Appendix B
Methods of Dose Calculations

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 foodstuff 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 and immersion pathways are provided by air surveillance monitoring, as described in Chapter 4.

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 pathway for ingestion of tritium in vegetation. 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, inhalation, and immersion pathways are based on the NRC Regulatory Guide 1.109, *Calculation of Annual Doses to Man from Routine Releases of Reactor Effluent* (U.S. Nuclear Regulatory Commission 1997). The dose and dose-rate conversion factors used in these calculations were obtained from the committed dose equivalent tables for DOE dose calculations and are consistent with those specified in *ICRP 30, Limits of Intakes of Radionuclides by Workers* (International Commission on Radiological Protection [ICRP] 1980).

The calculations use conventional activity units of picocuries (pCi) and dose units of millirem (mrem). The conversion constants that apply when converting to Système International (SI) activity units of becquerels (Bq) and dose units of sieverts (Sv) are:

1 pCi = (3.7×10^{-2}) Bq
1 mrem = (1×10^{-5}) Sv = 10 μSv = 1×10^{-2} mSv

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., in L / y), the radionuclide concentration (e.g., in pCi / L) in the food or drink, and the dose rate conversion factor (e.g., in mrem / pCi) for the radionuclide. In the following subsections, equations of this type are used to estimate the annual dose from tritium in water and milk (directly consumed), from tritium ingested by humans via the forage-cow-milk pathway, and, more generally the annual dose from radionuclides in meat, liquids, and leafy vegetables. Similar formulas are given for the inhalation dose and immersion dose, with HTO and HT, respectively, used as specific examples.

Generally, the concentrations are measured, while the 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 1 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 mrem / y is calculated using the following equation:

$$D_{\text{whole body}}(\text{mrem / y}) = C_{\text{w}} \times U_{\text{w}} \times D_{\text{w}} \quad \text{(B-1)}$$

where

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

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

D_{w} = dose conversion factor (mrem / pCi)

= 6.3×10^{-8} mrem / pCi for tritium for the whole-body ingestion pathway for an adult (similarly, for ^{40}K the dose conversion factor is 1.88×10^{-5} mrem / pCi, and for ^{137}Cs, it is 2.17×10^{-7} mrem / pCi)

$D_{\text{whole body}}$ = effective dose equivalent (mrem / y) from ingestion of 730 L of potable water with tritium concentration C_w.

Annual Dose from Forage-Cow-Milk Pathway for Tritium in Vegetation

Based on the assumption that all feed for the cattle was pasture grass, the effective dose equivalent per µCi / mL of tritiated water (HTO) for the maximally exposed individual is calculated using the following equation:

$$D_{\text{whole body}}(\text{mrem / y}) = D_{\text{veg}} + D_{\text{meat}} + D_{\text{milk}} \qquad \text{(B-2)}$$

where

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

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

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

Vegetation

$$D_{\text{veg(leafy)}} = U_{\text{veg}} \times C_{\text{veg}} \times D_{\text{HTO}} \qquad \text{(B-2a)}$$

where

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

C_{veg} = concentration (pCi / kg): $10^9 \dfrac{\text{pCi / kg}}{\mu\text{Ci / mL}} \times (C_{\text{veg}}\ [\mu\text{Ci / mL measured}])$

D_{HTO} = dose factor (mrem / pCi): 6.3×10^{-8} mrem / pCi for ^{3}H for the adult wholebody ingestion pathway.

The tritium dose from ingestion of vegetation is then

$$D_{\text{veg}}(\text{mrem / y}) = (0.40 \times 10^4) \times (C_{\text{veg}}\ [\mu\text{Ci / mL measured}]).$$

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 (0.40×10^4) carries units of $\dfrac{(\text{mL} \bullet \text{mrem})}{(\text{y} \bullet \mu\text{Ci})}$.

