Appendix A.
Methods of Dose Calculations

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Introduction

Radiological doses calculated from measured activities are a principal indicator of the potential impact of LLNL operations on surrounding populations. The doses from ingestion of water and locally produced foodstuffs are based on actual measurements of radionuclide concentrations in the various media, determined by sampling, as described in Chapters 7 through 11. Data needed to evaluate potential doses from the inhalation pathways are provided by air surveillance monitoring, as described in Chapter 5.

The data on radionuclide concentrations or activities in these media are necessary inputs to the dose-rate equations described here. The examples presented below concern dose assessments for significant agricultural products of the Livermore Valley, including wine and general vegetation, and, in particular, describe the forage-cow-milk / meat pathway for ingestion of tritium. The rate equations can also be used to estimate doses that would occur from ingestion of water at each of the Livermore Valley and Site 300 water sampling locations, though none of these is actually a primary source of drinking water.

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 NRC Regulatory Guide 1.109, *Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents* (U.S. Nuclear Regulatory Commission 1977). The dose and dose-rate conversion factors 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 of Intakes of Radionuclides by Workers* (International Commission on Radiological Protection [ICRP] 1980). The dose calculation for inhalation of tritiated hydrogen (HT) gas uses a dose-rate conversion factor from *ICRP 68, Limits of Intakes of Radionuclides by Workers* (ICRP, 1994).

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

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 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 in water and wine (directly consumed), from tritium ingested by humans via the forage-cow-milk pathway, and, more generally the annual dose from radionuclides in meat, and leafy vegetables. Similar formulas are given for the inhalation/skin absorption dose for HTO and inhalation dose for HT. Similar dose calculations for other radionuclides can be made using these equations with dose rate conversion factors specific to the radionuclide.

Generally, concentrations are measured, while appropriate consumption-rate factors are taken from the literature. The water and milk consumption rates are estimated to be 730 L/y and 310 L/y, respectively, in Appendix E of the NRC Regulatory Guide 1.109 (U.S. Nuclear Regulatory Commission 1997). In the absence of consumption data on locally produced wine, we employ the conservative (high dose) assumption that the intake rate for wine is the same as that for water. The resultant dose is expected to be several times too high for wine but well below levels of health concern.

LLNL's first use of these dose-rate formulas in our environmental annual reports is described by Silver et al. (1980).

Annual Dose from Potable Water

Based on the assumption that all water sampled is available as drinking water, the annual whole-body dose for tritium in µSv/y is calculated using the following equation:

$$D_{\text{whole body}}(\mu\text{Sv/y}) = C_w \times U_w \times D_w \qquad \text{(A-1)}$$

where

C_{w} = concentration of tritium in water (Bq / L)

U_{w} = water consumption rate (L / y) = 730 L / y for maximally exposed individual

D_{w} = dose conversion factor (µSv / Bq)

= 1.73×10^{-5} µSv / Bq [6.4×10^{-8} mrem / pCi] for tritium for the whole-body ingestion pathway for an adult

$D_{\mathrm{whole\ body}}$ = effective dose equivalent (µSv / y) from ingestion of 730 L of potable water with tritium concentration C_{w}.

This equation has been used to estimate maximum doses from drinking water from various locations (see Chapter 7). This equation can also be used to calculate effective dose equivalent from wine (see Chapter 11).

Annual Dose from Food Ingestion

The effective dose equivalent from ingestion of food is calculated by summing the contributions from leafy vegetables, milk and meat to the diet. The concentrations in these foodstuffs are based on measured tritium concentrations in annual grasses (see Chapter 11), and it is assumed that concentrations in leafy vegetables will be similar. Concentrations in milk and meat are calculated from measured concentrations in vegetation using the equations from the NRC Regulatory Guide, as mentioned.

