Appendix A.
Methods of Dose Calculations

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Introduction

Lawrence Livermore National Laboratory calculates doses to the public for radiation protection purposes using the U.S. Environmental Protection Agency's (EPA's) model, CAP88-PC (Parks 1992), and discusses them in detail in Chapter 13 (Radiological Dose Assessment). Emission rates of radionuclides from stacks and diffuse sources are used as input to CAP88-PC. In addition, doses may be calculated from concentrations in air, vegetation, and water measured during routine monitoring to estimate the potential impact of LLNL operations on surrounding populations. A different model than CAP88-PC is required for these calculations. Because CAP88-PC is expected to over-estimate doses to the public, doses calculated from environmental measurements should be lower, even when assumptions about intake rates are conservative. In Chapters 5, 7, 9, and 11, LLNL has calculated doses from inhalation and ingestion of water and locally produced foodstuffs based on measured concentrations in the various media and con-servative assumptions about intake rates. In this appendix, LLNL calculates doses using different models, compares assumptions, and presents the bulk transfer parameters used to calculate the doses in the chapters.

The data on radionuclide concentrations in air, vegetation, water (i.e., potential drinking water such as rain water), and wine are necessary inputs to the dose-rate equations described here. Although other 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 and is responsible for the dose received by the public. Thus, although the equations presented in this chapter can be applied to any radionuclide, only the dose from tritium will be calculated and discussed here. In the following equations, doses from inhalation and ingestion of vegetables and water or wine are calculated directly from measured tritium concentrations. Doses from ingesting milk and meat are calculated from measured concentrations in vegetation.

Appendix A. Methods of Dose Calculations

Dose Calculation Methods

The dose calculation methods given here for the ingestion and inhalation/skin absorption pathways for tritiated water (HTO) are based on the Nuclear Regulatory Commission (NRC) Regulatory Guide 1.109, *Calculation of Annual Doses to Man from Routine Releases of Reactor Effluent* (U.S. Nuclear Regulatory Commission 1977). The dose coefficients used in these calculations were obtained from the committed dose equivalent tables for DOE dose calculations (U.S. Department of Energy 1988) and are consistent with those specified in ICRP 30, *Limits for Intakes of Radionuclides by Workers* (International Commission on Radiological Protection [ICRP] 1979). The dose calculation for inhalation of tritiated hydrogen (HT) gas uses a dose-rate conversion factor from ICRP 68, *Dose Coefficients for Intakes of Radionuclides by Workers* (ICRP 1994). A comparison of dose coefficients is shown in **Table A-1**.

Table A-1. Comparison of dose coefficients for tritium; units are µSv Bq^{-1}.

	DOE	CAP88-PC[a]	ICRP
HTO (inhalation and skin absorption)	$1.5^{[b]} \times 1.73 \times 10^{-5}$	3.41×10^{-5}	$1.5^{[b]} \times 1.8 \times 10^{-5}$
HT (inhalation)	$3.31 \times 10^{-13[c]}$		1.8×10^{-9}
HTO (ingestion)	1.73×10^{-5}	2.43×10^{-5}	1.8×10^{-5}
OBT[d] (ingestion)			4.2×10^{-5}

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

b   1.5 accounts for dose from HTO absorbed through the skin from air.

c   Units are µSv/Bq $\times$ s/m^{-3} because dose is considered external from air submersion.

d   Organically bound tritium.

Although the analytical laboratories report concentrations in pCi and the DOE's dose-rate conversion factors have units of mrem/pCi, LLNL uses Système Internationale (SI) units of becquerel (Bq) for concentration and millisievert (mSv) or microsievert (µSv) 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

All units have been converted to SI units in the following dose calculations.

The annual whole-body dose rate from ingestion of a particular food or drink is expressible as a product of three factors: the rate at which the food or drink is consumed (e.g., kg/y), the radionuclide concentration (e.g., Bq/kg) in the food or drink, and the dose rate conversion factor (e.g., µSv/Bq) for the radionuclide. In the following subsections, equations of this type are used to estimate the annual dose from tritium

ingested from water (or wine) and food (e.g., leafy vegetables, produce, milk, and meat). Similar formulas are given for the inhalation/skin absorption dose for HTO and inhalation dose for HT.