Meat

$$D_{meat}(\text{mrem/y}) = U_{meat} \times C_{meat} \times D_{HTO} \tag{B-2b}$$

where

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

C_{meat} = $(F_f) \times (Q_f) \times (C_{veg}) \times (e^{[-\lambda i t s]})$

D_{HTO} = dose factor (mrem/pCi): 6.3×10^{-8} mrem/pCi for ^3H for the adult whole-body ingestion pathway

F_f = fraction of daily intake of nuclide per kilogram of animal/fish (pCi/kg in meat per pCi/d ingested by the animal) (d/kg): 1.2×10^{-2} d/kg

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

C_{veg} = concentration (pCi/kg): $10^9 \dfrac{\text{pCi / kg}}{\mu\text{Ci / mL}} \times (C_{veg}\,[\mu\text{Ci/mL measured}])$

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

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

$$C_{meat} = (1.2 \times 10^{-2}\ \text{d/kg}) \times (50\ \text{kg/d}) \times (C_{veg}\,[\mu\text{Ci/mL}]) \times \left(10^9 \frac{\text{pCi / kg}}{\mu\text{Ci / mL}}\right) \times (\exp[\{-1.5 \times 10^{-4}\} \times \{20\}])$$

$$= 0.6 \times 10^9 \frac{\text{pCi / kg}}{\mu\text{Ci / mL}}) \times (C_{veg}\,[\mu\text{Ci/mL measured}]).$$

The tritium dose rate from meat consumption is then

$$D_{meat}(\text{mrem/y}) = (110\ \text{kg/y}) \times (0.6 \times 10^9 \frac{\text{pCi / kg}}{\mu\text{Ci / mL}} \times C_{veg}\,[\mu\text{Ci/mL measured}]) \times (6.3 \times 10^{-8}\ \text{mrem/pCi})$$

$$= (0.41 \times 10^4) \times (C_{veg}\,[\mu\text{Ci/mL measured}]).$$

Milk

$$D_{milk}(\text{mrem/y}) = U_{milk} \times C_{milk} \times D_{HTO} \tag{B-2c}$$

where

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

D_{HTO} = dose factor (mrem / pCi): 6.3×10^{-8} mrem / pCi for ^3H for the adult whole-body ingestion pathway

C_{milk} = $(F_m) \times (Q_f) \times (C_{veg}) \times (e^{[-\lambda_i t_f]})$

F_m = fraction of daily intake of nuclide per liter of milk (pCi / L in milk per pCi / 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

C_{veg} = concentration (pCi / kg): $(10^9 \frac{\text{pCi / kg}}{\mu\text{Ci / mL}}) \times (C_{veg}\ [\mu\text{Ci / mL measured}])$

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

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

$$C_{milk} = (1.0 \times 10^{-2}\ \text{d / L}) \times (50\ \text{kg / d}) \times (C_{veg}\ [\mu\text{Ci / mL}]) \times (10^9 \frac{\text{pCi / kg}}{\mu\text{Ci / mL}}) \times (\exp[\{-1.5 \times 10^{-4}\} \times \{2\}])$$

$$= (0.5 \times 10^9 \frac{\text{pCi / kg}}{\mu\text{Ci / mL}}) \times (C_{veg}\ [\mu\text{Ci / mL measured}]).$$

The tritium dose rate from directly consumed milk is then

$$D_{milk}\ (\text{mrem / y}) = (310\ \text{L / y}) \times ([0.5 \times 10^9 \frac{\text{pCi / kg}}{\mu\text{Ci / mL}}] \times [C_{veg}\ \{\mu\text{Ci / mL measured}\}]) \times (6.3 \times 10^{-8}\ \text{mrem / pCi})$$

$$= (0.97 \times 10^4) \times (C_{veg}\ [\mu\text{Ci / mL measured}]).$$

Whole Body

$$D_{whole\ body}\ (\text{mrem / y}) = ([0.40 \times 10^4] \times [C_{veg}\ \{\mu\text{Ci / mL measured}\}]) + ([0.41 \times 10^4] \times [C_{veg}\ \{\mu\text{Ci / mL measured}\}]) + ([0.97 \times 10^4] \times [C_{veg}\ \{\mu\text{Ci / mL measured}\}]).$$