Therefore

$$D_{\mathrm{whole\ body}}(\mu\mathrm{Sv/y}) = D_{\mathrm{veg}} + D_{\mathrm{meat}} + D_{\mathrm{milk}} \tag{A-2}$$

where

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

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

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

Leafy Vegetation

$$D_{\mathrm{veg}}(\mu\mathrm{Sv/y}) = U_{\mathrm{veg}} \times C_{\mathrm{veg}} \times D_{\mathrm{HTO}} \tag{A-2a}$$

where

U_{veg} = intake rate (kg / y): 64 kg / y for maximally exposed individual

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

D_{HTO} = dose factor (μSv / Bq): 1.73×10^{-5} μSv / Bq [6.4×10^{-8} mrem / pCi] for ^{3}H for the adult whole-body ingestion pathway

The tritium dose from ingestion of vegetation is then

$$D_{\text{veg}}(\mu\text{Sv/y}) = 64\ (\text{kg/y}) \times 1.73 \times 10^{-5}\ (\mu\text{Sv/Bq}) \times C_{\text{veg}}\ (\text{Bq/L})$$

$$D_{\text{veg}}(\mu\text{Sv/y}) = 1.1 \times 10^{-3} \times C_{\text{veg}}\ (\text{Bq/L})$$

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 1.1×10^{-3} carries units of $\frac{(\text{L} \bullet \mu\text{Sv})}{(\text{y} \bullet \text{Bq})}$.

Also, for dose calculations, the conservative assumption is made that the plant is 100% water. Hence Bq / L = Bq / kg.

Meat (beef)

Based on the assumption that all feed for cattle was pasture grass and that cows drink water having the same tritium levels as water drunk by humans:

$$D_{\text{meat}}(\mu\text{Sv/y}) = U_{\text{meat}} \times C_{\text{meat}} \times D_{\text{HTO}} \qquad \text{(A-2b)}$$

where

U_{meat} = intake rate (kg / y): 110 kg / y for maximally exposed individual

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

D_{HTO} = dose factor (μSv / Bq): 1.73×10^{-5} μSv / Bq [6.4×10^{-8} mrem / pCi] for ^{3}H for the adult whole-body ingestion pathway and

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

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

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): 1.2×10^{-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 / kg)

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

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

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

Therefore

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

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

The tritium dose rate from meat consumption is then

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

Cow Milk

Based on the assumption that all feed for cattle was pasture grass and that cows drink water having the same tritium levels as water drunk by humans:

$$D_{\mathrm{milk}}(\mu\mathrm{Sv/y}) = U_{\mathrm{milk}} \times C_{\mathrm{milk}} \times D_{\mathrm{HTO}} \quad \text{(A-2c)}$$

where

U_{milk} = intake rate (L / y): 310 L / y for maximally exposed individual

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

D_{HTO} = dose factor (μSv / Bq): 1.73×10^{-5} μSv / Bq [6.4×10^{-8} mrem / pCi] for ^{3}H for the adult whole-body ingestion pathway

and

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

$$C_{\mathrm{milk\_w}} = F_m \ (\mathrm{d/L}) \times Q_w \ (\mathrm{L/d}) \times C_w \ (\mathrm{Bq/L}) \times \exp(-\lambda_i t_f)$$

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 animal (kg / d): 50 kg / d

Q_w = amount of water consumed by the animal (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}

t_f = time from milking to milk consumption (d): 2 d

Therefore

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

The tritium dose rate from directly consumed milk is then

$$\begin{aligned} \text{D}_{\text{milk}}(\mu\text{Sv}/\text{y}) &= 310\ (\text{L}/\text{y}) \times [(0.5 \times \text{C}_{\text{veg}}\ (\text{Bq}/\text{kg})) + (0.6 \times \text{C}_{\text{w}}\ (\text{Bq}/\text{L}))] \\ &\quad \times 1.73 \times 10^{-5}\ (\mu\text{Sv}/\text{Bq}) \\ &= 2.6 \times 10^{-3} \times \text{C}_{\text{veg}}\ (\text{Bq}/\text{L}) + 3.2 \times 10^{-3} \times C_{\text{w}}\ (\text{Bq}/\text{L}) \end{aligned}$$

Whole Body

$$\begin{aligned} D_{\text{whole body}}\ (\mu\text{Sv}/\text{y}) &= (1.1 \times 10^{-3} \times C_{\text{veg}}\ (\text{Bq}/\text{kg})) && \text{(dose from leafy vegetables)} \\ &\left.\begin{aligned} &+ (1.1 \times 10^{-3} \times C_{\text{veg}}\ (\text{Bq}/\text{kg}]) \\ &+ (1.1 \times 10^{-3} \times C_{\text{w}}\ (\text{Bq}/\text{L})) \end{aligned}\right\} && \text{(dose from meat)} \\ &\left.\begin{aligned} &+ (2.6 \times 10^{-3} \times C_{\text{veg}}\ (\text{Bq}/\text{kg})) \\ &+ (3.2 \times 10^{-3} \times C_{\text{w}}\ (\text{Bq}/\text{L})) \end{aligned}\right\} && \text{(dose from milk)} \end{aligned}$$