Different models recommend different consumption rates. In Appendix E of the NRC Regulatory Guide 1.109, two annual diets are recommended, one for maximum intake and one for average intake (see **Table A-2**). Two diets from CAP88-PC are also shown in **Table A-2**. One diet is recommended for all radionuclides except tritium and ^{14}C. The diet shown for tritium has been estimated from the CAP88-PC assumption that daily diet consists of 1638 g of water obtained from food. This assumption accounts for a complete diet with more food than an average person would eat. Values for fresh weight, protein, carbohydrate, and fat fractions, used to estimate the total water content of various foodstuffs, come from Ciba-Geigy (1981). Assumptions about the fractions of fruit, grain, root crops, and fruit vegetables that make up "produce" come from NRC Regulatory Guide 1.109.

Table A-2. Examples of annual inhalation and ingestion rates.

	NRC maximum	NRC average	CAP88-PC tritium	CAP88-PC other nuclides
Leafy vegetables (kg)	64	23 (est)	28	18
Produce (kg)	520	190	274	176
Milk (L)	310	110	185	112
Meat (kg)	110	95	111	85
Drinking water (L)	730	370	0	0
Inhalation (m^3)	8000	8000	8038	8038

It is clear from **Table A-2** that the NRC maximum consumption rates are much higher than the other consumption rates, with the exception of meat. CAP88-PC's (tritium) estimated rates are high but are still relatively low except for meat, and it is known that tritium doses estimated with CAP88-PC are conservative. LLNL has calculated the dose from maximum dietary intake (less produce) since these dose rate formulas were first used in the site environmental annual report (Silver et al. 1980). The NRC's maximum dietary intake is still used to estimate doses from water, food (less produce), and wine in Chapters 5, 7, 9, and 11 so that estimated doses can be compared year after year. In this appendix, however, we will use the average NRC intake plus produce concentrations, assuming (conservatively) that concentrations in produce equal concentrations in grass measured in LLNL's environmental monitoring program. This approach should yield more realistic doses that are nevertheless conservative. After the following equations, the numbers needed to estimate doses for both sets of assumptions will be presented.

Appendix A. Methods of Dose Calculations

Annual Dose from Potable Water

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

$$D_{water} \, (\mu Sv/y) = C_w \times U_w \times DC_{HTO} \qquad\qquad\qquad (A\text{-}1)$$

where

$$
\begin{aligned}
C_w &= \text{concentration of tritium measured in drinking water (Bq/L)} \\
U_w &= \text{water consumption rate (L/y)} \\
DC_{HTO} &= \text{dose coefficient (µSv/Bq) for HTO}
\end{aligned}
$$

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

$$D_{water} \, (\mu Sv/y) \quad 730 \, (L/y) \times 1.73 \times 10^{-5} \, (\mu Sv/Bq) \times C_w \, (Bq/L)$$

$$D_{water} \, (\mu Sv/y) \quad 6.4 \times 10^{-3} \times C_w \, (Bq/L)$$

In Chapter 7, we have used this equation to estimate doses from drinking water; the dose is calculated by multiplying the water concentration by 1.24×10^{-2} (based on annual water intake of 730 L). This equation can also be used to calculate the effective dose equivalent from wine (see Chapter 11).

Annual Dose from Food Ingestion

The effective dose equivalent from ingestion of food (D_{food}) is calculated by summing the contributions from leafy vegetables, produce, milk, and meat to the diet. The concentrations in these foodstuffs are based on measured tritium concentrations in annual grasses (see Chapter 11), and we assume that concentrations in leafy vegetables and produce are similar. Concentrations in milk and meat are calculated from measured concentrations in vegetation using the equations from NRC Regulatory Guide 1.109.