The total annual dose rate from the forage-cow-milk pathway for tritium in vegetation is then

$$D_{whole\ body}\ (\text{mrem / y}) = ([1.78 \times 10^4] \times [C_{veg}\ \{\mu\text{Ci / mL measured}\}]).$$

Inhalation/Immersion Dose

Doses due to inhalation of and immersion in 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 (Ci / m^3) at the location of interest. χ can be directly measured, or calculated using a Gaussian dispersion air transport model. In the latter approach, the calculated quantity is the atmospheric dispersion parameter, χ / Q, which is the product of the radionuclide concentration in air χ(Ci / m^3) at all locations of interest and the source release rate Q(Ci / s).

For inhalation dose, once χ or the product (χ / Q) $\times$ (Q) is evaluated, it is multiplied by the inhalation rate of a human to obtain the number of curies of radioactive material inhaled by the human body. 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. These dose factors provide estimates of 50-year dose from a one-year intake of radioactivity.

The inhalation dose is expressible as

$$D_{\text{whole body}}(\text{mrem / y}) = U_{\text{inhalation}} \times C_{\text{radionuclide}} \times D_{\text{radionuclide}} \qquad \text{(B-3)}$$

where

$U_{\text{inhalation}}$ = air intake rate (L / y): 8,400 m^3 / y for an adult

$D_{\text{radionuclide}}$ = dose conversion factor (mrem / pCi) for the radionuclide of interest (for HTO this factor is $1.5 \times 6.4 \times 10^{-8}$ mrem / pCi = 9.6×10^{-8} mrem / pCi for the adult whole body inhalation pathway, where the factor 1.5 accounts for absorption through the skin; for other radionuclides, see Table 2.1 in Eckerman et al. [1988])

$C_{\text{radionuclide}}$ = $(F) \times (\chi / Q) \times (Q)$ = radionuclide concentration at the receptor (pCi / m^3)

F = $\dfrac{1 \times 10^{12}\ \text{pCi / Ci}}{3.15 \times 10^{7}\ \text{s / y}} = 3.17 \times 10^{4}$ (pCi / Ci) / (s / y)

Q = radionuclide release rate (Ci / y)

χ / Q = diffusion parameter (s / m^3); calculated.

The wholebody inhalation dose rate is then

$$D_{\text{whole body}}(\text{mrem / y}) = (3.17 \times 10^4\ [\text{pCi / Ci}]/[\text{s / y}]) \times (\chi / \text{Q})(\text{s / m}^3) \times (\text{Q}[\text{Ci / y}]) \times (8.4 \times 10^3\ \text{m}^3/\text{y}) \times D_{\text{radionuclide}}\ (\text{mrem / pCi}).$$

The immersion dose is similarly expressible as

$$D_{\text{whole body}}(\text{mrem / y}) = C_{\text{radionuclide}} \times (DRF) \quad \text{(B-4)}$$

where

$C_{\text{radionuclide}}$ = $(F) \times (\chi / \text{Q}) \times (\text{Q})$ = radionuclide concentration at the receptor (pCi / m^3)

F = $\dfrac{1 \times 10^{12}\ \text{pCi / Ci}}{3.15 \times 10^7\ \text{s / y}} = 3.17 \times 10^4\ (\text{pCi / Ci})/(\text{s / y})$

Q = radionuclide release rate (Ci / y)

χ / Q = diffusion parameter (s / m^3), calculated

DRF = the external dose-equivalent rate factor per unit radionuclide concentration $(\text{mrem / y})/(\text{pCi / m}^3)$ [for elemental ^{3}H this factor DRF is $3.9 \times 10^{-8}\ (\text{mrem / y})/(\text{pCi / m}^3)$; for the short-lived isotopes ^{13}N and ^{15}O it equals $5.1 \times 10^{-3}\ (\text{mrem / y})/(\text{pCi / m}^3)$; for other radionuclides see Table 2.3 in Eckerman et al. (1988).