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Vols. 5 and 6

Technical Assistance for Regulatory Development: Review and Evaluation of the Draft EPA Standard 40CFR191 for Disposal of High-Level Waste

- Health Effects Associated with Unit Radionuclide Releases to the Environment
- Calculation of Health Effects per Curie Release for Comparison with the EPA Standard

Prepared by Fuel Cycle Risk Analysis Division

Sandia National Laboratories

Prepared for
U.S. Nuclear Regulatory Commission

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OTHER VOLUMES OF
SAND82-1557
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Main Title:

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Volume 1	Executive Summary N. R. Ortiz, K. Wahi
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Volume 5	Health Effects Associated with Unit Radionuclide Releases to the Environment J. C. Helton
Volume 6	Calculation of Health Effects Per Curie Release for Comparison with the EPA Standard G. E. Runkle

Volume 5

Health Effects Associated with Unit Radionuclide Releases to the Environment

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TECHNICAL ASSISTANCE FOR REGULATORY DEVELOPMENT: REVIEW AND EVALUATION OF THE DRAFT EPA STANDARD 40CFR191 FOR DISPOSAL OF HIGH-LEVEL WASTE

VOL. 5

HEALTH EFFECTS ASSOCIATED WITH UNIT RADIONUCLIDE RELEASES TO THE ENVIRONMENT

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ABSTRACT

Simple models are presented for the estimation of individual and population health effects (i.e., latent cancer fatalities) for long-term radionuclide releases to the surface environment. These models were suggested by techniques employed by the Environmental Protection Agency in the development of a proposed standard for the disposal of high-level radioactive waste. The modeling approach is based on the use of asymptotic solutions to mixed-cell models in conjunction with appropriate usage rates, dose factors, risk factors, and population estimates. Although the models are simple, it is felt that they can be used in preliminary investigations of topics in high-level waste disposal such as potential importance of individual radionuclides, relative importance of different release patterns or exposure pathways, and relationships between individual and population exposures. The use of the models is illustrated by calculating the population health effects along various exposure pathways for the radionuclides considered in the proposed Environmental Protection Agency Standard. The results of these calculations are compared with the calculated population exposures on which the proposed Environmental Protection Agency Standard is based.

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1. Overview

1.1 Preliminary Comments

The Environmental Protection Agency has recently performed an analysis of the population health effects associated with a release to the surface environment of selected radionuclides contained in high-level waste (Sm81). Table 1-1 contains a synopsis of the population health effects calculated in the Environmental Protection Agency analysis due to a one curie release of each of the indicated radionuclides over an extended period of time. In turn, the values contained in this table were used in the derivation of the Environmental Protection Agency's draft standard for the geologic disposal of high-level radioactive waste (En80). Specifically, it was decided to allow 1000 health effects (i.e., latent cancer fatalities) over a 10,000 year period per 100,000 metric tons of heavy metal (MTHM) used as reactor fuel. For each radionuclide, the allowable release limit per 1000 MTHM over a 10,000 year period was obtained by dividing 10 health effects by the health effects per curie for a release to surface water given in Table 1-1. The proposed standard and the results of the indicated calculation are given in Table 1-2.

Releases to surface water are probably the most likely, tended to dominate health effects in the Environmental Protection Agency calculations shown in Table 1-1, and were used in the derivation of the proposed standard given in Table 1-2. For these reasons, it was decided to examine the calculations related to the surface-water exposure pathway. Specifically, it was decided to examine the Environmental Protection Agency calculations by developing simple models of the same type that they used and then using these models to predict individual and population exposures and health effects. In this development, the dose and risk factors presented in Runkle et al. (Ru81) are used.

1.2 Computational Approach

The computational results presented are obtained with the use of simple linear models to represent radionuclide movement. Specifically, the models considered are of the form

$$dX/dt = R - AX \ , \qquad (1.1)$$

Table 1-1. Health Effects per Curie Released for Different Release Modes*

Nuclide	Releases to a River	Releases to an Ocean	Releases to Land Surface	Releases to the Air
C- 14	4.58 E- 2	1.12 E- 7	2.58 E- 5	2.04 E- 4
Ni- 59				
Sr- 90	1.21 E- 1	1.91 E- 6	9.75 E- 4	1.63 E- 2
Zr- 93				
Tc- 99	2.85 E- 4	1.04 E- 6	6.03 E- 8	3.67 E- 5
Sn-126	1.20 E- 1	7.86 E- 6	4.13 E- 2	1.12 E- 1
I-129	1.08 E- 2	9.62 E- 5	2.31 E- 5	1.38 E- 3
Cs-135	3.81 E- 3	1.58 E- 5	4.01 E- 4	7.36 E- 4
Cs-137	1.98 E- 2	1.60 E- 5	5.62 E- 4	6.91 E- 3
Sm-151				
Ra-226				
U-234				
Np-237	5.96 E- 1	2.44 E- 3	3.22 E- 3	8.03 E- 2
Pu-238	2.29 E- 2	2.38 E- 5	3.21 E- 3	1.47 E- 2
Pu-239	6.92 E- 2	1.31 E- 4	5.55 E- 2	5.18 E- 2
Pu-240	6.53 E- 2	1.15 E- 4	4.94 E- 2	4.76 E- 2
Am-241	7.19 E- 1	1.19 E- 2	8.98 E- 2	1.59 E- 1
Pu-242	6.76 E- 2	1.30 E- 4	5.63 E- 2	5.13 E- 2
Am-243	2.68 E 0	8.81 E- 2	1.03 E 0	1.14 E 0

*This table is a reprint of Table D-1 of (Sm81).

Table 1-2. Cumulative Releases to the Accessible Environment for 10,000 Years After Disposal Proposed by the Environmental Protection Agency

Radionuclide	Half-Life[a] (years)	Proposed Release Limit[b] (curies per 1000 MTHM)	Release Limit From Table 1-1[c] (curies per 1000 MTHM)
Americium-241	458.	10	13.9*
Americium-243	7370.	4	3.73
Carbon-14	5730	200	218.3
Cesium-135	3.E6	2000	2624.7
Cesium-137	30.2	500	505.0
Iodine-129	1.7E7	900	925.9
Neptunium-237	2.14E6	20	16.8
Plutonium-238	86.	400	436.7
Plutonium-239	2.44E4	100	141.5
Plutonium-240	6580.	100	153.1
Plutonium-242	3.79E5	100	147.9
Radium-226	1600.	3	
Strontium-90	28.1	80	82.6
Technetium-99	2.12E5	2000	35,087.7
Tin-126	1.E5	80	83.3
Any other alpha-emitting radionuclide		10	
Any other radionuclide which does not emit alpha particles		500	

a From (We74)
b From (En80)
c Derived from "Releases to a River" in Table 1-1.

where X is the amount of radionuclide in some region of interest (units: Ci), R is the rate of radionuclide input to this region (units: Ci/yr) and A is a rate constant for movement out of that region (units: yr^{-1}). The solution of the preceding equation is given by

$$X(t) = e^{-At}X_0 + (R/A)(1. - e^{-At}), \qquad (1.2)$$

where $X(0) = X_0$. Further, when A is positive as is the case for situations considered in this presentation, the asymptotic or steady state solution to (1.1) is given by

$$SX = R/A \ . \qquad (1.3)$$

It is this latter solution which will be used in the development of dose and risk results to be presented.

The equation appearing in (1.1) is used to represent three different situations. The first situation is a radionuclide release to a surface-water body. Here, for each radionuclide considered,

$$R = TD(I)/T \quad \text{and} \quad A = F/VW \ , \qquad (1.4)$$

where TD(I) equals total release for radionuclide I (units: Ci) over a time period of length T (units: yrs), F equals the flow rate out of the water body under consideration (units: L/yr), and VW equals the volume of the water body (units: L). For completeness, the rate constant A appearing in (1.4) should also contain a term representing radioactive decay. However, as this term would be very small relative to F/VW for the radionuclides commonly considered in the geologic disposal of high-level waste, it is omitted. Radionuclide releases over relatively long time periods will be considered. In particular, dose factors which provide a 70. year dose commitment from a 70. year chronic exposure will be used. Therefore, T must be significantly greater than 70. years. The coefficient A is derived from the assumption that the surface-water body can be treated as a uniformly mixed cell such that a radionuclide can leave the cell only by outward movement

of water. Additional discussion of R and A can be obtained in Chapter 3.

The second situation is a radionuclide release to soil. Here, for each radionuclide considered, R is defined as in (1.4) and A is defined by

$$A = \frac{S(I)*ER}{DP*(1. - PO)*DE} + \frac{(1. - S(I))*RO}{DP*PO*SA*1000.} + \frac{ALOG(2.)}{HLIFE(I)} , \quad (1.5)$$

where S(I) represents radionuclide partitioning between the liquid and solid phases of the soil and is defined in Table 1-5 (units: unitless), ER represents erosion rate per unit area (units: kg/m^2 per yr), DP represents depth of soil (units: m), PO represents porosity of soil (units: unitless), DE represents mean particle density of soil material (units: kg/m^3), RO represents runoff rate per unit area (units: L/m^2 per yr), SA represents percent saturation of pore space in soil (units: unitless), ALOG(2.) is the natural logarithm of 2. and HLIFE(I) is the half-life of radionuclide I (units: yr). Due to the slower processes associated with radionuclide movement in soil, radioactive decay is incorporated into the expression appearing in (1.5). The coefficient A is derived from the assumptions that the soil can be treated as a uniformly mixed cell with a water phase and a solid phase such that (1) a radionuclide is partitioned between the water and solid phases on the basis of a distribution coefficient and (2) a radionuclide can leave the cell only by radioactive decay or movements of water and solids. Additional discussion of A can be obtained in Chapter 4.

The third situation is radionuclide deposition on crops due to sprinkler irrigation. In this case,

$$R = FRET*TD(I)*FRIV/T \quad (1.6)$$

and

$$A = ALOG(2.)/WHRHL , \quad (1.7)$$

where TD(I), T and ALOG(2.) are already defined, FRET is

the fraction of deposited radionuclides in sprinkler irrigation initially retained on plants (units: unitless), FRIV is the fraction of the river receiving the radionuclide release used for sprinkler irrigation (units: unitless) and WHRHL is the weathering half life for radionuclides deposited by sprinkler irrigation (units: yrs). The variables R and A are derived from the assumption that the radionuclides retained on plants due to sprinkler irrigation can be treated as being in a uniformly-mixed cell such that radionuclides can enter this cell only by deposition on plants and can leave the cell only by weathering. Due to the generally short weathering half lives which are considered, radioactive decay is omitted in the definition of A. Additional discussion on the derivation of R and A is provided in Chapter 5.

For each of the situations indicated in the three preceding paragraphs, radionuclide movement can be represented by a differential equation of the form given in (1.1). As indicated in (1.3), each of these equations will have an asymptotic solution of the form R/A which represents the amount of radionuclide in the system at steady state. From this solution, steady state concentrations can be obtained by dividing by the appropriate volume or mass. For radionuclide I and release to surface water, the steady state solution is

$$R/A = (TD(I)/T)/(F/VW) = TD(I)*VW/(F*T) \qquad (1.8)$$

and so division by VW yields a steady-state concentration of

$$TD(I)/(F*T) \ . \qquad (1.9)$$

Similar calculations will yield steady-state concentrations for release to soil and deposition on plants due to sprinkler irrigation.

Once the concentrations indicated in the preceding paragraph are known, they can be used to calculate individual exposure rates. In turn, multiplication of these exposure rates by appropriate dose factors will yield individual dose rates. Then, multiplication by risk factors will yield individual cancer risk. Finally, multiplication of individual dose and risk by popula-

tion size will yield population dose and population risk. Tables 1-4, 1-5 and 1-6 contain selected formulas for individual dose (units: rem/ind) and associated population size (units: ind). Table 1-3 contains definitions for variables used in Tables 1-4, 1-5 and 1-6. Detailed derivations for all relations are given later in the presentation. However, all were derived as already indicated. That is, an asymptotic concentration was obtained in each substrate of interest. Next, these concentrations were used in conjunction with individual usage rates and dose factors to obtain individual dose. Then, multiplication by the appropriate risk factor yields individual risk, and multiplication by the indicated population size yields population dose and risk. Due to the assumed linearity of many of the relations, multiplication by population size often results in considerable simplification of the algebraic expressions for population dose and risk. The appearance of the factor 70. in many of the expressions results from the fact that dose factors for a 70. year dose commitment from a 70. year chronic exposure are being used for ingestion and inhalation. Multiplication of a one year chronic (i.e., assumed to be the same over an entire lifetime) exposure rate by these factors yields the indicated dose commitment.

1.3 Computational Results

This section presents population health effects obtained with the relations given in Tables 1-4, 1-5 and 1-6. These results are presented in Tables 1-7, 1-8 and 1-9 and were calculated for a total discharge of 1. curie per radionuclide (i.e., TD(I) = 1.). The dose factors used in these calculations are given in Tables 2.1, 2.2 and 2.3 of Runkle et al. (Ru81). The cancers and associated risk factors used are listed in Table 1-10. For each exposure mode, the indicated population health effect is the sum of the health effects for the individual cancers. All water treatment factors are assumed to be 1. (i.e., WT(I) = 1.), and concentration ratios (i.e., CRDM(I), CRDMT(I), CRSP(I), CRWF(I)) are taken from Tables A-8 and C-5 of Nuclear Regulatory Commission Guide 1.109 (Nu76). The distribution coefficients employed for surface water and soil are the same as those given in the Environmental Protection Agency analysis for sediment (Sm81, Table 5-5); however, all distribution coefficients indicated as being zero in the preceding table were assigned the value of 1. for our analysis. The Environmental Protection Agency may have used different distribution coefficients for soil calculations but their documentation does not make this clear

Table 1-3. Variables Appearing in Tables 1-4, 1-5 and 1-6

Variable	Definition
AIRCON	Concentration of suspended solids in air (units: kg/m^3)
ALOG(2.)	Natural logarithm of 2.
AR	Area of soil (units: m^2)
CMLK	Individual milk consumption (units: L/yr)
CMT	Individual meat consumption (units: kg/yr)
CPLT	Individual plant consumption (units: kg/yr)
CRDM(I)	Concentration ratio for radionuclide I from diet to milk (units: Ci/L per Ci/day)
CRDMT(I)	Concentration ratio for radionuclide I from diet to meat (units: Ci/kg per Ci/day)
CRSP(I)	Concentration ratio for radionuclide I from soil to plant (units: unitless)
CRWF(I)	Concentration ratio for radionuclide I from water to fish (units: Ci/kg per Ci/L)
DCOEF(I)	Distribution coefficient for radionuclide I (units: Ci/kg per Ci/L)
DE	Mean particle density of soil material (units: kg/m^3)
DENSITY	Mean particle density for external exposure calculations (units: kg/m^3)
DEPTH	Depth to which radionuclides are assumed to be concentrated on surface for external exposure calculations (units: m)
DFEXT(I,1,J)	Dose factor for ground exposure to organ J from radionuclide I (units: rem/hr per Ci/m^2)
DFEXT(I,2,J)	Same as DFEXT(I,1,J) but for water immersion (units: rem/hr per Ci/m^3)

Table 1-3. (continued)

Variable	Definition
DFEXT(I,3,J)	Same as DFEXT(I,1,J) but for air immersion (units: rem/hr per Ci/m^3)
DFING(I,J)	Dose factor for exposure to organ J from ingestion of radionuclide I (units: rem per Ci/yr)
DFINH(I,J)	Same as DFING(I,J) but for inhalation
DFSH	Constant relating fish production to river flow (units: kg/yr per L/yr)
DMLK	Individuals supported by milk production (units: ind/m^2)
DMT	Individuals supported by meat production (units: ind/m^2)
DP	Depth of soil (units: m)
DPLT	Individuals supported by plant production (units: ind/m^2)
DPOP	Constant relating population size to river flow (units: ind per L/yr)
DSL	Population density for inhalation and external exposure calculations (units: ind/m^2)
ER	Erosion rate (units: kg/m^2 per yr)
F	River flow rate (units: L/yr)
FMLK	Fraction of land used for milk production (units: unitless)
FMT	Fraction of land used for meat production (units: unitless)
FPLT	Fraction of land used to grow plants for human consumption (units: unitless)