Therefore

$$D_{food} \, (\mu Sv/y) = D_{veg\_and\_prod} + D_{meat} + D_{milk} \qquad\qquad (A\text{-}2)$$

where

$D_{veg\_and\_prod}$ = μSv/y dose from ingestion of leafy vegetables and produce (for calculations in Chapter 11, only leafy vegetables are considered)

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

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

Leafy Vegetation and Produce

For dose calculations, we make the conservative assumption that the leafy vegetation and produce are 100% water; therefore, Bq/L = Bq/kg. Note that the calculations in Chapter 11 are only for leafy vegetables.

$$D_{veg\_and\_prod} (\mu Sv/y) = U_{veg\_and\_prod} \times C_{veg} \times DC_{HTO} \qquad (A\text{-}3)$$

where

$U_{veg\_and\_prod}$ = intake rate (kg/y) of leafy vegetation and produce

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

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

The tritium dose from ingestion of leafy vegetables and produce is then

$$D_{veg\_and\_prod} (\mu Sv/y) = [23 \text{ (leafy)} + 190 \text{ (produce) (kg/y)}] \times 1.73 \times 10^{-5} (\mu Sv/Bq) \times C_{veg} (Bq/kg)$$

$$D_{veg\_and\_prod} (\mu Sv/y) = 3.7 \times 10^{-3} \times C_{veg} (Bq/L)$$

For the calculations in Chapter 11, C_{veg} is multiplied by 1.1×10^{-3} (based on 64 kg annual intake of leafy vegetables).

Note: In this and 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. For example, the above factor 3.7×10^{-3} carries units of $(L \cdot \mu Sv) \div (y \cdot Bq)$.

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Meat (Beef)

The dose from ingestion of meat is calculated:

$$D_{meat} \, (\mu Sv/y) \; = U_{meat} \times C_{meat} \times DC_{HTO} \tag{A-4}$$

where

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

C_{meat} = predicted concentration in meat at time of consumption from the contribution of vegetation (C_{meat_veg}) and drinking water (C_{meat_w})

DC_{HTO} = dose coefficient ($\mu Sv/Bq$) for HTO

and

$$C_{meat\_veg} = \; F_f \; (d/kg) \times Q_f \, (kg/d) \times C_{veg} \, (Bq/kg) \times \exp(-\lambda_i t_s)$$

$$C_{meat\_w} = \; F_f \; (d/kg) \times Q_w \, (kg/d) \times C_w \, (Bq/kg) \times \exp(-\lambda_i t_s)$$

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] (d/kg): $1.2 \times 10^{-2} \, d/kg$

Q_f = amount of feed consumed (kg/d): 50 kg/d

Q_w = amount of water consumed (kg/d): 50 L/d (1 L = 1 kg)

C_{veg} = concentration measured in vegetation (Bq/L)

C_w = concentration measured in drinking water (Bq/L)

λ_i = radiological decay constant (d^{-1}): $1.5 \times 10^{-4} \; d^{-1}$

t_s = time from slaughter to consumption (d): 20 d

Therefore

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

$$C_{meat\_w} = \; 1.2 \times 10^{-2} \; (d/kg) \times 50 \, (L/d) \times C_w \, (Bq/L) \times \exp[(-1.5 \times 10^{-4}) \times 20]$$
$$= \; 0.6 \times C_w \, (Bq/L)$$

The tritium dose rate from meat consumption is then

$$
\begin{aligned}
D_{\text{meat}} \, (\mu\text{Sv/y}) \; = \; & 95 \, (\text{kg/y}) \times \{[0.6 \times C_{\text{veg}} \, (\text{Bq/kg})] + [0.6 \times C_{\text{w}} \, (\text{Bq/L})]\} \\
& \times 1.73 \times 10^{-5} \, (\mu\text{Sv/Bq}) \\
= \; & [9.9 \times 10^{-4} \times C_{\text{veg}} \, (\text{Bq/L})] + [9.9 \times 10^{-4} \times C_{\text{w}} \, (\text{Bq/L})]
\end{aligned}
$$

The dose calculation for meat in Chapter 11 multiplies 1.1×10^{-3} times C_{veg} (based on meat intake of 110 kg/y). In Chapter 11, only the contribution from vegetation ingested by the meat animal is calculated.