The total annual dose rate from the injestion pathway for tritium (measured tritium in vegetation and drinking water) and water is then

$$D_{\text{whole body}}\ (\mu\text{Sv}/\text{y}) = (4.8 \times 10^{-3} \times C_{\text{veg}}\ (\text{Bq}/\text{Kg}) + (5.4 \times 10^{-3} \times C_{\text{w}}\ (\text{Bq}/\text{L}))$$

Inhalation and Skin Absorption Doses

Doses due to inhalation of radionuclide-contaminated air can be estimated in an analogous way 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, once the concentration of tritium in air is known, it is multiplied by the inhalation rate of a human to obtain the number of bequerels of tritium inhaled. Dose and dose-rate conversion factors provided by the DOE (U.S. Department of Energy 1988), which are consistent with those specified in *ICRP 30* (International Commission on Radiological Protection 1980), are used to relate the intake of radioactive material into the body to dose commitment. The dose-rate conversion factor 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 50-year dose from a one-year intake of radioactivity.

The inhalation / skin absorption dose is expressible as

$$D_{\text{whole body}}(\mu\text{Sv}/\text{y}) = U_{\text{air}} \times C_{\text{air}} \times D_{\text{HTO\_inh/abs}} \qquad \text{(A-3)}$$

where

U_{air} = air intake rate (m^3 / y): 8400 m^3 / y for an adult

C_{air} = radionuclide concentration measured in air at the receptor (Bq / m^3)

$D_{\text{HTO\_inh/abs}}$ = dose conversion factor (µSv / Bq): $1.5 \times 1.73 \times 10^{-5}$ µSv / Bq $= 2.6 \times 10^{-5}$ µSv / Bq [$1.5 \times 6.4 \times 10^{-8}$ mrem / pCi $= 9.6 \times 10^{-8}$ mrem / pCi] for the adult whole body inhalation / skin absorption pathway

The whole body inhalation dose rate from HTO is then

$$D_{\text{whole body}}(\mu\text{Sv}/\text{y}) = 0.22 \times \text{C}_{\text{air}}\ (\text{Bq}/\text{m}^3)$$

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

$$D_{\text{whole body}}(\mu\text{Sv}/\text{y}) = C_{\text{air\_HT}} \times U_{\text{air\_HT}} \times D_{\text{HT}} \qquad \text{(A-4)}$$

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): 8400 m^3 / y for an adult

D_{HT} = effective dose per unit intake: 1.8×10^{-9} µSv / Bq (ICRP 1994)

The whole body inhalation dose rate from HT is then

$$D_{\text{whole body}}\ (\mu\text{Sv}/\text{y}) = 1.5 \times 10^{-5} \times C_{air\_HT}\ (\text{Bq}/\text{m}^3)$$

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

Comparison of Model Predictions

As has been shown, there are different ways to model doses from tritium. 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, quantities of food consumed), although the user can select the fractions of each food type that are contaminated. In this appendix, equations have been shown which calculate dose from measured (or predicted) air concentrations using a different set of assumptions than are used in CAP88-PC. The assumptions set forth here are based on maximum, rather than average, consumption rates and should assure that the dose predicted is greatly in excess of any that could possibly be received. The total dose from HTO predicted using CAP88-PC is a factor of three times higher than the dose predicted using the equations shown here.

There is a great deal of uncertainty associated with doses predicted by simulation models. Because the health of people is at stake, the models err on the side of over-estimating doses. One way to reduce the uncertainty and increase the accuracy of model predictions is to use environmental monitoring data whenever possible. Because of the comprehensive monitoring program at LLNL, reliable concentration data for air, vegetation and water can be used in models to improve dose predictions.

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 the Visitor's Center for 1998 was 0.0914 Bq/m^3, which is only 30% of HTO at VIS (0.301 Bq/m^3). Also measured at VIS are vegetation (median value 6.5 Bq/L) (Chapter 11) and rainwater (5.365 Bq/L)(Chapter 7). 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 1998 had a median concentration of 2.75 Bq/L (Chapter 11). Consumption of tritiated rainwater gives the highest (i.e., most conservative) dose estimate.

