAP88PC for a complete diet.

Realistic Dose Estimates

NEWTRIT is the model best suited for a realistic dose assessment because it accounts for doses from releases of HT and HTO separately and determines the contribution of OBT to dose. Furthermore, its default parameter values may be altered to account for site-specific data. For example, in this calculation, the average absolute humidity for 2002 at LLNL (7.8 g/m^3) was used instead of the default (8 g/m^3). If it were possible for a person to live at the Visitors Center, it would still be highly unlikely that they would spend all their time there, or that all their food would be homegrown. This person also might drink local wine and swim in the LLNL swimming pool. Doses from swimming and drinking wine can be calculated with the equations presented in this appendix. Doses for 2002, based on realistic yet conservative assumptions, are shown in **Table C-7**.

Table C-7. Realistic, yet conservative, assumptions and consequent doses for the tritium exposure of an individual living at the Visitors Center in 2002 based on observed HTO in air concentrations and predicted HT in air concentrations

Source of dose	Annual dose (nSv)	Assumption
Inhalation	9.8	Breathes air at VIS 16 hours a day, all year
Ingesting food, including OBT	14	Raises and eats 50% homegrown leafy vegetables, fruit vegetables, fruits and root crops, no homegrown milk, beef, or grain and 20% homegrown meat (chickens and eggs). Assume the feed for the chickens is 50% homegrown; chickens drink water from puddles at 50% air moisture.
Drinking water	[5.9][a]	Drinks well water at average concentration of California groundwater
Drinking wine	1.3	Drinks one bottle of Livermore Valley wine each week
Immersion	0.020	Swims in the LLNL pool 100 hours per year
Total tritium	25	

a Drinking water dose should not be included in a realistic estimate of the dose impacts of LLNL releases of tritium to the atmosphere because Livermore drinking water is obtained from the South Bay Aqueduct, Lake Del Valle, and various wells, all unaffected by local atmospheric tritium.

The total annual "realistic" tritium dose from LLNL operations (**Table C-7**) is therefore 25 nSv/y, which is a factor of about 7.6 below the maximum dose predicted by CAP88-PC, and a factor of 3.8 below the dose from observed concentrations predicted by NEWTRIT, neither of which accounts for wine intake or swimming. The drinking water dose shown in **Table C-7**, which is entirely due to global sources of tritium, is nearly 25% of the total tritium dose from LLNL operations. This demonstrates how small the impact of LLNL operations is upon dose to the public.

On average the doses presented here are about a thousand times lower than the EPA's radiation dose limit to the member of the public from an atmospheric release (100 µSv/y). CAP88-PC's dose, by far the highest, is just 1.9% of an annual effective dose equivalent of 10 µSv, which corresponds to the National Council on Radiation Protection and Measurements' (1987a) concept of Negligible Individual Risk Level. Thus, even though artificially high, this dose is still small.