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Cow Milk

The dose from consumption of milk is calculated:

$$
D_{\text{milk}} \, (\mu\text{Sv/y}) \; = \; U_{\text{milk}} \times C_{\text{milk}} \times DC_{\text{HTO}} \tag{A-5}
$$

where

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

C_{milk} = predicted concentration in milk at time of consumption from the contribution of vegetation ($C_{\text{milk\_veg}}$) and drinking water ($C_{\text{milk\_w}}$)

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

and

$$
C_{\text{milk\_veg}} \; = \; F_{\text{m}} \, (\text{d/L}) \times Q_{\text{f}} \, (\text{kg/d}) \times C_{\text{veg}} \, (\text{Bq/kg}) \times \exp(-\lambda_{\text{i}} t_{\text{f}})
$$

$$
C_{\text{milk\_w}} \; = \; F_{\text{m}} \, (\text{d/L}) \times Q_{\text{w}_{\text{m}}} \, (\text{L/d}) \times C_{\text{w}} \, (\text{Bq/L}) \times \exp(-\lambda_{\text{i}} t_{\text{f}})
$$

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] (d/L): 1.0×10^{-2} d/L

Q_{f} = amount of feed consumed by the milk cow (kg/d): 50 kg/d

$Q_{\text{w}_{\text{m}}}$ = amount of water consumed by the milk cow (kg/d): 60 L/d (1 L = 1 kg)

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

C_{w} = concentration measured in drinking water (Bq/L)

λ_{i} = radiological decay constant (d^{-1}): 1.5×10^{-4} d^{-1}

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$$t_f = \text{time from milking to milk consumption (d): 2 d}$$

Therefore

$$
\begin{aligned}
C_{\text{milk\_veg}} &= 1.0 \times 10^{-2} \, (\text{d/L}) \times 50 \, (\text{kg/d}) \times C_{\text{veg}} \, (\text{Bq/kg}) \\
&\quad \times \exp[(-1.5 \times 10^{-4}) \times 2] \\
&= 0.5 \times C_{\text{veg}} \, (\text{Bq/L}) \\
C_{\text{milk\_w}} &= 1.0 \times 10^{-2} \, (\text{d/L}) \times 60 \, (\text{L/d}) \times C_w \, (\text{Bq/L}) \times \exp[(-1.5 \times 10^{-4}) \times 2] \\
&= 0.6 \times C_w \, (\text{Bq/L})
\end{aligned}
$$

The tritium dose rate from directly consumed milk is then

$$
\begin{aligned}
D_{\text{milk}} \, (\mu\text{Sv/y}) &= 110 \, (\text{L/y}) \times \{[0.5 \times C_{\text{veg}} \, (\text{Bq/kg})] + [0.6 \times C_w \, (\text{Bq/L})]\} \\
&\quad \times 1.73 \times 10^{-5} \, (\mu\text{Sv/Bq}) \\
&= 9.5 \times 10^{-4} \times C_{\text{veg}} \, (\text{Bq/L}) + 1.1 \times 10^{-3} \times C_w \, (\text{Bq/L})
\end{aligned}
$$

The dose calculation for milk in Chapter 11 multiplies 2.7×10^{-3} times C_{veg} (based on milk intake of 310 L/y). In Chapter 11 only the contribution from vegetation ingested by the cow is calculated.