Table 1-3. (continued)

Variable	Definition
FRET	Fraction of radionuclides in sprinkler irrigation initially retained on plants (units: unitless)
FRIV	Fraction of river used for sprinkler irrigation (units: unitless)
HLIFE(I)	Half-life for radiouclide I (units: yr)
PDEN	Plant density (units: kg/m^2)
PMLK	Plant consumption by dairy cattle (units: kg/day)
PMT	Plant consumption by beef cattle (units: kg/day)
PO	Porosity of soil (units: unitless)
POROSIT	Porosity for external exposure calculations (units: unitless)
REXARSD	Exposure to suspended sediment (units: hr/yr)
REXARSL	Exposure to suspended soil (units: hr/yr)
REXTSD	Exposure to sediment (units: hr/yr)
REXTSL	Exposure to soil (units: hr/yr)
REXTWAT	Exposure water (units: hr/yr)
RINGWAT	Water ingestion rate (units: L/yr)
RINHAIR	Inhalation rate (units: m^3/yr)
RO	Runoff rate (units: L/m^2 per yr)
SA	Percent saturation of pore space in soil (units: unitless)
T	Length of radionuclide discharge (units: yr)
TD(I)	Total discharge of radionuclide I (units: Ci)

Table 1-3. (continued)

Variable	Definition
TMINSD	Fraction of year that individual is exposed to suspended sediment (units: unitless)
TMINSL	Fraction of year that individual is exposed to suspended soil (units: unitless)
WHRHL	Weathering half life for radionuclides deposited by sprinkler irrigation (units: yr)
WMLK	Water consumption by dairy cattle (units: L/day)
WMT	Water consumption by beef cattle (units: L/day)
WT(I)	Water treatment factor for radionuclide I (units: unitless)
70.	Average life expectancy (units: yr)

Table 1-4. Exposure to Organ Associated With Cancer J Due to Radionuclide I for Releases to Surface Water

Exposure From Water Consumption

Individual : RINGWAT*TD(I)*WT(I)*DFING(I,J)/(F*T)
(rem/ind)

Pop. Size : DPOP*F*T/70.
(ind)

Exposure From Fish Consumption

Individual : TD(I)*CRWF(I)*DFSH*DFING(I,J)/(DPOP*F*T)
(rem/ind)

Pop. Size : DPOP*F*T/70.
(ind)

Exposure From Inhalation of Suspended Sediment

Individual : DCOEF(I)*TD(I)*AIRCON*RINHAIR*TMINSD*DFINH(I,J)/(F*T)
(rem/ind)

Pop. Size : DPOP*F*T/70.
(ind)

Exposure From Water Immersion

Individual : TD(I)*REXTWAT*DF(I,2,J)*7.E4/(F*T)
(rem/ind)

Pop. Size : DPOP*F*T/70.
(ind)

Exposure From Shoreline Sediment

Individual : DCOEF(I)*TD(I)*DEPTH*DENSITY*(1.-POROSIT)*REXTSD
(rem/ind) *DFEXT(I,1,J)*70./(F*T)

Pop. Size : DPOP*F*T/70.
(ind)

Exposure From Suspended Sediment

Individual : DCOEF(I)*TD(I)*AIRCON*REXARSD*DFEXT(I,3,J)*70./(F*T)
(rem/ind)

Pop. Size : DPOP*F*T/70.
(ind)

Table 1-5. Exposure to Organ Associated With Cancer J Due to Radionuclide I for Releases to Soil

Expressions Introduced to Simplify Notation

$$S(I) = DCOEF(I)*(1. - PO)*DE/(DCOEF(I)*(1. - PO)*DE + PO*1000.)$$

(units: unitless)

$$A(I) = S(I)*ER/(DP*(1. - PO)*DE) + (1. - S(I))*RO/(DP*PO*1000.) + ALOG(2.)/HLIFE(I)$$

(units: yr^{-1})

$$FAC(I) = 1./(A(I)*DP*(1. - PO)*DE)$$

(units: m^2 yr/kg)

Exposure From Plant Consumption

Individual (rem/ind): CPLT*TD(I)*FAC(I)*CRSP(I)*DFING(I,J)/(T*AR)

Pop. Size (ind): AR*FPLT*DPLT*T/70.

Exposure From Milk Consumption

Individual (rem/ind): TD(I)*FAC(I)*CRSP(I)*PMLK*CRDM(I)*CMLK*DFING(I,J)/(T*AR)

Pop. Size (ind): AR*FMLK*DMLK*T/70.

Exposure From Meat Consumption

Individual (rem/ind): TD(I)*FAC(I)*CRSP(I)*PMT*CRDMT(I)*CMT*DFING(I,J)/(T*AR)

Pop. Size (ind.): AR*FMT*LMT*T/70.

Table 1-5. (continued)

Exposure From Inhalation of Suspended Soil

Individual : TD(I)*FAC(I)(AIRCON*RINHAIR*TMINSL*DFINH(I,J)/(T*AR)
(rem/ind)

Pop. Size : AR*DSL*T/70.
(ind)

Exposure From Soil

Individual : TD(I)*FAC(I)*DEPTH*DENSITY*(1. - POROSIT)*REXTSL
(rem/ind)

*DFEXT(I,1,J)*70./(T*AR)

Pop. Size : AR*DSL*T/70.
(ind)

Exposure From Suspended Soil

Individual : TD(I)*FAC(I)*AIRCON*REXARSL*DFEXT(I,3,J)*70./(T*AR)
(rem/ind)

Pop. Size : AR*DSL*T/70.
(ind.)

Table 1-6. Exposure to Organ Associated With Cancer J Due to Radionuclide I for Releases to Surface Water With Subsequent Use of Surface Water for Livestock and Sprinkler Irrigation

Exposure From Plant Consumption

Individual (rem/ind) : FRET*TD(I)*FRIV*WHRHL*CPLT*DFING(I,J)/(T*AR*PDEN*ALOG(2.))

Pop. Size (ind) : AR*FPLT*DPLT*T/70.

Exposure From Milk Consumption

Individual[a] (rem/ind): FRET*TD(I)*FRIV*WHRHL*PMLK*CRDM(I)*CMLK*DFING(I,J)
/(T*AR*PDEN*ALOG(2.))

Individual[b] (rem/ind): TD(I)*WMLK*CRDM(I)*CMLK*DFING(I,J)/(F*T)

Pop. Size (ind.) : AR*FMLK*DMLK*T/70.

Exposure From Meat Consumption

Individual[a] (rem/ind): FRET*TD(I)*FRIV*WHRHL*PMT*CRDMT(I)*CMT*DFING(I,J)
/(T*AR*PDEN*ALOG(2.))

Individual[b] (rem/ind): TD(I)*WMT*CRDMT(I)*CMT*DFING(I,J)/(F*T)

Pop. Size (ind) : AR*FMT*DMT*T/70.

[a]Exposure from radionuclides deposited by sprinkler irrigation on plants which are subsequently used as animal feed.

[b]Exposure from radionuclides in water used for livestock.

Table 1-7. Population Health Effects for 1. Curie Radionuclide Releases to Surface Water

NUCLIDE	WRHETOT[a]	FHHETOT[b]	INSDTOT[c]	EXWRTOT[d]	EXSDTOT[e]	EXARSDT[f]
C14	2.08E-05	2.58E-04	9.95E-16	0.	0.	1.98E-20
NI59	5.75E-05	1.55E-05	5.34E-14	0.	0.	0.
SR90	3.91E-02	3.17E-03	2.15E-11	2.18E-10	0.	6.78E-19
ZR93	5.89E-06	5.25E-08	7.24E-11	1.61E-11	3.42E-08	4.71E-17
TC99	2.00E-06	8.10E-08	2.22E-14	5.24E-11	0.	8.19E-20
SN126	4.68E-04	3.79E-03	3.55E-13	7.26E-09	1.27E-07	1.86E-14
I129	8.87E-05	3.60E-06	4.35E-15	6.86E-09	6.35E-09	2.54E-17
CS135	1.60E-04	8.65E-04	4.89E-13	2.66E-11	0.	7.91E-19
CS137	9.72E-04	5.255-03	2.95E-12	4.03E-07	1.19E-06	1.33E-14
SM151	1.26E-05	8.53E-07	1.90E-11	1.05E-10	2.03E-07	1.14E-12
RA226	2.34E+00	3.17E-01	2.07E-09	1.31E-06	1.81E-06	2.13E-14
U234	4.39E-03	2.37E-05	5.36E-09	4.76E-10	3.10E-08	2.19E-16
NP237	5.04E-03	1.36E-04	7.90E-10	1.45E-07	1.98E-08	2.05E-16
PU238	1.73E-04	1.64E-06	7.69E-08	6.05E-11	3.67E-08	1.92E-16
PU239	2.87E-03	2.72E-05	3.04E-06	4.84E-11	2.23E-08	1.58E-16
PU240	2.87E-03	2.72E-05	3.04E-06	5.65E-11	3.67E-08	1.84E-16
AM241	3.21E-03	2.17E-04	5.14E-07	1.57E-08	2.54E-06	2.54E-14
PU242	2.68E-03	2.53E-05	2.83E-06	4.44E-11	3.11E-08	1.44E-16
AM243	3.22E-03	2.18E-04	5.11E-07	1.25E-07	1.84E-05	1.98E-13

[a]WRHETOT ~ Total health effects from drinking water

[b]FHHETOT ~ Total health effects from eating fish

[c]INSDTOT ~ Total health effects from inhalation of sediment

[d]EXWRTOT ~ Total health effects from water imersion

[e]EXSDTOT ~ Total health effects from external exposure to sediment

[f]EXARSDT ~ Total health effects from external exposure to suspended sediment

Table 1-8. Population Health Effects for 1. Curie Radionuclide Release to Soil

NUCLIDE	PLHETOT[a]	MKHETOT[b]	MTHETOT[c]	INSLTOT[d]	EXSLTOT[e]	EXARSLT[f]
C14	2.05E-04	5.35E-05	1.67E-05	4.89E-13	0.	9.74E-18
NI59	1.36E-05	1.97E-06	1.89E-07	2.27E-11	0.	0.
SR90	2.16E-03	3.75E-05	3.40E-06	9.56E-09	0.	3.02E-16
ZR93	1.29E-06	1.40E-10	1.15E-07	1.27E-08	6.02E-06	8.31E-15
TC99	8.97E-07	4.87E-07	9.42E-07	1.09E-11	0.	4.03E-17
SN126	2.10E-06	1.14E-07	4.41E-07	1.74E-10	6.26E-05	9.18E-12
I129	3.19E-06	4.15E-07	2.43E-08	2.14E-12	3.13E-06	1.25E-14
CS135	4.86E-05	1.27E-05	5.10E-07	2.03E-10	0.	3.29E-16
CS137	2.48E-04	6.47E-05	2.61E-06	1.03E-09	4.15E-04	4.65E-12
SM151	6.80E-06	7.38E-10	8.92E-08	3.72E-09	4.00E-05	2.25E-10
RA226	1.12E-02	1.94E-03	9.99E-04	8.71E-07	7.63E-04	9.00E-12
U234	4.17E-03	4.52E-05	3.72E-06	1.86E-06	1.08E-05	7.61E-14
NP237	2.26E-05	2.46E-09	1.19E-08	3.88E-07	9.74E-06	1.01E-13
PU238	1.47E-05	6.37E-10	5.39E-10	3.56E-06	1.70E-06	8.91E-15
PU239	9.15E-04	3.97E-08	3.36E-08	5.30E-04	3.89E-06	2.76E-14
PU240	8.91E-04	3.87E-08	3.28E-08	5.15E-04	6.24E-06	3.12E-14
AM241	5.30E-04	5.75E-08	2.78E-07	9.28E-05	4.60E-04	4.60E-12
PU242	8.60E-04	3.73E-08	3.16E-08	4.97E-04	5.47E-06	2.54E-14
AM243	7.13E-04	7.74E-08	3.74E-07	1.23E-04	4.45E-03	4.79E-11

[a]PLHETOT ~ Total health effects from plant ingestion due to radionuclide uptake by plants from soil

[b]MKHETOT ~ Total health effects from milk ingestion due to radionuclide uptake by plants from soil

[c]MTHETOT ~ Total health effects from meat ingestion due to radionuclide uptake by plants from soil

[d]INSLTOT ~ Total health effects from inhalation of suspended soil

[e]EXSLTOT ~ Total health effects from external exposure to soil

[f]EXARSLT ~ Total health effects from external exposure to suspended soil

Table 1-9. Population Health Effects for 1. Curie Radionuclide Release to Surface Water With Subsequent Use of Surface Water for Livestock and Sprinkler Irrigation

NUCLIDE	IPLRHET[a]	PLHETOT[b]	IRPLHET[c]
C14	1.12E-04	2.05E-04	3.17E-04
NI59	3.10E-04	1.36E-05	3.23E-04
SR90	2.10E-01	2.16E-03	2.13E-01
ZR93	3.17E-05	1.29E-06	3.30E-05
TC99	1.08E-05	8.97E-07	1.17E-05
SN126	2.52E-03	2.10E-06	2.52E-03
I129	4.78E-04	3.19E-06	4.81E-04
CS135	8.62E-04	4.86E-05	9.11E-04
CS137	5.24E-03	2.48E-04	5.48E-03
SM151	6.80E-05	6.80E-06	7.48E-05
RA226	1.26E+01	1.12E-02	1.26E+01
U234	2.36E-02	4.17E-03	2.78E-02
NP237	2.71E-02	2.26E-05	2.72E-02
PU238	9.34E-04	1.47E-05	9.48E-04
PU239	1.55E-02	9.15E-04	1.64E-02
PU240	1.55E-02	8.91E-04	1.64E-02
AM241	1.73E-02	5.30E-04	1.78E-02
PU242	1.44E-02	8.60E-04	1.53E-02
AM243	1.74E-02	7.13E-04	1.81E-02

[a]IPLRHET ~ Total health effects from plant ingestion due to foliar deposition

[b]PLHETOT ~ Total health effects from plant ingestion due to radionuclide uptake by plants from soil

[c]IRPLHET ~ IPLRHET + PLHETOT

Table 1-9. (continued)

NUCLIDE	IMKRHET[d]	IMKWHET[e]	MKHETOT[f]	IRMKHET[g]
C14	2.92E-05	1.69E-05	5.35E-05	9.95E-05
NI59	4.51E-05	2.60E-05	1.97E-06	7.30E-05
SR90	3.66E-03	2.11E-03	3.75E-05	5.81E-03
ZR93	3.44E-09	1.99E-09	1.40E-10	5.57E-09
TC99	5.84E-06	3.37E-06	4.87E-07	9.70E-06
SN126	1.37E-04	7.91E-05	1.14E-07	2.16E-04
I129	6.23E-05	3.60E-05	4.15E-07	9.86E-05
CS135	2.25E-04	1.30E-04	1.27E-05	3.67E-04
CS137	1.36E-03	7.88E-04	6.47E-05	2.22E-03
SM151	7.38E-09	4.27E-03	7.38E-10	1.24E-08
RA226	2.19E+00	1.27E-00	1.94E-03	3.46E+00
U234	2.57E-04	1.48E-04	4.52E-05	4.50E-04
NP237	2.94E-06	1.70E-06	2.46E-09	4.65E-06
PU238	4.05E-08	2.34E-08	6.37E-10	6.46E-08
PU239	6.73E-07	3.88E-07	3.97E-08	1.10E-06
PU240	6.72E-07	3.88E-07	3.87E-08	1.10E-06
AM241	1.88E-06	1.08E-06	5.75E-08	3.02E-06
PU242	6.26E-07	3.625-07	3.73E-08	1.02E-06
AM243	1.88E-06	1.09E-08	7.74E-08	3/05E-06