In Chapter 13, the dose to the SW-MEI from releases of tritiated water (HTO) from the Tritium Facility is calculated as 0.23 µSv/y using CAP88-PC, and the dose to the SW-MEI from all sources of tritium at the Livermore site is similarly calculated to be 0.46 µSv/y. Doses from HTO released from the Tritium Facility and all Livermore site sources (also calculated with CAP88-PC) at the nearby Visitor's Center are 0.21 and 0.44 µSv/y respectively. The dose calculated using the equations and assumptions in this appendix is 0.145 µSv/y, less than a third of the dose calculated by CAP88-PC.

The assumptions behind both CAP88-PC and NRC Regulatory Guide 1.109 are extremely conservative and different from each other. They are 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 site; for our comparison, the NRC Regulatory Guide 1-109 assumes that 100% of leafy vegetables, milk, and meat (beef) are grown there. CAP88-PC, being a model for atmospheric releases only, does not calculate concentrations in water, so the drinking water pathway is ignored. Drinking water can be included in Regulatory Guide 1-109.

Doses calculated by CAP88-PC for both predicted (0.3013 Bq/m^3) and observed (0.0914 Bq/m^3) air concentrations are compared in **Table A-1** with doses calculated using the NRC equations and observed air concentrations. The CAP88-PC predictions for observed air concentrations result from multiplying predicted dose rates by the ratio of observed to predicted air concentrations (0.303). Line 1 of **Table A-1** compares inhalation dose rates. Line 2 compares predictions when milk is not included in the diet (as in CAP88-PC) and animals drink uncontaminated water. Since CAP88-PC assumes all vegetables consumed contain tritium and the Regulatory Guide assumes only leafy vegetables contain tritium, the numbers in brackets have been added to show what would be predicted by the Regulatory Guide if all vegetables consumed contained tritium. Similarly, line 3 compares predictions when the assumed diets include

Table A-1. Comparison of hypothetical annual doses from HTO at the Visitor's Center.

	Doses in µSv/y	CAP88-PC predicted air concentrations	CAP88-PC observed air concentrations	NRC RG 1.109 observed air concentrations
1	Inhalation	0.0826	0.0251	0.0190
2	Food ingestion – (no milk)	0.360	0.109	0.0142 [0.0722]
3	Food ingestion	0.521	0.158	0.0312 [0.0892]
4	Food ingestion – Animal water ingestion	Not Calculated	Not Calculated	0.0542 [0.112]
5	Drinking water ingestion	Not Calculated	Not Calculated	0.0677
6	Comparison #1	0.442	0.134	0.145
7	Comparison #2	0.604	0.183	[0.199]

vegetables, milk and beef. Results in line 4 show the considerable effect on dose of animals consuming drinking water with the same tritium concentration as rainwater at the Visitor's Center. Drinking water dose for humans is shown in line 5. Line 6 compares dose predictions from the two models based on the assumptions used in each model, and line 7 compares doses based on assumptions that all vegetables, milk and meat in the diets contain tritium.

Table A-1 shows that dose depends strongly on assumptions in the model. The Regulatory Guide's dose (0.145 µSv / y) is known to be much higher than would be expected because of the maximum ingestion rates used (730 L per year drinking water, 64 kg leafy vegetables, 310 L milk and 110 kg of meat consumed). Average consumption rates (370 L drinking water, 21 kg leafy vegetables {estimated}, 110 L milk and 95 kg meat {beef}) recommended by the Regulatory Guide will produce lower doses. The dose from the drinking water pathway, totally neglected in CAP88-PC, can be significant depending on tritium concentrations in drinking water. All of the dose estimates for HTO shown in **Table A-1** are high because of unreasonable assumptions. The Visitor's Center is not a subsistence farm, nor does anyone live there. Realistically, the assumptions used in these calculations can only be applied to someone living at a location where the majority of that person's diet is grown and consumed, in which case the dose would be lower (probably significantly) since no such locations are near the perimeter of LLNL.

A small contribution to dose will arise from air concentrations of tritium gas, HT. 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, a concentration of 0.041 $\mathrm{Bq/m^3}$ is calculated. From this an insignificant inhalation dose from HT of 6.2×10^{-7} µSv / y is calculated.