Whole Body

$$
\begin{aligned}
D_{\text{food}} \, (\mu\text{Sv/y}) \quad &= [3.7 \times 10^{-3} \times C_{\text{veg}} \, (\text{Bq/L})] \qquad \text{(dose from leafy} \qquad \text{(A-6)} \\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad \text{vegetables and produce)}
\end{aligned}
$$

$$
\begin{aligned}
&+ [9.9 \times 10^{-4} \times C_{\text{veg}} \, (\text{Bq/L})] \\
&+ [9.9 \times 10^{-4} \times C_w \, (\text{Bq/L})]
\end{aligned} \Bigg\} \text{(dose from meat)}
$$

$$
\begin{aligned}
&+ [9.5 \times 10^{-4} \times C_{\text{veg}} \, (\text{Bq/L})] \\
&+ [1.1 \times 10^{-3} \times C_w \, (\text{Bq/L})]
\end{aligned} \Bigg\} \text{(dose from milk)}
$$

Summing the above, the total annual dose rate from the food ingestion pathway for tritium (measured tritium in vegetation and drinking water) is then

$$D_{food} \text{ (µSv/y)} = [5.6 \times 10^{-3} \times C_{veg} \text{ (Bq/L)} + 2.1 \times 10^{-3} \times C_w \text{ (Bq/L)}]$$

In previous years, this equation has had more than double the input from drinking water ($5.4 \times 10^{-3} \times C_w$) and about 84% of the input from food ($4.8 \times 10^{-3} \times C_{veg}$). In Chapter 11, based on maximum food intakes and no intake of water, C_{veg} is multiplied by 4.8×10^{-3}.

Inhalation and Skin Absorption Doses

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

$$D_{inh/sa} \text{ (µSv/y)} = 1.5 \times U_{air} \times C_{air} \times DC_{HTO\_inh} \tag{A-7}$$

where

$$1.5 = \text{the factor that accounts for skin absorption}$$
$$U_{air} = \text{air intake rate (m}^3/\text{y)}$$
$$C_{air} = \text{HTO concentration measured in air at the receptor (Bq/m}^3)$$
$$DC_{HTO\_inh} = \text{dose coefficient (µSv/Bq) for inhalation}$$

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The whole-body inhalation dose rate from HTO is then

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

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

Doses in Chapter 5 are calculated as shown here. The breathing rate of $8000 \; m^3/y$ has been corrected from $8400 \; m^3/y$ used in previous years to conform to NRC 1.109.

In the recent past, HT doses were treated as immersion doses (Eckermann and Ryman 1993), because HT has a low-energy β 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, and an inhalation dose is calculated.

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

$$D_{inh\_HT} \; (\mu Sv/y) = C_{air\_HT} \times U_{air} \times DC_{HT} \tag{A-8}$$

where

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

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

$\quad\quad DC_{HT} = $ effective dose per unit intake $(\mu Sv/Bq)$

The whole-body inhalation dose rate from HT is then

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

$$= 1.4 \times 10^{-5} \times C_{air\_HT} \; (Bq/m^3)$$

Comparison of Model Predictions

The use of different models and different assumptions will result in very different dose predictions. 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. In CAP88-PC, doses are based on air concentrations calculated from dispersion of annual releases to the atmosphere. The transfer of tritium from air concentration to dose is based on assumptions within the code that cannot be altered by the user (e.g., absolute humidity, fractions of vegetables, milk, and meat that are ingested). Of course, as with NRC Regulatory Guide 1.109, the fractions of each food type that are

contaminated may be selected. In this appendix, equations have been shown that calculate dose from measured air (or predicted air, for HT) and plant water concentrations using a set of assumptions different from those used in CAP88-PC. The total dose from HTO releases from the Livermore site predicted using CAP88-PC is a factor of 1.8 times higher than the dose predicted using the equations shown here.

Assumptions about the transfer of tritium through the environment and the amount of contaminated food consumed annually can vary considerably among models (see **Tables A-2** and **A-3**). Use of different assumptions can result in estimated doses being very different and is the reason for most of the uncertainty associated with doses predicted by simulation models. Because the health of people is at stake, the models err on the side of overestimating doses. One way to reduce the uncertainty and increase the accuracy of model predictions is to use environmental monitoring data whenever possible. Because of LLNL's comprehensive monitoring program, reliable concentration data for air, vegetation, and water can be used in models to improve dose predictions.