[d]IMKRHET ~ Total health effects from foliar deposition and subsequent plant use in milk production

[e]IMKWHET ~ Total health effects from water used for milk cattle

[f]MKHETOT ~ Total health effects from milk ingestion due to radionuclide uptake by plants from soil

[g]IRMKHET ~ IMKRHET + IMKWHET + MKHETOT

Table 1-9. (Continued)

NUCLIDE	IMTRHET[h]	IMTWHET[i]	MTHETOT[j]	IRMTHET[k]
C14	9.11E-06	4.39E-06	1.67E-05	3.02E-05
N159	4.31E-06	2.07E-06	1.89E-07	6.57E-06
SR90	3.32E-04	1.60E-04	3.40E-06	4.94E-04
ZR93	2.83E-06	1.36E-06	1.15E-07	4.31E-06
TC99	1.13E-05	5.44E-06	9.42E-07	1.77E-05
SN126	5.30E-04	2.55E-04	4.41E-07	7.85E-04
I129	3.64E-06	1.75E-06	2.43E-08	5.41E-06
CS135	9.05E-06	4.36E-06	5.10E-07	1.39E-05
CS137	5.50E-05	2.65E-05	2.61E-06	8.41E-05
SM151	8.93E-07	4.30E-07	8.92E-08	1.41E-06
RA226	1.13E+00	5.43E-01	9.99E-04	1.67E+00
U234	2.11E-05	1.02E-05	3.72E-06	3.50E-05
NP237	1.42E-05	6.86E-06	1.19E-08	2.11E-05
PU238	3.43E-08	1.65E-08	5.39E-10	5.14E-08
PU239	5.69E-07	2.74E-07	3.36E-08	8.77E-07
PU240	5.69E-07	2.74E-07	3.28E-08	8.75E-07
AM241	9.07E-06	4.37E-06	2.78E-07	1.37E-05
PU242	5.30E-07	2.55E-07	3.16E-08	8.16E-07
AM243	9.12E-06	4.39E-06	3.74E-07	1.39E-05

[h]IMTRHET ~ To health effects from foliar deposition and subsequent plant use in meat production

[i]IMTWHET ~ Total health effects from water used for meat production

[j]MTHETOT ~ Total health effects from meat ingestion due to radionuclide uptake by plants from soil

[k]IRMTHET ~ IMTRHET + IMTWHET + MTHETOT

Table 1-10. Organs and Risk Factors Considered

Organ/Cancer	Risk Factor EPA[a] (cancer/ind-rem)	Risk Factor Sandia[b] (cancer/ind-rem)
Bone	1.00E-5	9.75E-6
Red Marrow/ Leukemia	4.00E-5	2.85E-5[c]
Lung	4.00E-5	2.5E-5
Liver	1.00E-5	
GI-LLI	2.00E-5	
Stomach		1.15E-5[d]
Pancreas		3.85E-6[d]
Other GI		3.85E-6[d]
Thyroid	1.00E-6	
Kidney	1.00E-5	
Breast		2.88E-5[e]
Other	7.00E-5	3.60E-5[e]

[a]From Table 4.3-1 of (Sm81)

[b]From Table 3.4 of (Ru81)

[c]Dose factor for bone used

[d]Dose factor for GI-LLI used

[e]Dose factor for total body used

(see Sm81, p. 93). The values used for all other variables are indicated in Table 1-11.

To generate the values for IMKWHET and IMTWHET in Table 1-9, it was necessary to know the area AR under consideration. This was obtained by assuming that an irrigation rate IRAT of 300 L/m^2 per yr was used. Then, AR can be expressed in terms of IRAT, F and FRIV.

1.4 Comparison With Environmental Protection Agency Results

The Environmental Protection Agency results for a release to surface water are presented in Table 1-12. As already noted, it is the numbers appearing in the column labeled "TOTAL" of this table that were used in obtaining the Environmental Protection Agency draft standard for radionuclide releases in the context of geologic disposal for high-level waste; these numbers were obtained by summing the numbers in the other columns and represent total population health effects. The population health effects in columns labeled "p = 1" through "p = 8" are now compared with related results in Tables 1-7, 1-8 and 1-9.

The results for drinking water ingestion appearing in column p = 1 of Table 1-12 and column WRHETOT of Table 1-7 were calculated with models that are essentially identical. This similarity tends to be obscured by the differences in notation and derivation technique used in this report and in (Sm81). Therefore, the computational approach used in the two developments will be compared. Much of the apparent difference arises from the nature of the dose factors used. In this regard, the reader is reminded that the dose factors in (Sm81) for ingestion and inhalation yield a 50. year dose commitment from a 1. year exposure. In contrast, in our analysis the dose factors for ingestion and inhalation yield a 70. year dose commitment from a 70. year chronic exposure. For the former dose factors, multiplication of a 1. year ingestion or inhalation rate by the dose factor provides the 50. year commitment from the 1. year of exposure; for the latter dose factors, multiplication of the average annual ingestion or inhalation rate by the dose factor provides the dose commitment over 70. years which results from 70. years of exposure.

Table 1-11. Variables Used in Calculation of Results Presented in Tables 1-7, 1-8 and 1-9

Variable	Definition	Variable	Definition
AIRCON	3.5E-9 kg/m^3 (Bon73, Table 1.4-5)	PDEN	2. kg/m^2 (Nu76, p. 1.109-55)
CMLK	110. L/yr (Nu76, Table D-1)	PMLK	50. kg/day (Nu76, Table A-10)
CMT	95. kg/yr (Nu76, Table D-1)	PMT	50. kg/day (Nu76, Table A-10)
CPLT	190. kg/yr (Nu76, Table D-1)	PO	.5 (To70, Table 4-25)
DE	2800. kg/m^3 (Cu73, Table 34-20)	POROSIT	.5 (To70, Table 4-25)
DENSITY	2800. kg/m^3 (Cu73, Table 34-20)	REXARSD	8.3 hr/yr (Nu76, Table D-1)
DEPTH	.025 m	REXARSL	8760. hr/yr (Nu76, Table D-1)
DFSH	3.3E-7 kg/L (Sm81, p. 87)	REXTSD	8.3 hr/yr (Nu76, Table D-1)
DMLK	1.5E-3 ind/m^2 (Sm81, p. 91)	REXTSL	8760 hr/yr (Nu76, Table D-1)
DMT	2.1E-4 ind/m^2 (Sm81, p. 91)	REXTWAT	8.3 hr/yr (Nu76, Table D-1)
DP	.15m (Sm81, p. 85)	RINGWAT	370. L/yr (Nu76, Table D-1)
DPLT	1.0E-3 ind/m^2 (Sm81, p. 91)	RINHAIR	7300 m^3/yr (Nu76, Table D-1)
DPOP	3.3E-7 ind-yr/L (Sm81, p. 86)	RO	510 L/m^2-yr (To70, Table 2-22)
DSL	6.67E-5 ind/m^2 (Sm81, p. 91)	SA	.5 (To70, Figure 4-2)
ER	.36 kg-yr/m^2 (To70, Table 2-33)	TMINSD	9.5E-4 (Nu76, Table D-1)
FMLK	.25 (SM81, p. 89)	TMINSL	1. (Nu76, Table D-1)
FMT	.25 (Sm81, p. 89)	WHRHL	.038 yr (Boo81)
FPLT	.5 (Sm81, p. 89)	WMLK	60 L/day (Nu76, Table A-10)
FRET	.25 (Boo81)	WMT	50 L/day (Nu76, Table A-10)
FRIV	1.		

Table 1-12. Health Effects per Curie Released for Releases to a River[a]

Nuclide	TOTAL	Drinking Water Ingestion (p = 1)	Freshwater Fish Ingestion (p = 2)	Above Surface Crops Ingestion (p = 3)	Milk Ingestion (p = 4)	Beef Ingestion (p = 5)	Inhalation of Resuspended Material (p = 6)	External Dose - Ground Contam. (p = 7)	External Dose - Air Submersion (p = 8)
C- 14	4.58 E- 2	7.40 E- 5	5.59 E- 4	2.99 E- 2	1.11 E- 2	4.10 E- 3	1.46 E-12	0.0	0.0
Ni- 59									
Sr- 90	1.21 E- 1	8.03 E- 3	6.66 E- 5	1.05 E- 1	7.79 E- 3	1.04 E- 4	7.87 E- 7	0.0	0.0
Zr- 93									
Tc- 99	2.85 E- 4	2.42 E- 5	6.02 E- 7	1.92 E- 4	6.25 E- 5	5.82 E- 6	4.92 E-10	0.0	0.0
Sn-126	1.20 E- 1	1.41 E- 3	7.01 E- 3	6.66 E- 3	2.95 E- 4	2.09 E- 3	3.71 E- 6	1.02 E- 1	5.61 E- 9
I-129	1.08 E- 2	1.63 E- 3	4.05 E- 5	6.43 E- 3	2.44 E- 3	1.84 E- 4	1.22 E- 8	9.19 E- 5	1.54 E-12
Cs-135	3.81 E- 3	2.55 E- 4	1.69 E- 4	2.13 E- 3	9.99 E- 4	2.65 E- 4	1.12 E- 7	0.0	0.0
Cs-137	1.98 E- 2	2.01 E- 3	1.33 E- 3	7.83 E- 3	2.08 E- 3	5.55 E- 4	7.51 E- 8	5.96 E- 3	3.35 E-10
Sm-151									
Ra-226									
U-234									
Np-237	5.96 E- 1	1.30 E- 1	2.15 E- 3	4.60 E- 1	9.21 E- 5	3.90 E- 4	1.03 E- 1	4.95 E- 1	2.22 E- 8
Pu-238	2.29 E- 2	3.92 E- 3	2.28 E- 3	1.42 E- 2	3.03 E- 8	1.16 E- 9	2.40 E- 3	5.16 E- 5	2.63 E-13
Pu-239	6.92 E- 2	4.32 E- 3	2.50 E- 3	2.51 E- 2	5.39 E- 8	2.06 E- 9	3.69 E- 2	3.24 E- 4	1.71 E-12
Pu-240	6.53 E- 2	4.32 E- 3	2.51 E- 3	2.37 E- 2	5.16 E- 8	1.97 E- 9	3.41 E- 2	5.86 E- 4	3.00 E-12
Am-241	7.19 E- 1	1.32 E- 1	5.47 E- 3	5.61 E- 1	8.32 E- 4	3.91 E- 6	1.14 E- 2	8.61 E- 3	1.64 E-10
Pu-242	6.76 E- 2	4.10 E- 3	2.38 E- 3	2.43 E- 2	4.44 E- 8	4.29 E- 8	3.62 E- 2	6.07 E- 4	3.10 E-12
Am-243	2.68 E 0	3.38 E- 1	1.40 E- 2	2.13 E 0	3.28 E- 3	1.55 E- 5	8.93 E- 2	1.13 E- 1	4.61 E- 9

[a]This table is a reprint of Table D-2 of (Sm81).

From (3.1.2-6) in (Sm81), the population exposure from a release to a river is given by

$$S_{nop} = P_R I_W D_{nop} Q_{np}/R, \qquad (1.8)$$

where S_{nop} represents population exposure to organ o from radionuclide n for path p (in this case, p = 1), P_R represents the size of the population exposed each year to drinking water, I_W represents individual water consumption per year, D_{nop} represents the dose factor to organ o from radionuclide n for path p, Q_{np} represents the total release of radionuclide n for path p, and R represents annual river discharge. From the relations in Table 1-4, the same population exposure is given by

```
RINGWAT*TD(I)*WT(I)*DFING(I,J)*DPOP/70.          (1.9)
```

The expressions for population exposure in (1.8) and (1.9) are essentially the same as the following correspondences exist:

P_R/R = DPOP = 3.3E-7 ind-yr/L in both analyses

I_W = RINGWAT = $\begin{cases} 603 \text{ L/yr in EPA analysis} \\ 370 \text{ L/yr in present analysis} \end{cases}$

Q_{np} = TD(I) = 1. Ci in both analyses

WT(I) = 1. in both analyses.

The difference between the expressions D_{nop} and DFING(I,J)/70. arises from the nature of the dose factors; this is best seen by first calculating an individual dose commitment and then converting to a population dose commitment.

From (3.1.2-1) in (Sm81), the 50. year dose commitment to an individual from the radionuclides in water ingested during 1. year is given by

$$DI'_{nop} = Q'_{np} I_W D_{nop} / R. \tag{1.10}$$

For the preceding relation, DI_{nop} and Q_{np} are being considered functions of time $DI_{nop}(t)$ and $Q_{np}(t)$ such that $DI_{nop}(t)$ is the total dose commitment to an individual from birth to time t and $Q_{np}(t)$ is the total radionuclide release from time 0 to time t. Then, $DI'_{nop}(t)$ and $Q'_{np}(t)$ represent the derivatives of these functions with respect to time and thus correspond to annual individual dose commitment rate at time t and annual discharge rate at time t. Multiplication of the expression in (1.10) by population size P_R yields the population dose commitment rate

$$S'_{nop} = DI'_{nop} P_R = Q'_{np} I_W D_{nop} P_R / R. \tag{1.11}$$

Now, integration can be used to recover S_{nop} for a time period of length T in the following manner:

$$\begin{aligned} S_{nop}(T) &= \int_0^T S'_{nop}(t)dt \\ &= \int_0^T Q'_{np}(t) I_W D_{nop} P_R / R dt \\ &= Q_{np}(T) I_W D_{nop} P_R / R, \end{aligned} \tag{1.12}$$

which yields the relation in (1.8).

In comparison, Table 1-4 provides the following expression for a 70. year dose commitment to an individual from a chronic 70. year exposure:

$$RINGWAT*TD(I)*WT(I)*DFING(I,J)/(F*T). \tag{1.13}$$

The expression for total population size is derived from the assumptions that the size of the population exposed to drinking water each year is DPOP*F, that the time period considered is of length T, and that the average life expectancy is 70. years. Thus, if T is significantly larger than 70., then the total number of individuals exposed is given by

$$DPOP*F*T/70. \qquad (1.14)$$

Now, multiplication of the expressions in (1.13) and (1.14) yields the relation in (1.9).

The use of derivatives and integrals in (1.10), (1.11), and (1.12) tends to obscure the relation between the expressions in (1.8) and (1.9). Therefore, the expression in (1.10) for individual dose commitment will be reconsidered with an average annual discharge rate rather than a time varying discharge rate obtained by differentiating $Q_{np}(t)$. Specifically, with the assumption that a total discharge of size Q_{np} takes place over a time period of length T, the expression for 50. year dose commitment to an individual from 1. year of exposure in (1.10) becomes

$$Q_{np}I_W D_{nop}/(R*T), \qquad (1.15)$$

and so the dose commitment to an individual from 50. years of exposure can be estimated as

$$Q_{np}I_W D_{nop}*50./(R*T). \qquad (1.16)$$

The expression for lifetime dose commitment in (1.16) from the Environmental Protection Agency analysis is comparable to the similar expression in (1.13) for lifetime dose commitment. For both expressions, multiplication by total population size for the time period considered will yield population dose. The population for (1.16) is

$$P_R*T/50. = DPOP*R*T/50. \qquad (1.17)$$

while the population for (1.13) is given in (1.14). Now, multiplication of the expressions in (1.16) and (1.17) will yield (1.8). Similarly, multiplication of the expressions in (1.13) and (1.14) will yield (1.9).

Overall, the results appearing for drinking water ingestion in Tables 1-12 and 1-7 are quite similar. In most cases, the difference was less than one order of magnitude; however, in a few cases the difference was greater. As both approaches used the same technique to calculate surface water concentration, the differences are due to the water ingestion rates assumed, the cancers considered and the dose and risk factors used. The organs and risk factors used for ingestion and inhalation calculations are given in Table 1-10. Further, the differences in the dose factors considered has already been discussed.