Table A-3. Comparison of hypothetical annual doses from HTO at the Visitor's Center.

Doses in µSv/y	CAP88-PC[a] (from predicted air concentrations)	NRC Regulatory Guide 1.109 (from observed air concentrations)
Inhalation	0.14	0.019
Leafy vegetables and produce	0.44	0.063
Milk	[0.27]	0.055
Meat	0.16	0.051
Drinking water	Not calculated	0.22
Total ingestion dose (food and water)	0.60 [0.87]	0.39
Total dose from HTO	0.74 [1.0]	0.41

a   Numbers in brackets (i.e., dose from milk) are not calculated for reported LLNL doses. See *LLNL NESHAPs 1998 Annual Report* (Biermann et al. 1999*), Guidance for Radiological Dose Assessment* (Harrach 1998), and Chapter 13.

Concentrations of tritium in air (Chapter 5) are monitored at 11 on-site locations, including the Visitor's Center (VIS), which is a convenient location for comparing doses from different modeling approaches. The measured median air concentration (HTO) at VIS for 1999 was 0.0899 Bq/m^3, which is only 18% of the HTO concentration estimated by CAP88-PC at VIS (0.502 Bq/m^3) from all Livermore site releases. Also measured at VIS are vegetation (median value 17 Bq/L) (Table 11-1, Data Supplement) and rainwater (median value 34.6 Bq/L) (Table 7-12, Data Supplement). Measured concentrations in vegetation can be used, as shown, to estimate tritium intake from vegetables by people and from pasture vegetation by animals. A conservative assumption can be made that rainwater is consumed as drinking water, which will

result in a much higher estimated dose than could ever be achieved by drinking local tap water. Wine from the Livermore Valley is also measured and, for 1999, had a median concentration of 1.7 Bq/L (**Table 11-2**).

The assumptions behind both CAP88-PC and NRC Regulatory Guide 1.109 are conservative and different from each other. They were chosen so that a predicted dose will be far in excess of what is likely to be received. In our example, both models assume the person lives at VIS 100% of the time. For LLNL calculations, CAP88-PC assumes that 100% of the vegetables and meat in the diet are grown at the location at which the dose is calculated (i.e., at VIS, in our example). This assumption is highly conservative, of course, and represents the possibility that all vegetables and meat for ingestion can be grown locally. Milk has not been included because there are no milk cows in the Livermore Valley. For our comparison, the NRC Regulatory Guide 1.109 assumes that essentially the entire diet [leafy vegetables, produce, milk, and meat (beef)] is grown there. CAP88-PC, being a model for atmospheric releases only, does not calculate concentrations in water, so the drinking water pathway is ignored in both models for this comparison. Drinking water is included in Regulatory Guide 1.109, for both animals and people (**Table A-3**).

Doses calculated by CAP88-PC for predicted (0.502 Bq/m^3) air concentrations are compared in **Table A-3** with doses calculated using the NRC equations and observed (0.0899 Bq/m^3) air concentrations. Differences in results are caused by different assumptions (**Tables A-1** and **A-2**), different models, and the lower observed air concentrations compared with predicted air concentrations. Given the relatively high concentration of tritium in rainwater in 1999, resulting from slightly elevated emissions from the Tritium Facility during January, February, and March, the 1999 dose from potential drinking water is half the total tritium dose. Rainwater drunk by cows triples the ingestion dose from milk or meat over that which would be received if drinking water were not contaminated. It would be much more realistic, and yet still conservative, to calculate doses from drinking water using the highest observed values of drinking and surface waters (Table 7-21, Data Supplement) for animals and people, respectively. If this is done, drinking water would be 0.356 Bq/L from location ORCH, surface water would be 1.2 Bq/L from location SHAD, and the total dose from tritium would be reduced from 0.41 µSv/y to 0.12 µSv/y.

All dose estimates for HTO shown in **Table A-3** are high because of highly conservative assumptions. Dose estimates made with NRC Regulatory Guide 1.109 are also high because of the unusually high concentration in rainfall that contributes 50% directly to the total tritium dose. However, although these doses are high compared with doses that would result using less conservative assumptions, they are nevertheless a small fraction

of the EPA's radiation dose standard to a member of the public of 100 µSv/y from an atmospheric release. More realistic assumptions would reduce the dose at VIS significantly. For example, the Visitor's Center is not a subsistence farm nor does anyone live there. Realistically, the assumptions used in these calculations can be applied only to someone living at a location where the majority of that person's diet is grown and consumed.

Tritium Doses Not Calculated by CAP88-PC or NRC Regulatory Guide 1.109

A small contribution to dose arises from air concentrations of tritiated hydrogen (HT) gas. The concentration of HT in air is not measured at VIS, but using release rates from the Tritium Facility and the dispersion model in CAP88-PC, we calculate a concentration of 0.13 Bq/m^3. From this an insignificant inhalation dose from HT of 1.9×10^{-6} µSv/y is calculated. The measured HTO concentrations in air and vegetation account for the dose from any HT that has been converted to HTO in the environment.

Dose from ingestion of organically bound tritium (OBT) is known to be higher than that from ingestion of an equal amount of tritium in the free water of plants and animals. The higher dose coefficient for OBT reflects this fact (**Table A-1**). The concentration of tritium in organic matter can be estimated by knowing the dry matter content and water equivalent factor (the fraction of dry matter that combusts to water; L kg^{-1}) of foodstuffs (Ciba-Geigy Ltd. 1981). Using the assumptions of the NRC model and estimated concentrations of HTO and OBT in Bq/kg fresh weight, doses for total tritium (HTO and OBT) from vegetables, milk, and meat are 0.072, 0.063, and 0.073 µSv/y, respectively, based on the 17 Bq/L in plant water measured at VIS. By including OBT, the doses are increased by 15, 15, and 43%, respectively. The greater effect on dose from beef is caused by the relatively high dry matter content of beef. The overall food ingestion dose is increased from 0.17 to 0.21 µSv/y, but this is still 35% of the potential food ingestion dose (0.60 µSv/y—milk not included) predicted at VIS by CAP88-PC.

Immersion in water is another pathway to dose from tritium because tritium can be absorbed through the skin. The LLNL pool had a median concentration for 1999 of 5 Bq/L (Table 7-21, Data Supplement). The intake of water by skin diffusion is 0.4 mL per minute (Osborne 1968). If it is assumed that a swimmer spends 250 hours a year in the pool, the resulting dose will be 0.54 nSv.

Appendix A. Methods of Dose Calculations

Dose Implications

In this appendix, LLNL has compared doses predicted with two models—CAP88-PC and NRC 1.109—and different assumptions for a hypothetical individual living at the Visitor's Center. Furthermore, doses from inhalation of HT, ingestion of organically bound tritium, and swimming have been estimated. Based on measurements of HTO in air, vegetation, and waters and on the following assumptions, the dose to a hypothetical individual living at the Visitor's Center is presented on **Table A-4**.

Table A-4. Individual living at Visitor's Center.

Assumption	Annual dose
Breathes air with the highest tritium concentrations of any perimeter location except POOL	Inhalation dose: 0.019 μSv HTO + 1.9×10^{-6} μSv HT = 0.019 μSv
Raises and eats all his own vegetables, milk, and beef (and the animals eat pasture and grain grown for them at the Visitor's Center)	Ingestion dose from food, including OBT: 0.21 μSv
Drinks rainwater collected in the winter and stored for the rest of the year	Drinking water dose, 0.22 μSv
Drinks three bottles of Livermore Valley wine each week	Dose from drinking wine, 3.6×10^{-3} μSv
Swims in the LLNL pool 250 hours per year	Immersion dose, 5.4×10^{-4} μSv

The total annual dose resulting from these assumptions is 0.45 μSv (compare this to **Table A-3**), which is 0.45% of the EPA's radiation dose limit to the member of the public from an atmospheric release. It is 4.5% 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.