The results for freshwater fish ingestion appearing in column p = 2 of Table 1-13 and column FHHETOT of Table 1-7 were calculated with models that are essentially identical. Again, the results are similar; in most cases, the results are within an order of magnitude. However, in some cases, the difference is closer to two orders of magnitude. As for water ingestion, differences are introduced by the cancers, dose factors and risk factors used. Although most of the concentration ratios from water to fish used in the two analyses are similar, some variation is also introduced here (see Table 5-2 of (Sm81) and Table A-8 of (Nu76)).

The results for plant ingestion appearing in column p = 3 of Table 1-12 and column IRPLHET of Table 1-9 are calculated with similar models. Both models have a submodel for radionuclide build-up on plants due to sprinkler irrigation and a submodel for radionuclide build-up in soil. For IRPLHET, the population health effects associated with these two submodels are given in the columns labeled IPLRHET and PLHETOT, respectively, in Table 1-9; no such distinction is made in the results presented in (Sm81). For both analyses, a radionuclide release is assumed to take place to soil through sprinkler irrigation with 50 percent of the soil being used to grow plant material for direct human consumption. In the Environmental Protection Agency study (Sm81), it is assumed that a .5 curie release to the soil for each radionuclide takes place; for the calculations that generated Table 1-9, a 1. curie release is assumed to take place. Therefore, as the models are linear with respect to radionuclide input, the appropriate comparison between the ingestion rates should be made with the indicated values for IRPLHET divided by 2. Both models use the same exponential model for radionuclide build-up on plants due to sprinkler irrigation (i.e., the submodel

used in determining IPLRHET); however, some of the parameters used within the model were different (e.g., .20 for fraction of radionuclides initially retained in the Environmental Protection Agency analysis and .25 in our analysis). Both models also use similar exponential models to represent radionuclide build-up in the soil (i.e., the submodel used in determining PLHETOT). In the Environmental Protection Agency analysis, radionuclide removal is by water flow and radioactive decay. Our analysis includes those two removal mechanisms and also solid-material outflow. However, the models may differ in some details (e.g., the exact manner in which the rate constants for radionuclide outflow in water were determined) and in the actual parameters used in the analyses (e.g., water outflow rates, distribution coefficients). However, the final calculated health effects are generally within an order of magnitude of each other. The differences are probably due to the different cancers, dose factors and risk factors considered and to the different values used for the same or similar parameters. Also, the inclusion of soil removal (i.e., erosion) in the calculation of PLHETOT may have an effect.

The results for milk ingestion appearing in column p = 4 of Table 1-12 can be compared with the sum of the values appearing in columns IMKRHET and MKHETOT of Table 1-9. In both analyses, it is assumed that 25 percent of the available land is used to grow plant material for use in milk production. The values for IMKRHET result from the radionuclides retained on plants due to sprinkler irrigation and the values for MKHETOT result from the radionuclides in plants due to uptake from soil. As for direct plant ingestion, the results in Table 1-12 are the sum of these two paths. Also, as a 1. curie release was considered in the generation of the results contained in Table 1-9, the proper comparison is between the values in Table 1-12 and one-half of the sum of IMKRHET and MKHETOT. As radionuclide concentration in plants for animal feed was determined in the same manner as radionuclide concentration in plants for human consumption, the discussion in the preceding paragraph is also relevant to the present comparison. There is a considerable amount of difference between the milk ingestion results in the Environmental Protection Agency analysis and in our analysis. Although the results are similar for some radionuclides, for other radionuclides a difference of up to three orders of magnitude exists. These differences are probably caused by factors of the

type already indicated. However, to identify the major causes of these differences, it would be necessary to compare calculations for the same radionuclides on a parameter-by-parameter basis. The health effects that result from radionuclides in livestock water for dairy cattle are indicated in column IMKWHET of Table 1-9. This path is not included in the calculation of the results presented in Table 1.12.

The results for beef ingestion appearing in column p = 5 of Table 1-12 can be compared with the sum of values appearing in columns IMTRHET and MTHETOT of Table 1-9. As the calculations for beef ingestion are the same as those for milk ingestion except for the use of appropriate concentration ratios and ingestion rates, the discussion for milk ingestion also pertains to beef ingestion. Overall, the results for beef ingestion for the two analyses are more similar than those for milk ingestion. For most radionuclides, the results are within one order of magnitude. However, in some cases, this difference goes up to approximately two orders of magnitude. The health effects that result from radionuclides in livestock water for beef cattle are indicated in column IMTWHET of Table 1-9. As for milk consumption, this path is not included in the calculation of the results presented in Table 1-12.

Results in the Environmental Protection Agency analysis for health effects due to inhalation of suspended material, external exposure due to ground contamination and external exposure due to suspended material in air are presented in columns p = 6, p = 7, and p = 8, respectively, of Table 1-12. Similar results for our analysis are presented in columns INSLTOT, EXSLTOT, and EXARSLT, respectively, of Table 1-8. As our analysis was for a total release of 1. curie, the values in Table 1-12 should be compared with one-half the corresponding values in Table 1-8. Generally, the results in our analysis are one to two orders of magnitude below corresponding results in Table 1-12. In the Environmental Protection Agency analysis, it is assumed that all radionuclides in the soil are concenttrated on the surface for the calculation of the exposure modes now under consideration (see Equations (3.1.5-9) and (3.1.5-10) in (Sm81)). This alone is sufficient to cause discernable differences between the results.

To determine inhalation exposure, the Environmental Protection Agency obtained suspended radionuclide concentration through multiplication of surface radionuclide concentration (units: Ci/m^2) by a resuspension factor of 10^{-9} m^{-1} (Sm81, p. 92). In contrast, we obtained suspended radionuclide concentration by multiplication of soil radionuclide concentration (units: Ci/m^3) by an assumed concentration of suspended material in air of 3.5E-9 kg/m^3. For an assumed amount X of a particular radionuclide in a soil region of area AR, the Environmental Protection Agency approach yields a suspended concentration of

$$(X/AR)*10^{-9} = X*10^{-9}/AR \ Ci/m^3 \qquad (1.18)$$

while our approach yields a suspended radionuclide concentration of

$$(X/(AR*.15*2800.*.5))*3.5E-9$$

$$= (X/AR)*1.7E-11 \ Ci/m^3. \qquad (1.19)$$

Thus, this difference alone will cause the results from Tables 1-12 and 1-8 for inhalation of radionuclides and external exposure to suspended radionuclides to differ by a factor of approximately 59. Similarly, for ground exposure, we assume that only the radionuclides in the top 2.5 cm of the soil are available for external exposure. Thus, as our soil was assumed to be 15. cm deep and the Environmental Protection Agency analysis assumed that all radionuclides in soil were on the surface, this difference alone will cause the results from Table 1-12 and 1-8 for ground exposure to differ by a factor of 6. Other differences are due to the cancers, dose factors and risk factors considered and to the individual parameters used in determining the amount of each radionuclide in soil.

In summary, the population health effects in our analysis were generally within one to two orders of magnitude of the results obtained in the Environmental Protection Agency analysis. However, in some cases, the differences were closer to three orders of magnitude. As the two analyses used similar models, these differences are due primarily to the cancers, dose factors,

and risk factors used and to the parameters actually used within the models. If desired, the exact cause of the differences can be determined for individual radionuclides and specific exposure pathways from a parameter by parameter comparison of the two calculations.

1.5 Discussion

Overall, it is felt that the computational relationships indicated in Tables 1-4, 1-5 and 1-6 will yield conservative results. For example, no radionuclide removal by sedimentation is considered in the results related to surface-water concentration in Table 1-4. However, the individual using these relationships has a great deal of control on the conservatism of the final calculated results through the selection of ingestion rates, concentration ratios, risk factors, constants used in the definition of population size, and other parameters.

The relationships presented in Tables 1-4, 1-5 and 1-6 provide a convenient way to observe the differences between exposures to individuals and populations. In particular, the exposure to individuals can vary dramatically while population exposure remains unchanged. This results from the assumed linearity of the processes considered. Thus, while length of release and size of river receiving the release will affect individual exposure, these properties will not affect population exposure obtained with the models in use.

Computational relationships of the form given in Tables 1-4, 1-5 and 1-6 provide a way of comparing hazards from different substances. They could be used to compare risks between artificially and naturally occurring radioactivity. Also, there is nothing in the models which is inherently tied to radioactive materials. Therefore, provided appropriate dose and risk factors were defined, they could be used to calculate the consequences associated with nonradioactive pollutants. In turn, such values could be used in the comparison of the risks associated with waste disposal and the risks associated with other activities. In making such comparisons, it is essential that the compared risks be calculated in the same manner and with the same degree of conservatism. Otherwise, the comparisons are meaningless. Hopefully, with relatively simple models such as those in Tables 1-4, 1-5 and 1-6, it would be possible to treat all the substances considered in the same manner.

The computational relationships in Tables 1-4, 1-5 and 1-6 provide a way to screen for the most appropriate radionuclides to consider in the regulation of geologic disposal of high-level waste. The consequences associated with a unit release of each radionuclide of possible interest can be calculated. These consequences can then be weighted by the inventory of the radionuclide present. Once this has been done for all radionuclides, consideration of the relative size of the weighted consequences provides one way to select the radionuclides for regulatory consideration.

Unfortunately, many of the variables used in Tables 1-4, 1-5 and 1-6 will be imprecisely known in any analysis. The relative simplicity of the relationships in these tables permits an easy inspection of the effects of uncertainty in individual variables. Quite often, this effect is linear. For example, a doubling of the water ingestion rate will double the associated consequences. Discernment of the effects of variation in several (possibly correlated) variables is more difficult. However, techniques exist which can be used in such analyses (Im78).

Tables 1-7, 1-8 and 1-9 present the population health effects for the various pathways considered in Tables 1-4, 1-5 and 1-6 with a release of 1. Ci. The individual parameters used in the associated calculations are indicated in Section 1.3. It is often possible to investigate the effects of other parameters without reproducing an entire calculation. For example, the health effects for a water ingestion rate of 603. L/yr (Sm81, p. 86) rather than 370. L/yr can be obtained by multiplying the results in column WRHETOT of Table 1-7 by 603./370. The combined effects of various release modes can be obtained by taking appropriate linear combinations of values in Tables 1-7, 1-8 and 1-9. For example, the population health effects for each radionuclide due to water and plant ingestion resulting from a release to a river with 10 percent of the river used for flood irrigation are given by

$$1.*\text{WRHETOT} + .1*\text{PLHETOT}. \qquad (1.20)$$

Such relationships can be used to investigate different sites and different assumptions about a specific site.

This discussion ends with a caveat. The models presented are very simple and probably tend to overestimate health effects. They will certainly do so if one is sufficiently aggressive in seeking out conservative values for the individual parameters in the models. Therefore, care must be exercised in the interpretation and presentation of model predictions. In particular, care must be taken in comparing results obtained with these models with results obtained with other methods. However, there is also an advantage to this simplicity. It permits consideration of different hazards at an equivalent level of complexity.

2. Mixed-Cell Models

The exposure calculations presented in later chapters are based on radionuclide concentrations obtained by using one compartment mixed-cell models. For releases to surface water, no radionuclide partitioning within the cell is considered. However, for releases to soil, such partitioning is considered. To facilitate presentation of the later exposure calculations, derivations are presented in this chapter for the differential equations which underlie the models in use. This presentation is adapted from Sections B-2 and B-3 of Helton and Finley (He82).

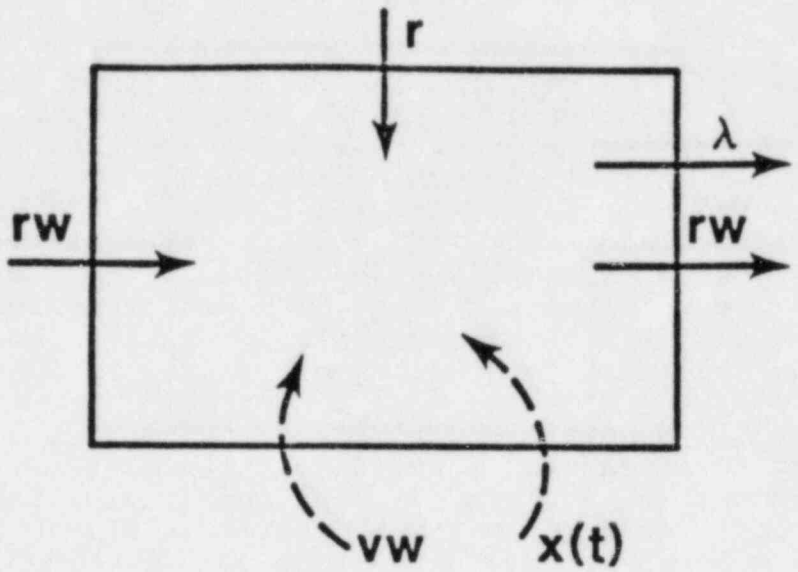
The differential equation for a single uniformly-mixed cell without radionuclide partitioning between a liquid and a solid phase is presented first. The situation under consideration is indicated in Figure 2-1. The cell is assumed to have a constant volume VW (units: L). Further, it is assumed that water enters and leaves the cell at a rate RW (units: L/yr) and that a radionuclide with decay constant λ (units: yr^{-1}) enters the cell at a rate R (units: Ci/yr). It is desired to determine the amount X(t) (units: Ci) of the radionuclide present in the cell at time t (units: yrs). The basic assumption used in deriving X(t) is that the cell is uniformly-mixed; mathematically, this means that the radionuclide concentration C(t) (units: Ci/L) at any time t is given by

$$C(t) = X(t)/VW. \tag{2.1}$$

A differential equation representing the rate of change of X(t) is now derived. Then, X(t) can be obtained by solving this equation. The derivative dX(t)/dt (units: Ci/yr) is defined by the limit

$$\lim_{\Delta t \to 0} \frac{X(t + \Delta t) - X(t)}{\Delta t} \tag{2.2}$$

and represents the rate at which X(t) is changing. In turn, this rate is equal to the difference between the rate R_1 (units: Ci/yr) at which the radionuclide is entering the cell and the rate R_2 (units: Ci/yr) at which the radionuclide is leaving the cell. The rate



R: rate at which radionuclide enters cell
(units: Ci/yr)

RW: rate at which water enters and leaves cell
(units: L/yr)

λ: decay constant for radionuclide
(units: yr^{-1})

VW: volume of water in cell (units: L)

X(t): amount of radionuclide in cell at time t
(units: Ci)

Figure 2-1. Flows Associated With a Single Uniformly-Mixed Cell With no Radionuclide Partitioning Between a Liquid and a Solid Phase.

R_1 is given by R. The rate R_2 is the sum of two components: a rate due to physical flow out of the cell, and a rate due to radioactive decay. The rate due to physical flow is equal to the product of the radionuclide concentration X(t)/VW in the cell and the rate of water flow RW out of the cell; the rate due to decay is equal to the product of the decay constant λ and the amount X(t) of radionuclide present. Thus,

$$R_1 = R \text{ and } R_2 = [(RW/VW) + \lambda] X(t), \qquad (2.3)$$

and hence, the desired equation is given by

$$\begin{aligned} dX(t)/dt &= R_1 - R_2 \\ &= R - [(RW/VW) + \lambda] X(t). \end{aligned} \qquad (2.4)$$

Also associated with the preceding equation is an initial value condition $X(0) = X_0$, which represents the amount of radionuclide present at time t = 0.

Thus, determination of X(t) reduces to the solution of an initial value problem of the form

$$dX(t)/dt = R - AX(t), \; X(0) = X_0, \qquad (2.5)$$

where

$$A = (RW/VW) + \lambda . \qquad (2.6)$$

Such problems are relatively easy to solve and applicable solution techniques include separation of variables, introduction of integration factors, and application of Laplace transforms. The preceding techniques are discussed in introductory texts on differential equations and lead to the following unique solution for the initial value problem in (2.5):

$$X(t) = e^{-At} X_0 + (R/A)(1 - e^{-At}). \qquad (2.7)$$

If the initial value condition is $X(0) = 0$, then the preceding solution becomes

$$X(t) = (R/A)(1 - e^{-At}). \tag{2.8}$$

Further, regardless of the initial value condition, the steady state or asymptotic solution SX to which any solution of (2.5) converges is given by

$$SX = \lim_{t \to \infty} X(t)$$

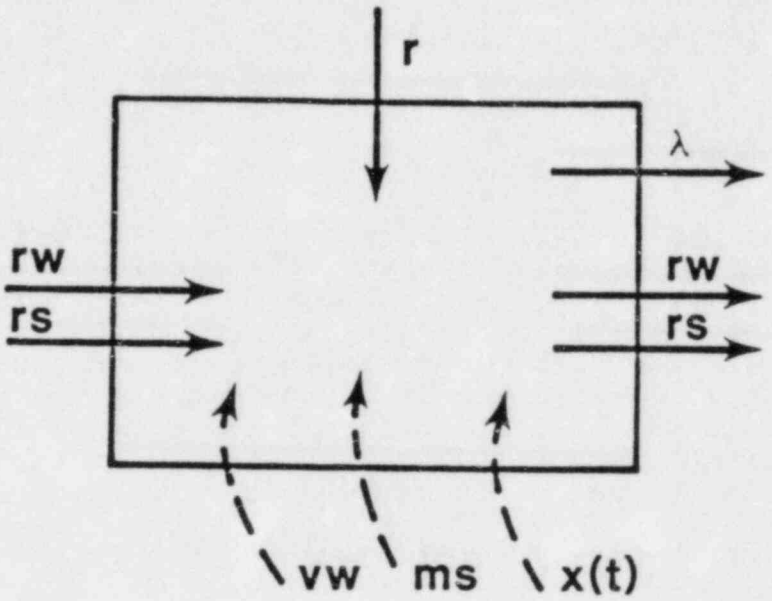
$$= \lim_{t \to \infty} [e^{-At} X_0 + (R/A)(1 - e^{-At})]$$

$$= R/A, \tag{2.9}$$

provided $A > 0$.

The differential equation for a single uniformly-mixed cell with radionuclide partitioning between a liquid and a solid phase is presented next. The situation under consideration is indicated in Figure 2-2. The cell is assumed to have a constant volume VW (units: L) and to contain a constant mass MS of solid material (units: kg). Further, it is assumed that water enters and leaves the cell at a rate RW (units: L/yr), that solid material enters and leaves the cell at a rate RS (units: kg/yr), and that a radionuclide with decay constant λ(units: yr^{-1}) enters the cell at a rate R (units: Ci/yr). The partitioning of the radionuclide between the liquid and solid phases of the system is assumed to be described by the ratio

$$KD = \frac{\text{conc. of radionuclide sorbed to solids}}{\text{conc. of radionuclide dissolved in water}} = \frac{AW/MS}{AW/VW}, \tag{2.10}$$



R: rate at which radionuclide enters cell (units: Ci/yr)

RW: rate at which water enters and leaves cell (units: L/yr)

RS: rate at which solid material enters and leaves cell (units: kg/yr)

λ: decay constant for radionuclide (units: yr^{-1})

VW: volume of water in cell (units: L)

MS: mass of solids in cell (units: kg)

X(t): amount of radionuclide in cell at time t (units: Ci)

Figure 2-2. Flows Associated With a Single Uniformly-Mixed Cell With Radionuclide Partitioning Between a Liquid and a Solid Phase.

where AS (units: Ci) is the amount of radionuclide in the system sorbed to solids and AW (units: Ci) is the amount of radionuclide in the system dissolved in water. The ratio in (2.10) is known as a KD-value or a distribution coefficient.

It is desired to determine the amount X(t) (units: Ci) of the radionuclide present in the cell at time t (units: yr). Three basic assumptions underlie the derivation of X(t). First, it is assumed that the radionuclide is uniformly distributed through the cell and is partitioned between the liquid and solid phases on the basis of its distribution coefficient. A derivation for this partitioning is presented in the next paragraph. Second, it is assumed that the flow of water and solid material out of the cell is the only mechanism involved in the physical transport of the radionuclide. Third, it is assumed that all radionuclides associated with a phase, liquid or solid, remain with that phase in movements out of the cell. In essence, the cell is treated as a uniformly mixed "vessel" in which the radionuclides are partitioned between the liquid and solid phases on the basis of the distribution coefficient and such that radionuclides can be carried out of this "vessel" and out of the system only by movements of water or solid material.

A derivation for the partitioning of a radionuclide between the liquid and solid phases of a system is now presented. The following notation is used in the derivation:

X = amount of radionuclide in system (units: Ci),

XS = amount of radionuclide in system sorbed to solids (units: Ci),

XW = amount of radionuclide in system dissolved in water (units: Ci),

MS = mass of solid in system (units: kg),

VW = volume of water in system (units: L).

Assume X, MS, VW, and KD are known for the system under consideration. Now, XS and XW are determined. Since

$$KD = (XS/MS)(XW/VW)^{-1} \text{ and } X = XS + XW, \tag{2.11}$$

we have that

$$(KD)(MS) = (XS)(VW)(XW)^{-1} \text{ and } XW = X - XS. \tag{2.12}$$

Thus,

$$(KD)(MS) = (XS)(VW)(X - XS)^{-1}. \tag{2.13}$$

Further, multiplication by (X - XS) gives

$$(KD)(MS)(X) - (KD)(MS)(XS) = (XS)(VW) \tag{2.14}$$

or

$$(KD)(MS)(X) = [(KD)(MS) + VW]\ XS, \tag{2.15}$$

and hence

$$XS = \left[\frac{(KD)(MS)}{(KD)(MS) + VW}\right] X. \tag{2.16}$$

Further, since XW = X - XS,

$$XW = \left[1. - \frac{(KD)(MS)}{(KD)(MS) + VW}\right] X. \tag{2.17}$$

The relations in (2.16) and (2.17) represent the desired partitioning.

A differential equation representing the rate of change of X(t) is now derived. Then, X(t) can be obtained by solving this equation. The following derivation is similar to that previously presented for a uniformly-mixed cell without partitioning. As for that case, dX(t)/dt is equal to the difference between the rate R_1 at which the radionuclide is entering the cell and the rate R_2 at which the radionuclide is leaving the cell. The rate R_1 is given by R. The rate R_2 is the sum of three components: a rate due to physical flow out of the cell with solid material, a rate due to physical flow out of the cell with water, and a rate due to radioactive decay. The two rates due to physical flow are equal to the products of the concentrations XS(t)/MS and XW(t)/VW with the flow rates RS and RW, where XS(t) represents the amount of radionuclide in the cell sorbed to solid material and XW(t) represents the amount of radionuclide in the cell dissolved in water. The functions XS(t) and XW(t) can be obtained from (2.16) and (2.17). The rate due to decay is equal to the product of the decay constant and the amount X(t) of radionuclide present. Thus,

$$R_1 = R \tag{2.18}$$

and

$$R_2 = [XS(t)/MS][RS] + [XW(t)/VW][RW] + \lambda X(t)$$

$$= \left[\frac{(KD)(MS)}{(KD)(MS) + VW}\right]\left[X(t)\right]\left[\frac{RS}{MS}\right]$$

$$+ \left[1. - \frac{(KD)(MS)}{(KD)(MS) + VW}\right]\left[X(t)\right]\left[\frac{RW}{VW}\right] + \lambda X(t)$$

[From (2.16) and (2.17)]

$$= \left[\frac{S(RS)}{MS} + \frac{(1. - S)(RW)}{VW} + \lambda\right] X(t) \tag{2.19}$$

where

$$S = \frac{(KD)(MS)}{(KD)(MS) + VW} \quad . \tag{2.20}$$

Hence, the desired equation is given by

$$dX(t)/dt = R_1 - R_2$$

$$= R - \left[\frac{S(RS)}{MS} + \frac{(1. - S)(RW)}{VW} + \lambda\right] X(t). \tag{2.21}$$

Also associated with the preceding equation is an initial value condition $X(0) = X_0$.

Thus, determination of X(t) reduces to the solution of an initial value problem of the form

$$dX(t)/dt = R - AX(t), \; X(0) = X_0, \tag{2.22}$$

where

$$A = \frac{S(RS)}{MS} + \frac{(1. - S)(RW)}{VW} + \lambda \tag{2.23}$$

with S defined as in (2.20). Various forms of the solution to the preceding initial value problem are given in (2.7), (2.8), and (2.9).

3. Release to Surface Water

3.1 Preliminary Comments

Population exposures and resultant health effects are now calculated for radionuclide release to a surface-water body. In particular, WRDS(I,J),WRHE(I,J) and WRHETOT(I) are determined for exposure from water consumption, where

WRDS(I,J) = population dose (units: rems) to organ associated with cancer J from radionuclide I,

WRHE(I,J) = number of occurrences of cancer J in population due to radionuclide I,

WRHETOT(I) = total number of cancers in population due to radionuclide I.

Similarly, FHDS(I,J), FHHE(I,J) and FHHETOT(I) are determined for fish ingestion; INSDDS(I,J), INSDHE(I,J) and INSDTOT(I) are determined for inhalation of suspended sediment; EXWRDS(I,J), EXWRHE(I,J) and EXWRTOT(I) are determined for water immersion; EXSDDS(I,J), EXSDHE(I,J) and EXSDTOT(I) are determined for external exposure from shoreline sediments; and EXARSDD(I,J), EXARSDH(I,J) and EXARSDT(I) are determined for external exposure from suspended sediments.

The quantities indicated in the preceding paragraph are obtained in the following manner. First, individual radionuclide exposure rates are determined. Then, these exposure rates are used in conjunction with appropriate dose and risk factors to yield individual dose and risk for selected organs and cancers. Next, these individual doses and risks are multiplied by population size to obtain population dose and risk for selected organs and cancers. Further, as many algebraic simplifications as possible are carried out; due to the nature of the models used, this results in relatively simple expressions for population dose and risk which are independent of the population size, river size, and time period considered. Finally, population risk from the various cancers is summed to give an overall population risk estimate.

It is assumed that the surface-water body under consideration can be represented as a single uniformly-mixed cell as described by the differential equation appearing in (2.5). For radionuclide I, it is assumed that a release of size TD(I) (units: Ci) takes place into the surface water over a time period of length T (units: yrs). Further, for use in (2.5), it is assumed that the annual discharge (units: Ci/yr) for radionuclide I is given by TD(I)/T. Thus, for each radionuclide, the asymptotic concentration (units: Ci/L) in the surface water is given by

$$CW(I) = TD(I)/F*T \ , \qquad (3.1)$$

where F denotes the annual flow (units: L/yr) of the river which constitutes the surface water body under consideration.

As in the EPA analysis (Sm81), it is assumed that population size and fish production are linear, homogeneous functions of river flow F. That is, it is assumed that

$$POP = DPOP*F \qquad (3.2)$$

and

$$FSH = DFSH*F \ , \qquad (3.3)$$

where

POP = population (units: ind*) supported by river

DPOP = constant (units: ind per L/yr)

FSH = fish production (units: kg/yr) supported by river

DFSH = constant (units: kg/yr per L/yr).

Further, with an assumed life expectancy of 70. yr, the total population TP (units: ind) supported by the river over a time period of length T is

---

*individuals

$$TP = DPOP*F*T/70. \qquad (3.4)$$

3.2 Exposure From Water Consumption

The population exposures and resultant health effects are now calculated for water ingestion. It follows from (3.1) that the amount of radionuclide I ingested by an individual (units: Ci/yr) is given by

$$CW(I)*RINGWAT*WT(I) = RINGWAT*TD(I)*WT(I)/F*T\ , \qquad (3.5)$$

where

RINGWAT = individual water ingestion rate (units: L/yr)

WT(I) = water treatment removal factor for radionuclide I (units: unitless).

Thus, the dose (units: rem/ind) to the organ associated with cancer J due to radionuclide I and the resultant cancer risk (units: cancer/ind) are given by

$$RINGWAT*TD(I)*WT(I)*DFING(I,J)/F*T \qquad (3.6)$$

and

$$RINGWAT*TD(I)*WT(I)*DFING(I,J)*RISK(J)/F*T\ , \qquad (3.7)$$

respectively.

Population exposure and risk now follow from the expressions in (3.6) and (3.7). Specifically, with use of the relation in (3.4),

$$WRDS(I,J) = [RINGWAT*TD(I)*WT(I)*DFING(I,J)/F*T]$$

$$*[DPOP*F*T/70.]$$

$$= RINGWAT*TD(I)*WT(I)*DFING(I,J)*DPOP/70. \qquad (3.8)$$

and

$$WRHE(I,J) = [RINGWAT*TD(I)*WT(I)*DFING(I,J)*RISK(J)/F*T]$$

$$*[DPOP*F*T/70.]$$

$$= RINGWAT*TD(I)*WT(I)*DFING(I,J)*RISK(J)$$

$$*DPOP/70. \qquad (3.9)$$

Thus, the total cancers from radionuclide I are given by

$$WRHETOT(I) = \Sigma_J WRHE(I,J) \ . \qquad (3.10)$$

3.3 Exposure from Fish Consumption

The population exposures and resultant health effects are now calculated for fish ingestion. It follows from (3.2) and (3.3) that average individual fish consumption is

$$(DFSH*F)/(DPOP*F) = DFSH/DPOP \ . \qquad (3.11)$$

Thus, it follows from (3.1) that the amount of radionuclide I ingested by an individual from fish consumption (units: Ci/yr) is given by

$$CW(I)*CRWF(I)*(DFSH/DPOP)$$

$$= TD(I)*CRWF(I)*DFSH/(DPOP*F*T) \ , \qquad (3.12)$$

where

CRWF(I) = concentration ratio for radionuclide I from water to fish (units: Ci/kg per Ci/L).

Thus, the dose (units: rem/ind) to the organ associated with cancer J due to radionuclide I and the resultant cancer risk (units: cancer/ind) are given by

$$(TD(I)*CRWF(I)*DFSH*DFING(I,J))/(DPOP*F*T) \qquad (3.13)$$

and

$$(TD(I)*CRWF(I)*DFSH*DFING(I,J)*RISK(J))$$

$$/(DPOP*F*T)\ , \qquad (3.14)$$

respectively.

Population exposure and risk now follow from the expressions in (3.13) and (3.14). Specifically, with use of the relation in (3.4),

$$FHDS(I,J) = \left|[TD(I)*CRWF(I)*DFSH*DFING(I,J)]\right.$$

$$\left./[DPOP*F*T]\right| * \left|DPOP*F*T/70.\right|$$

$$= TD(I)*CRWF(I)*DFSH*DFING(I,J)/70 \qquad (3.15)$$

and

$$FHHE(I,J) = \left|[TD(I)*CRWF(I)*DFSH*DFING(I,J)*RISK(J)]\right.$$

$$\left./[DPOP*F*T]\right| * \left|DPOP*F*T/70.\right|$$

$$= TD(I)*CRWF(I)*DFSH*DFING(I,J)*RISK(J)/70. \qquad (3.16)$$

Thus, the total cancers from radionuclide I are given by

$$FHHETOT(I) = \Sigma_J \, FHHE(I,J) \; . \qquad (3.17)$$

3.4 Exposure From Inhalation of Suspended Sediment

The population exposures and resultant health effects are now calculated for inhalation of suspended sediment. For this calculation and for subsequent exposure calculations involving sediment, it is assumed that sediment concentration CSED(I) (units: Ci/kg) of the I^{th} radionuclide is given by

$$CSED(I) = DCOEF(I)*CW(I)$$

$$= DCOEF(I)*TD(I)/F*T \; , \qquad (3.18)$$

[From (3.1)]

where

DCOEF(I) = distribution coefficient for radionuclide I (units: Ci/kg per Ci/L).

Hence, the amount of radionuclide I inhaled by an individual (units: Ci/yr) is given by

$$CSED(I)*AIRCON*RINHAIR*TMINSD$$

$$= DCOEF(I)*TD(I)*AIRCON*RINHAIR*TMINSD/F*T \; , \qquad (3.19)$$

where

AIRCON = concentration of suspended sediment in the air (units: kg/m^3),

RINHAIR = rate of inhalation (units: m^3/yr),

TMINSD = fraction of year that individual is exposed to suspended sediment (units: unitless).

Thus, the dose (units: rem/ind) to the organ associated with cancer J due to radionuclide I and the resultant cancer risk (units: cancer/ind) are given by

[DCOEF(I)*TD(I)*AIRCON*RINHAIR*TMINSD*DFINH(I,J)]/[F*T]

(3.20)

and

[DCOEF(I)*TD(I)*AIRCON*RINHAIR*TMINSD*DFINH(I,J)

*RISK(J)]/[F*T] , (3.21)

respectively.

Population exposure and risk now follow from the expressions in (3.20) and (3.21). Specifically, with the use of the relation in (3.4),

$$\begin{aligned} INSDDS(I,J) &= \left\{[DCOEF(I)*TD(I)*AIRCON*RINHAIR*TMINSD \right. \\ &\quad \left. *DFINH(I,J)]/[F*T]\right\} * \left\{DPOP*F*T/70.\right\} \\ &= [DCOEF(I)*TD(I)*AIRCON*RINHAIR*TMINSD \\ &\quad *DFINH(I,J)*DPOP]/70. \end{aligned} \tag{3.22}$$

and

$$\begin{aligned} INSDHE(I,J) &= \left\{[DCOEF(I)*TD(I)*AIRCON*RINHAIR*TMINSD \right. \\ &\quad \left. *DFINH(I,J)*RISK(J)]/[F*T]\right\} * \left\{DPOP*F*T/70.\right\} \\ &= [DCOEF(I)*TD(I)*AIRCON*RINHAIR*TMINSD \\ &\quad *DFINH(I,J)*RISK(J)*DPOP]/70. \end{aligned} \tag{3.23}$$

Thus, the total cancers from radionuclide I are given by

$$INSDTOT(I) = \Sigma_J\ INSDHE(I,J)\ . \qquad (3.24)$$

3.5 Exposure From Water Immersion

The population exposures and resultant health effects are now calculated for water immersion. The external exposure (units: rem/ind) to the organ associated with cancer J due to radionuclide I and the resultant cancer risk (units: cancer/ind) are given by

$$CW(I)*REXTWAT*DFEXT(I,2,J)*70.*1000.$$

$$= TD(I)*REXTWAT*DFEXT(I,2,J)*7.E4/F*T \qquad (3.25)$$

[From (3.1)]

and

$$TD(I)*REXTWAT*DFEXT(I,2,J)*7.E4*RISK(J)/F*T\ , \qquad (3.26)$$

where

REXTWAT = exposure rate to contaminated water (units: hr/yr),

70. = average life expectancy (units: yr/ind)

1000. = liters per cubic meter (units: L/m^3).

The factors 70. yr/ind and 1000. L/m^3 appear in (3.25) to produce necessary unit conversions.

Population exposure and risk now follow from the expressions in (3.25) and (3.26). Specifically, with use of the relation in (3.4),

$$EXWRDS(I,J) = [TD(I)*REXTWAT*DFEXT(I,2,J)*7.E4/F*T]$$

$$*[DPOP*F*T/70.]$$

$$= TD(I)*REXTWAT*DFEXT(I,2,J)*DPOP*1.E3 \quad (3.27)$$

and

$$EXWRHE(I,J) = [TD(I)*REXTWAT*DFEXT(I,2,J)*7.E4*RISK(J)$$

$$/F*T]*[DPOP*F*T/70.]$$

$$= TD(I)*REXTWAT*DFEXT(I,2,J)*RISK(J)$$

$$*DPOP*1.E3. \quad (3.28)$$

Thus, the total cancers from radionuclide I are given by

$$EXWRTOT(I) = \Sigma_J \; EXWRHE(I,J) \; . \quad (3.29)$$

3.6 Exposure From Shoreline Sediment

The population exposures and resultant health effects are now calculated for external exposure to shoreline sediment. For these calculations, it is first necessary to determine a surface radionuclide concentration. To do this, it is assumed that all radionuclides down to a certain depth in the sediment are concentrated on the sediment surface. Then, the surface concentration CSURF(I) (units: Ci/m^2) for radionuclide I is given by

$$CSURF(I) = CSED(I)*DEPTH*DENSITY*(1. - POROSIT)$$

$$= DCOEF(I)*TD(I)*DEPTH*DENSITY*(1. - POROSIT)$$

$$/F*T \; , \quad (3.30)$$

[From (3.18)]

where

DEPTH = depth to which radionuclides are assumed to be concentrated on surface (units: m),

DENSITY = mean particle density of sediment (units: kg/m^3),

POROSIT = porosity of sediments (units: unitless).

Hence, the external exposure (units: rem/ind) to the organ associated with cancer J due to radionuclide I and the resultant cancer risk (units: cancer/ind) are given by

CSURF(I)*REXTSD*DFEXT(I,1,J)*70.

= [DCOEF(I)*TD(I)*DEPTH*DENSITY*(1. - POROSIT)/F*T]

*[REXTSD*DFEXT(I,1,J)*70.] (3.31)

[From (3.30)]

and

[DCOEF(I)*TD(I)*DEPTH*DENSITY*(1. - POROSIT)/F*T]

*[REXTSD*DFEXT(I,1,J)*70.]*RISK(J) , (3.32)

respectively, where

REXTSD = exposure rate to sediment (units: hr/yr),

70. = average life expectancy (units: yr/ind).

Population exposure and risk now follow from the expressions in (3.31) and (3.32). Specifically, with use of the relation in (3.4),

$$
\begin{aligned}
EXSDDS(I,J) &= [DCOEF(I)*TD(I)*DEPTH*DENSITY \\
&\quad *(1. - POROSIT)/F*T]*[REXTSD*DFEXT(I,1,J) \\
&\quad *70.]*[DPOP*F*T/70.] \\
&= DCOEF(I)*TD(I)*DEPTH*DENSITY \\
&\quad *(1. - POROSIT)*REXTSD*DFEXT(I,1,J)*DPOP
\end{aligned}
\tag{3.33}
$$

and

$$
\begin{aligned}
EXSDHE(I,J) &= [DCOEF(1)*TD(I)*DEPTH*DENSITY \\
&\quad *(1. - POROSIT)/F*T]*[REXTSD*DFEXT(I,1,J) \\
&\quad *70.]*RISK(J)*[DPOP*F*T/70.] \\
&= DCOEF(I)*TD(I)*DEPTH*DENSITY*(1. - POROSIT) \\
&\quad *REXTSD*DFEXT(I,1,J)*RISK(J)*DPOP \; .
\end{aligned}
\tag{3.34}
$$

Thus, the total cancers from radionuclide I are given by

$$EXSDHET(I) = \sum_J EXSDHE(I,J) \; . \tag{3.35}$$

3.7 Exposure From Suspended Sediment

The population exposures and resultant health effects are now calculated for external exposure from suspended sediment. The external exposure (units: rem/ind) to the organ associated with cancer J due to radionuclide I and the resultant cancer risk (units: cancer/ind) are given by

CSED(I)*AIRCON*REXARSD*DFEXT(I,3,J)*70.

= [DCOEF(I)*TD(I)*AIRCON*REXARSD*DFEXT(I,3,J)*70.]

/[F*T] (3.36)

[From (3.18)]

and

[DCOEF(I)*TD(I)*AIRCON*REXARSD*DFEXT(I,3,J)*70.*RISK(J)]

/[F*T] , (3.37)

respectively, where

REXARSD = exposure rate to suspended sediment (units: hr/yr),

70. = average life expectancy (units: yr/ind).

Population exposure and risk now follow from the expressions in (3.36) and (3.37). Specifically, with use of the relation in (3.4),

$$\text{EXARSDD}(I,J) = \left\{[\text{DCOEF}(I)*\text{TD}(I)*\text{AIRCON}*\text{REXARSD} *\text{DFEXT}(I,3,J)*70.]/[F*T]\right\} * \left\{\text{DPOP}*F*T/70.\right\}$$

$$= \text{DCOEF}(I)*\text{TD}(I)*\text{AIRCON}*\text{REXARSD} *\text{DFEXT}(I,3,J)*\text{DPOP} \quad (3.38)$$

and

$$\text{EXARSDH}(I,J) = \Big\{[\text{DCOEF}(I)*\text{TD}(I)*\text{AIRCON}*\text{REXARSD}$$

$$*\text{DFEXT}(I,3,J)*70.*\text{RISK}(J)]$$

$$/[F*T]\Big\} * \Big\{\text{DPOP}*F*T/70.\Big\}$$

$$= \text{DCOEF}(I)*\text{TD}(I)*\text{AIRCON}*\text{REXARSD}$$

$$*\text{DFEXT}(I,3,J)*\text{DPOP}*\text{RISK}(J) \; . \qquad (3.39)$$

Thus, the total cancers from radionuclide I are given by

$$\text{EXARSDT}(I) = \sum_J \text{EXARSDH}(I,J) \; . \qquad (3.40)$$

4. Release to Soil

4.1 Preliminary Comments

Population exposures and resultant health effects are now calculated for radionuclide release to soil. In particular, PLDS(I,J), PLHE(I,J) and PLHETOT(I) are determined for exposure from plant consumption, where

PLDS(I,J) = population dose (units: rems) to organ associated with cancer J from radionuclide I,

PLHE(I,J) = number of occurrences of cancer J in population due to radionuclide I,

PLHETOT(I) = total number of cancers in population due to radionuclide I.

Similarly, MKDS(I,J), MKHE(I,J) and MKHETOT(I) are determined for milk consumption; MTDS(I,J), MTHE(I,J) and MTHETOT(I) are determined for meat consumption; INSLDS(I,J),,INSLHE(I,J) and INSLTOT(I) are determined for inhalation of suspended soil; EXSLDS(I,J), EXSLHE(I,J) and EXSLTOT(I) are determined for external exposure from soil; and EXARSLD(I,J), EXARSLH(I,J) and EXARSLT(I) are determined for external exposure from suspended soil. The preceding quantities are determined in a manner similar to that used in Chapter 3.

It is assumed that the region under consideration can be represented as a single uniformly-mixed cell as described by the differential equation appearing in (2.21). A specific form of this equation is now derived for use in this chapter. The following symbols are introduced for use in this derivation:

X(I) = amount of radionuclide I in soil (units: Ci),

XS(I) = amount of radionuclide I in soil sorbed to solid material (units: Ci),

XW(I) = amount of radionuclide I in soil dissolved in water (units: Ci),

DP = depth of soil (units: m),

AR = area of soil (units: m^2),

ER = erosion rate per unit area (units: kg/m^2 per yr),

RO = runoff rate per unit area (units: L/m^2 per yr),

DCOEF(I) = distribution coefficient for radionuclide I (units: Ci/kg per Ci/L),

MS = mass of solid material in soil (units: kg),

VW = volume of water in soil (units: L),

PO = porosity of soil (units: unitless),

DE = mean particle density of soil material (units: kg/m^3),

SA = percent saturation of pore space in soil (units: unitless).

Radionuclide partitioning is considered first. The solid mass MS and the water volume VW in the soil are given by

$$MS = AR*DP*(1. - PO)*DE \qquad (4.1)$$

and

$$VW = AR*DP*PO*SA*1000 . \qquad (4.2)$$

Thus, the factor S(I) used in the determination of radionuclide partitioning between the liquid and solid phases of a system is given by

$$S(I) = \frac{DCOEF(I)*MS}{DCOEF(I)*MS + VW} \qquad \text{[From (2.20)]}$$

$$= \frac{DCOEF(I)*AR*DP*(1. - PO)*DE}{DCOEF(I)*AR*DP*(1. - PO)*DE + AR*DP*PO*SA*1000}$$

$$= \frac{DCOEF(I)*(1. - PO)*DE}{DCOEF(I)*(1. - PO)*DE + PO*SA*1000} \qquad (4.3)$$

Hence, it follows from (2.16) and (2.17) that the partitioning of radionuclide I between the liquid and solid phases of the system is given by

$$XS(I) = S(I)*X(I) \quad \text{and} \quad XW(I) = [1. - S(I)]*X(I) . \qquad (4.4)$$

The desired equation can now be constructed. In particular, it follows from (2.21) that

$$\begin{aligned} dX(I)/dt &= R(I) - [XS(I)/MS]*AR*ER \\ &\quad - [XW(I)/VW]*AR*RO - \lambda*X(I) \\ &= R(I) - \left\{\frac{S(I)*X(I)}{AR*DP*(1. - PO)*DE}\right\}*AR*ER \\ &\quad - \left\{\frac{[1. - S(I)]*X(I)}{AR*DP*PO*SA*1000}\right\}*AR*RO - \lambda*X(I) \\ &\qquad\qquad [\text{From (4.1), (4.2), (4.4)}] \\ &= R(I) - A(I)*X(I) , \qquad (4.5) \end{aligned}$$

where

$$A(I) = \frac{S(I)*ER}{DP*(1. - PO)*DE} + \frac{[1. - S(I)]*RO}{DP*PO*SA*1000} + \lambda . \qquad (4.6)$$

For radionuclide I, the decay constant λ is given by

$$\lambda = ALOG(2.)/HLIFE(I) , \qquad (4.7)$$

where

HLIFE(I) = half-life of radionuclide I (units: yr).

As indicated in (2.9), the asymptotic solution to the equation in (4.5) is given by

$$R/A(I) = TD(I)/T*A(I) \ , \qquad (4.8)$$

where the second part of the preceding equality follows from the assumption that the annual discharge (units: Ci/yr) for radionuclide I is given by TD(I)/T. Thus, for each radionuclide, the asymptotic concentration (units: Ci/kg) in the soil is given by

$$CSL(I) = [TD(I)/T*A(I)]/MS$$

$$= [TD(I)]/[T*A(I)*AR*DP*(1. - PO)*DE]$$

[From (4.1)]

$$= TD(I)*FAC(I)/T*AR \ , \qquad (4.9)$$

where the factor FAC(I) is introduced for notational convenience and is defined by

$$FAC(I) = [A(I)*DP*(1. - PO)*DE]^{-1} \ . \qquad (4.10)$$

It is noted that FAC(I) contains no term which depends on the area AR of the soil region under consideration or the length T of the time period under consideration.

In similarity to the Environmental Protection Agency analysis, the following parameters are assumed to be known for the region under consideration:

FPLT = fraction of land used to grow plants for human consumption (units: unitless),

FMLK = fraction of land used for milk production (units: unitless),

FMT = fraction of land used for meat production (units: unitless),

DPLT = number of people supported per m^2 by plant production (units: ind/m^2),

DMLK = number of people supported per m^2 by milk production (units: ind/m^2),

DMT = number of people supported per m^2 by meat production (units: ind/m^2)

DSL = population density for inhalation and external exposure calculations (units: ind/m^2).

The preceding variables lead to the following populations for use in later exposure calculations:

$$TPPLT = AR*FPLT*DPLT*T/70. \quad (4.11)$$

$$TPMLK = AR*FMLK*DMLK*T/70. \quad (4.12)$$

$$TPMT = AR*FMT*DMT*T/70. \quad (4.13)$$

$$TPSL = AR*DSL*T/70. , \quad (4.14)$$

where

TPPLT = total population exposed to plant ingestion (units: ind),

TPMLK = total population exposed to milk consumption (units: ind),

TPMT = total population exposed to meat consumption (units: ind),

TPSL = total population for inhalation and external exposure calculations (units: ind),

70. = average life expectancy (units: yr).

4.2 Exposure From Plant Consumption

The population exposures and resultant health effects are now calculated for plant ingestion. It follows from (4.9) that the amount of radionuclide I ingested by an individual (units: Ci/yr) is given by

CPLT*CSL(I)*CRSP(I)

$$= \text{CPLT*TD(I)*FAC(I)*CRSP(I)/T*AR} , \qquad (4.15)$$

where

CPLT = individual plant consumption (units: kg/yr),

CRSP(I) = concentration ratio from soil to plant for radionuclide I (units: Ci/kg per Ci/kg).

Thus, the dose (units: rem/ind) to the organ associated with cancer J due to radionuclide I and the resultant cancer risk (units: cancer/ind) are given by

$$\text{CPLT*TD(I)*FAC(I)*CRSP(I)*DFING(I,J)/T*AR} \qquad (4.16)$$

and

$$\text{CPLT*TD(I)*FAC(I)*CRSP(I)*DFING(I,J)*RISK(J)/T*AR} , \qquad (4.17)$$

respectively.

Population exposure and risk now follow from the expressions in (4.16) and (4.17). Specifically, with use of the relation in (4.11),

PLDS(I,J) = [CPLT*TD(I)*FAC(I)*CRSP(I)*DFING(I,J)/T*AR]

*[AR*FPLT*DPLT*T/70.]

= CPLT*TD(I)*FAC(I)*CRSP(I)DFING(I,J)*FPLT

*DPLT/70. (4.18)

and

$$PLHE(I,J) = [CPLT*TD(I)*FAC(I)*CRSP(I)*DFING(I,J)$$

$$*RISK(J)/T*AR]*[AR*FPLT*DPLT*T/70.]$$

$$= [CPLT*TD(I)*FAC(I)*CRSP(I)*DFING(I,J)$$

$$*RISK(J)*FPLT*DPLT]/70. \qquad (4.19)$$

Thus, the total cancers from radionuclide I are given by

$$PLHETOT(I) = \Sigma_J \, PLHE(I,J) \; . \qquad (4.20)$$

4.3 Exposure From Milk Consumption

The population exposures and resultant health effects are now calculated for milk ingestion. It follows from (4.9) that the amount of radionuclide I ingested by an individual (units: Ci/yr) is given by

$$CSL(I)*CRSP(I)*PMLK*CRDM(I)*CMLK \qquad (4.21)$$

$$= TD(I)*FAC(I)*CRSP(I)*PMLK*CRDM(I)*CMLK/T*AR \; ,$$

where

PMLK = plant consumption by dairy cattle (units: kg/day),

CRDM(I) = concentration ratio from diet to milk for radionuclide I (units: Ci/L per Ci/day),

CMLK = individual milk consumption (units: L/yr).

Thus, the dose (units: rem/ind) to the organ associated with cancer J due to radionuclide I and the resultant cancer risk (units: cancer/ind) are given by

TD(I)*FAC(I)*CRSP(I)*PMLK*CRDM(I)*CMLK*DFING(I,J)/T*AR

(4.22)

and

[TD(I)*FAC(I)*CRSP(I)*PMLK*CRDM(I)*CMLK*DFING(I,J)

*RISK(J)]/[T*AR] , (4.23)

respectively.

Population exposure and risk now follow from the expressions in (4.22) and (4.23). Specifically, with use of the relation in (4.12),

MKDS(I,J) = {[TD(I)*FAC(I)*CRSP(I)*PMLK*CRDM(I)*CMLK

*DFING(I,J)]/[T*AR]}*{AR*FMLK*DMLK*T/70.}

= [TD(I)*FAC(I)*CRSP(I)*PMLK*CRDM(I)*CMLK

*DFING(I,J)*FMLK*DMLK]/70. (4.24)

and

MKHE(I,J) = {[TD(I)*FAC(I)*CRSP(I)*PMLK*CRDM(I)*CMLK

*DFING(I,J)*RISK(J)]/[T*AR]}*{AR*FMLK*DMLK

*T/70.}

= [TD(I)*FAC(I)*CRSP(I)*PMLK*CRDM(I)*CMLK

*DFING(I,J)*RISK(J)*FMLK*DMLK]/70. (4.25)

Thus, the total cancers from radionuclide I are given by

$$MKHETOT(I) = \sum_J MKHE(I,J) \ . \qquad (4.26)$$

4.4 Exposure From Meat Consumption

The population exposures and resultant health effects for meat consumption are determined the same as those for milk consumption with the exceptions that PMT, CRDMT(I), CMT, FMT and DMT are used instead of PMLK, CRDM(I), CMLK, FMLK and DMLK, respectively, where

PMT = plant consumption by beef cattle (units: kg/day),

CRDMT(I) = concentration ratio from diet to meat for radionuclide I (units: Ci/kg per Ci/day),

CMT = individual meat consumption (units: kg/yr)

and the remaining two variables are defined after (4.14). Thus,

$$MTDS(I,J) = [TD(I)*FAC(I)*CRSP(I)*PMT*CRDMT(I)*CMT *DFING(I,J)*FMT*DMT]/70. \ , \qquad (4.27)$$

$$MTHE(I,J) = [TD(I)*FAC(I)*CRSP(I)*PMT*CRDMT(I)*CMT *DFING(I,J)*RISK(J)*FMT*DMT]/70. \qquad (4.28)$$

and

$$MTHETOT(I) = \sum_J MTHE(I,J) \ . \qquad (4.29)$$

4.5 Exposure From Inhalation of Suspended Soil

The population exposures and resultant health effects for inhalation of suspended soil are determined in the same manner as those for inhalation of suspended sediment with the exceptions that CSL(I), TPSL and TMINSL are used instead of CSED(I), TP and TMINSD, respectively, where

TMINSL = fraction of year that individual is exposed to suspended soil (units: unitless).

Specifically, the amount of radionuclide inhaled by an individual (units: Ci/yr) is given by

$$\begin{aligned} &CSL(I)*AIRCON*RINHAIR*TMINSL \\ &= TD(I)*FAC(I)*AIRCON*RINHAIR*TMINSL/T*AR \ . \end{aligned} \tag{4.30}$$

Thus, the dose (units: rem/ind) to the organ associated with cancer J due to radionuclide I and the resultant cancer risk (units: cancer/ind) are given by

$$TD(I)*FAC(I)*AIRCON*RINHAIR*TMINSL*DFINH(I,J)/T*AR \tag{4.31}$$

and

$$[TD(I)*FAC(I)*AIRCON*RINHAIR*TMINSL*DFINH(I,J)*RISK(J)] \ /[T*AR] \ , \tag{4.32}$$

respectively.

Population exposure and risk now follow from the expressions in (4.31) and (4.32). Specifically, with use of the relation in (4.14),

$$\begin{aligned} INSLDS(I,J) &= \{[TD(I)*FAC(I)*AIRCON*RINHAIR*TMINSL \\ &\quad *DFINH(I,J)]/[T*AR]\} * \{AR*DSL*T/70.\} \\ &= TD(I)*FAC(I)*AIRCON*RINHAIR*TMINSL \\ &\quad *DFINH(I,J)*DSL/70. \end{aligned} \tag{4.33}$$

and

$$INSLHE(I,J) = \{[TD(I)*FAC(I)*AIRCON*RINHAIR*TMINSL$$

$$*DFINH(I,J)*RISK(J)]/[T*AR]\} * \{AR*DSL*T/70\}.$$

$$= [TD(I)*FAC(I)*AIRCON*RINHAIR*TMINSL$$

$$*DFINH(I,J)*RISK(J)*DSL]/70. \qquad (4.34)$$

Thus, the total cancers from radionuclide I are given by

$$INSLTOT(I) = \Sigma_J \; INSLHE(I,J) \; . \qquad (4.35)$$

4.6 Exposure From Soil

The population exposures and resultant health effects for external exposure from soil are determined in the same manner as those for external exposure from sediment with the exceptions that CSL(I), TPSL and REXTSL are used instead of CSED(I), TP and REXTSED, respectively, where

REXTSL = exposure rate to soil (units: hr/yr).

First, as was done in (3.30), it is necessary to convert the soil concentration CSL(I) (units: Ci/kg) to a surface concentration CSURF(I) (units: Ci/m^2), where

$$CSURF(I) = CSL(I)*DEPTH*DENSITY*(1. - POROSIT)$$

$$= TD(I)*FAC(I)*DEPTH*DENSITY*(1. - POROSIT)/T*AR \qquad (4.36)$$

Hence, the external exposure (units: rem/ind) to the organ associated with cancer J due to radionuclide I and the resultant cancer risk (units: cancer/ind) are given by

CSURF(I)*REXTSL*DFEXT(I,1,J)*70.

= [TD(I)*FAC(I)*DEPTH*DENSITY*(1. - POROSIT)/T*AR]

*[REXTSL*DFEXT(I,1,J)*70.] (4.37)

and

[TD(I)*FAC(I)*DEPTH*DENSITY*(1. - POROSIT)/T*AR]

*[REXTSL*DFEXT(I,1,J)*70.]*RISK(J) , (4.38

respectively.

Population exposure and risk now follow from the expressions in (4.37) and (4.38). Specifically, with use of the relation in (4.14),

EXSLDS(I,J) = [TD(I)*FAC(I)*DEPTH*DENSITY*(1. - POROSIT)

/T*AR]*[REXTSL*DFEXT(I,1,J)*70.]

*[AR*DSL*T/70.]

= TD(I)*FAC(I)*DEPTH*DENSITY*(1. - POROSIT)

*REXTSL*DFEXT(I,1,J)*DSL (4.39)

and

$$EXSLHE(I,J) = [TD(I)*FAC(I)*DEPTH*DENSITY*(1. - POROSIT)$$

$$/T*AR]*[REXTSL*DFEXT(I,1,J)*70.]*RISK(J)$$

$$*[AR*DSL*T/70.]$$

$$= TD(I)*FAC(I)*DEPTH*DENSITY*(1. - POROSIT)$$

$$*REXTSL*DFEXT(I,1,J)*RISK(J)*DSL . \quad (4.40)$$

Thus, the total cancers from radionuclide I are given by

$$EXSLTOT(I) = \Sigma_J \; EXSLHE(I,J). \quad (4.41)$$

4.7 Exposure From Suspended Soil

The population exposures and resultant health effects for external exposure from suspended soil are determined in the same manner as those for external exposure from suspended sediment with the exceptions that CSL(I), and REXARSL are used instead of CSED(I) and REXARSD, respectively, where

REXARSL = exposure rate to suspended soil (units: hr/yr).

The external exposure (units: rem/ind) to the organ associated with cancer J due to radionuclide I and the resultant cancer risk (units: cancer/ind) are given by

$$CSL(I)*AIRCON*REXARSL*DFEXT(I,3,J)*70.$$

$$= [TD(I)*FAC(I)*AIRCON*REXARSL*DFEXT(I,3,J)*70.]$$

$$/[T*AR] \quad (4.42)$$

and

$$[TD(I)*FAC(I)*AIRCON*REXARSL*DFEXT(I,3,J)*70.*RISK(J)]$$

$$/[T*AR] \ , \qquad (4.43)$$

respectively.

Population exposure and risk now follow from the expressions in (4.42) and (4.43). Specifically, with use of the relation in (4.14),

$$EXARSLD(I,J) = \{[TD(I)*FAC(I)*AIRCON*REXARSL*DFEXT(I,3,J)$$

$$*70.]/[T*AR]\}*\{AR*DSL*T/70.\}$$

$$= TD(I)*FAC(I)*AIRCON*REXARSL*DFEXT(I,3,J)*DSL \qquad (4.44)$$

and

$$EXARSLH(I,J) = \{[TD(I)*FAC(I)*AIRCON*REXARSL*DFEXT(I,3,J)$$

$$*70.*RISK(J)]/[T*AR]\}*\{AR*DSL*T/70.\}$$

$$= TD(I)*FAC(I)*AIRCON*REXARSL*DFEXT(I,3,J)$$

$$*RISK(J)*DSL \ . \qquad (4.45)$$

Thus, the total cancers from radionuclide I are given by

$$EXARSLT(I) = \Sigma_J \ EXARSLH(I,J) \ . \qquad (4.46)$$

5. Irrigation After Release to Surface Water

5.1 Preliminary Comments

Population exposures and resultant health effects are now calculated for irrigation after a radionuclide release to a surface-water body. Similar calculations are considered in Chapter 4. However, there the only uptake mode considered is direct uptake from soil to plant. In this chapter the additional uptake modes resulting from radionuclides retained on plants due to sprinkler irrigation and from radionuclides in drinking water for milk and beef cattle are considered. In particular, IPLRDS(I,J), IPLRHE(I,J) and IPLRHET(I) are determined for exposure resulting from human ingestion of plants containing radionuclides deposited by sprinkler irrigation, where

IPLRDS(I,J) = population dose (units: rems) to organ associated with cancer J due to radionuclide I,

IPLRHE(I,J) = number of occurrences of cancer J in population due to radionuclide I,

IPLRHET(I) = total number of cancers in population due to radionuclide I.

Further, IMKRDS(I,J), IMKRHE(I,J) and IMKRHET(I) are determined for that part of the dose from milk ingestion which results from milk cattle ingesting radionuclides deposited on feed due to sprinkler irrigation, where

IMKRDS(I,J) = population dose (units: rems) to organ associated with cancer J due to radionuclide I,

IMKRHE(I,J) = number of occurrences of cancer J in population due to radionuclide I,

IMKRHET(I) = total number of cancers in population due to radionuclide I.

Similarly, IMKWDS(I,J), IMKWHE(I,J) and IMKWHET(I) are determined for that part of the dose from milk ingestion which results from milk cattle ingesting radionuclides in their drinking water. In like manner, IMTRDS(I,J), IMTRHE(I,J), IMTRHET(I), IMTWDS(I,J), IMTWHE(I,J) and IMTWHET(I) are determined for human ingestion of beef.

The preceding quantities are determined in a manner similar to that used in Chapter 4.

As already indicated, this section considers foliar deposition due to sprinkler irrigation. The concentration of radionuclide retained on, or in a plant, as the result of sprinkler irrigation is determined by solving a differential equation which represents the change in this concentration as the difference between the rate at which the radionuclide is contaminating the plant and the rate at which the radionuclide is being removed by weathering. This equation is

$$dC(t)/dt = D(t) - \lambda_w(t) \qquad (5.1)$$

where

$C(t)$ = concentration of radionuclide on plant material (in Ci/kg),

$D(t)$ = rate of radionuclide deposition (in Ci/kg/yr), and

λ_w = rate constant for removal by weathering (in yr^{-1}).

With the initial condition $C(0) = 0$ and the assumption that $D(t)$ has a constant value D, the preceding equation has the solution

$$C(t) = (D/\lambda_w)\ (1 - e^{-t}), \qquad (5.2)$$

which provides the concentration due to foliar deposition.

The weathering half-life is often taken to be 14 days. This yields a value for λ_w of 18.1 yr^{-1}. It is pointed out that $1 - e^{-\lambda_w t}$ approaches 1 rapidly. With $t = 0.17$ yr, the value is 0.95, and with $t = 0.25$ yr, the value is 0.99. Thus, the length of time for irrigation is probably not critical. The deposition rate D is given by

$$D = FRET*CWAT*IRAT/PDEN\ , \qquad (5.3)$$

where

FRET = fraction of deposited radionuclides retained on crops, often taken to be 0.25 (dimensionless),

CWAT = concentration of radionuclide in irrigation water (in Ci/L),

IRAT = irrigation rate (in $L/m^2/yr$), and

PDEN = standing crop (in kg/m^2).

The values indicated for λ_w and FRET are widely used and appear to come from a study by Milbourn and Taylor [M65].

The manner in which the relations in (5.2) and (5.3) will be used is now indicated. First, for simplicity, the asymptotic value for C(t) will be used. That is, the concentration C (units: Ci/kg) due to foliar deposition as a result of sprinkler irrigation is taken as

$$C = D/\lambda_w = FRET*CWAT*IRAT/\lambda_w*PDEN \ . \qquad (5.4)$$

Values for the variables in (5.4) are now obtained for radionuclide I in the context of the situation under consideration. From (3.1),

$$CWAT(I) = TD(I)/F*T \ . \qquad (5.5)$$

Further,

$$IRAT = FRIV*F/AR \ , \qquad (5.6)$$

where

FRIV = fraction of river used for sprinkler irrigation (units: unitless).

Also,

$$\lambda_w = ALOG(2.)/WHRHL \ , \qquad (5.7)$$

where

WHRHL = weathering half-life for radionuclides deposited by sprinkler irrigation (units: yrs).

Thus, the concentration C(I) (units: Ci/kg) of radionuclide I on plants due to sprinkler irrigation is given by

$$C(I) = [FRET*TD(I)*FRIV*WHRHL] / [T*AR*PDEN*ALOG(2.)] \quad (5.8)$$

5.2 Exposure From Plant Consumption

The population exposures and resultant health effects are now determined for human ingestion of plants containing radionuclides deposited by sprinkler irrigation. It follows from (5.8) that the amount of radionuclide I ingested by an individual (units: Ci/yr) is given by

$$C(I)*CPLT = [FRET*TD(I)*FRIV*WHRHL*CPLT] / [T*AR*PDEN*ALOG(2.)] . \quad (5.9)$$

Thus, the dose (units: rem/ind) to the organ associated with cancer J due to radionuclide I and the resultant cancer risk (units: cancer/ind) are given by

$$[FRET*TD(I)*FRIV*WHRHL*CPLT*DFING(I,J)] / [T*AR*PDEN*ALOG(2.)] \quad (5.10)$$

and

$$[FRET*TD(I)*FRIV*WHRHL*CPLT*DFING(I,J)*RISK(J)] / [T*AR*PDEN*ALOG(2.)] , \quad (5.11)$$

respectively.

Population exposure and risk now follow from the expressions in (5.10) and (5.11). Specifically, with use of the relation in (4.11) for total population available for plant consumption,

$$\begin{aligned}
IPLRDS(I,J) &= \{[FRET*TD(I)*FRIV*WHRHL*CPLT*DFING(I,J)] \\
&\quad /[T*AR*PDEN*ALOG(2.)]\}*\{AR*FPLT*DPLT*T/70.\} \\
&= [FRET*TD(I)*FRIV*WHRHL*CPLT*DFING(I,J) \\
&\quad *FPLT*DPLT]/[PDEN*ALOG(2.)*70.] \qquad (5.12)
\end{aligned}$$

and

$$\begin{aligned}
IPLRHE(I,J) &= \{[FRET*TD(I)*FRIV*WHRHL*CPLT*DFING(I,J) \\
&\quad *RISK(J)]/[T*AR*PDEN*ALOG(2.)]\} \\
&\quad *\{AR*FPLT*DPLT*T/70.\} \\
&= [FRET*TD(I)*FRIV*WHRHL*CPLT*DFING(I,J) \\
&\quad *RISK(J)*FPLT*DPLT]/[PDEN*ALOG(2.)*70.] \\
&\qquad (5.13)
\end{aligned}$$

Thus, the total cancers from radionuclide I are given by

$$IPLRHET(I) = \sum_J IPLRHE(I,J) \ . \qquad (5.14)$$

5.3 Exposure From Milk Consumption

The population exposures and resultant health effects are now determined for milk ingestion. Two sets of determinations are made. The first is for that part of exposure and health effects which results from foliar deposition of radionuclides due to sprinkler irrigation. The second is

for that part of exposure and health effects which results from radionuclides in water given to livestock.

It follows from (5.8) that the amount of radionuclide I ingested by an individual (units: Ci/yr) due to foliar deposition and subsequent plant use in milk production is given by

$$
\begin{aligned}
&C(I)*PMLK*CRDM(I)*CMLK \\
&= \left\{[FRET*TD(I)*FRIV*WHRHL]/[T*AR*PDEN*ALOG(2.)]\right\} \\
&\quad *\left\{PMLK*CRDM(I)*CMLK\right\} \\
&= [FRET*TD(I)*FRIV*WHRHL*PMLK*CRDM(I)*CMLK] \\
&\quad /[T*AR*PDEN*ALOG(2.)] \; . \qquad (5.15)
\end{aligned}
$$

Thus, the dose (units: rem/ind) to the organ associated with cancer J due to radionuclide I and the resultant cancer risk (units: cancer/ind) are given by

$$
\begin{aligned}
&[FRET*TD(I)*FRIV*WHRHL*PMLK*CRDM(I)*CMLK \\
&*DFING(I,J)]/[T*AR*PDEN*ALOG(2.)] \qquad (5.16)
\end{aligned}
$$

and

$$
\begin{aligned}
&[FRET*TD(I)*FRIV*WHRHL*PMLK*CRDM(I)*CMLK \\
&*DFING(I,J)*RISK(J)]/[T*AR*PDEN*ALOG(2.)] \; , \qquad (5.17)
\end{aligned}
$$

respectively.

Population exposure and risk now follow from the expressions in (5.16) and (5.17). Specifically, with use of the relation in (4.12) for total population available for milk consumption,

$$IMKRDS(I,J) = \left\{[FRET*TD(I)*FRIV*WHRHL*PMLK*CRDM(I) *CMLK*DFING(I,J)]/[T*AR*PDEN*ALOG(2.)]\right\} * \left\{AR*FMLK*DMLK*T/70\right\}.$$

$$= [FRET*TD(I)*FRIV*WHRHL*PMLK*CRDM(I)*CMLK *DFING(I,J)*FMLK*DMLK]/[PDEN*ALOG(2.)*70.] \quad (5.18)$$

and

$$IMKRHE(I,J) = \left\{[FRET*TD(I)*FRIV*WHRHL*PMLK*CRDM(I) *CMLK*DFING(I,J)*RISK(J)]/[T*AR*PDEN *ALOG(2.)]\right\} * \left\{AR*FMLK*DMLK*T/70\right\}.$$

$$= [FRET*TD(I)*FRIV*WHRHL*PMLK*CRDM(I)*CMLK *DFING(I,J)*RISK(J)*FMLK*DMLK] /[PDEN*ALOG(2.)*70.] . \quad (5.19)$$

Thus, the total cancers from radionuclide I are given by

$$IMKRHET(I) = \sum_J IMKRHE(I,J) . \quad (5.20)$$

It follows from (3.1) that the amount of radionuclide I ingested by an individual (units: Ci/yr) due to water used for milk cattle is given by

$$CW(I)*WMLK*CRDM(I)*CMLK = TD(I)*WMLK*CRDM(I)*CMLK/F*T, \quad (5.21)$$

where

WMLK = water consumption by dairy cattle (units: L/day).

Thus, the dose (units: rem/ind) to the organ associated with cancer J due to radionuclide I and the resultant cancer risk (units: cancer/ind) are given by

$$TD(I)*WMLK*CRDM(I)*CMLK*DFING(I,J)/F*T \qquad (5.22)$$

and

$$TD(I)*WMLK*CRDM(I)*CMLK*DFING(I,J)*RISK(J)/F*T\ , \qquad (5.23)$$

respectively.

Population exposure and risk now follow from the expressions in (5.22) and (5.23). Specifically, with use of the relation in (4.12) for total population available for milk consumption,

$$\begin{aligned} IMKWDS(I,J) &= [TD(I)*WMLK*CRDM(I)*CMLK*DFING(I,J)/F*T] \\ &\quad *[AR*FMLK*DMLK*T/70.] \\ &= [TD(I)*WMLK*CRDM(I)*CMLK*DFING(I,J)*AR \\ &\quad *FMLK*DMLK]/[F*70.] \end{aligned} \qquad (5.24)$$

and

$$\begin{aligned} IMKWHE(I,J) &= [TD(I)*WMLK*CRDM(I)*CMLK*DFING(I,J)*RISK(J) \\ &\quad /F*T]*[AR*FMLK*DMLK*T/70.] \\ &= [TD(I)*WMLK*CRDM(I)*CMLK*DFING(I,J)*RISK(J) \\ &\quad *AR*FMLK*DMLK]/[F*70.]\ . \end{aligned} \qquad (5.25)$$

Thus, the total cancers from radionuclide I are given by

$$IMKWHET(I,J) = \sum_J IMKWHE(I,J) \quad . \qquad (5.26)$$

Unlike all earlier calculations for population effects, tne variables F and AR did not drop out of the expressions in (5.24) and (5.25). However, if one assumes that the irrigation rate IRAT (units: L/m^2 per yr) is known, it is possible to remove F and AR. Specifically,

$$F*FRIV = AR*IRAT \qquad (5.27)$$

and so

$$AR/F = FRIV/IRAT \quad . \qquad (5.28)$$

Now, with use of the relation in (5.28), the equalities in (5.24) and (5.25) can be rewritten as

$$IMKWDS(I,J) = [TD(I)*WMLK*CRDM(I)*CMLK*DFING(I,J)*FRIV$$
$$*FMLK*DMLK]/[IRAT*70.] \qquad (5.29)$$

and

$$IMKWHE(I,J) = [TD(I)*WMLK*CRDM(I)*CMLK*DFING(I,J)*RISK(J)$$
$$*FRIV*FMLK*DMLK]/[IRAT*70.] \quad . \qquad (5.30)$$

5.4 Exposure From Meat Consumption

The population exposures and resultant health effects for meat consumption are determined in the same manner as those for milk consumption with the exceptions that PMT, CRDMT(I), CMT, FMT, DMT and WMT are used instead of PMLK, CRDM(I), CMLK, FMLK, DMLK and WMLK, respectively.

Thus,

$$IMTRDS(I,J) = [FRET*TD(I)*FRIV*WHRHL*PMT*CRDMT(I)*CMT*DFING(I,J)*FMT*DMT]/[PDEN*ALOG(2.)*70.] , \quad (5.31)$$

$$IMTRHE(I,J) = [FRET*TD(I)*FRIV*WHRHL*PMT*CRDMT(I)*CMT*DFING(I,J)*RISK(J)*FMT*DMT]/[PDEN*ALOG(2.)*70.] \quad (5.32)$$

$$IMTWDS(I,J) = [TD(I)*WMT*CRDMT(I)*CMT*DFING(I,J)*AR*FMT*DMT]/[F*70.]$$

$$= [TD(I)*WMT*CRDMT(I)*CMT*DFING(I,J)*FRIV*FMT*DMT]/[IRAT*70.] \quad (5.33)$$

and

$$IMTWHE(I,J) = [TD(I)*WMT*CRDMT(I)*CMT*DFING(I,J)*RISK(J)*AR*FMT*DMT]/[F*70.]$$

$$= [TD(I)*WMT*CRDMT(I)*CMT*DFING(I,J)*RISK(J)*FRIV*FMT*DMT/[IRAT*70.] . \quad (5.34)$$

The total cancers from radionuclide I are given by

$$\text{IMTRHET} = \sum_J \text{IMTRHE}(I,J) \qquad (5.35)$$

and

$$\text{IMTWHET} = \sum_J \text{IMTWHE}(I,J). \qquad (5.36)$$

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Volume 6

Calculation of Health Effects per Curie Release for Comparison with the EPA Standard

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WH

TECHNICAL ASSISTANCE FOR REGULATORY DEVELOPMENT: REVIEW AND EVALUATION OF THE DRAFT EPA STANDARD 40CFR191 FOR DISPOSAL OF HIGH-LEVEL WASTE

VOL. 6

CALCULATION OF HEALTH EFFECTS PER CURIE RELEASE FOR COMPARISON WITH THE EPA STANDARD

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ABSTRACT

The Environmental Protection Agency (EPA) is developing a standard for geologic disposal of high-level radioactive wastes (40CFR191) based on radioactive releases (expressed in curies) that may result in 1,000 health effects (i.e., latent cancer fatalities) over a 10,000 year period. Health effects calculations were used by EPA to establish the curie release limits. The Fuel Cycle Risk Analysis Division of Sandia National Laboratories was requested by the Nuclear Regulatory Commission (NRC) High-Level Waste Licensing Management Branch to perform calculations, using the methodology developed under the Risk Assessment Methodology Program, to compare with the results from the EPA analysis. The intent was to provide some insights into the degree of conservatism in the health effects per curie values presented by the EPA standard. No attempt was made to encompass all the uncertainty in the input parameters used in the calculations and some of the modeling assumptions used in this analysis are different from those of the EPA. Three sets of calculations of health effects (cancer deaths) per curie release were performed in this analysis. The calculational methods, the results of the analysis, and the potential implication of these results upon the curie release limits of the EPA are discussed in this report.

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1.0 Introduction

The Environmental Protection Agency (EPA) is developing a standard for geologic disposal of high-level radioactive wastes that would limit the curie releases to the accessible environment of the various radionuclides found in high-level waste. The EPA guidance establishes that the releases of radionuclides to the accessible environment from the wastes from 100,000 Metric Ton of Heavy Metal (MTHM) should not result in excess of 1,000 health effects (i.e., latent cancer fatalities) over a 10,000 year period. The process by which EPA established the release limits consisted of two steps. In the first step, the projected releases of radioactivity from a generic geologic repository in various geologic media (bedded salt, domed salt, granite, basalt and shale) were calculated and in the second step, the potential excess cancer deaths from the releases were estimated. A set of calculated health effects per curie released into the environment for all the radionuclides considered in the EPA analysis was established to estimate the potential health hazard. The EPA analyses of the various media were used to select the limit of 1,000 health effects over 10,000 years for a 100,000 MTHM repository. The 1,000 health effects criteria was then used to establish the release limits for individual radionuclides. The Nuclear Regulatory Commission (NRC) requested the Fuel Cycle Risk Analysis Division of Sandia National Laboratories (SNL) to perform an evaluation using the methodology developed under the Risk Assessment Methodology Program (FIN:A-1192) to calculate the health effects that may result from the release of one curie of each of various radionuclides to the biosphere. The intent of this two week effort was to provide some insights into the degree of conservatism in the health effects per curie values calculated by the EPA. The intent was not to present values to replace the EPA curie values, but rather to perform calculations similar to the EPA analysis that would provide some perspective on the EPA release limits. No attempt was made to bound all of the uncertainty in the input parameters in the pathway modeling effort, to encompass all the possibilities of release or to address the uncertainties in the dose conversion factors and health effects estimates. The calculations presented in this report were designed to flag potential problems with the EPA release limits that may warrant further analysis.

Three sets of calculations were performed in this work. The first set of calculations (EPA/SANDIA Analysis) used the Pathways Model developed at Sandia (Helton and Kaestner, 1981) and the input parameters (e.g., distribution coefficients (Kd), concentration ratios, dose conversion factors, risk estimates, etc.) and the health effects calculational methods from the EPA. A second set of calculations (SANDIA Analysis) was made using the Pathways Model (Helton and Kaestner, 1981) and the

Dosimetry and Health Effects Model (Runkle, et al., 1981). In these calculations the input parameters to the Pathways Model were selected from those used in demonstrating the Risk Assessment Methodology (described in Cranwell, et al., 1982). The reference site used in this demonstration was based on a hypothetical site and generic parameters representing several sites throughout the United States. The EPA point value for the distribution coefficients (Kd) for the various radionuclides were used in the analysis. The third set of calculations (SAMPLED SANDIA Analysis) were performed using a statistical technique to sample an assigned range of values for some of the input parameters to the Pathways Model. A distribution was assigned to each range of values. This approach can be used to represent some of the uncertainty in the calculated results due to input data uncertainties. Many other uncertainties have not been addressed in this analysis and include uncertainties in the concentration ratios, the dose conversion factors, and the risk estimators of health effects, to name only a few.

There are several differences in the modeling approaches used in this analysis that may affect the results and are therefore detailed below. First, for calculating the health effects per curie release for the water based pathway, the EPA input a unit curie source over 10,000 years (i.e., 10^{-4} Ci/yr) into the surface (river) water to calculate the drinking water and fish intakes. For the land based pathways (which include ingestion of crops, beef and milk), EPA input a 0.5 curie source into the soil compartment over 10,000 years (i.e., 5×10^{-5} Ci/yr) to estimate the soil concentrations, and further assumed that 50% of the contaminated land was used for crop production for direct human consumption, 25% for milk production and 25% for beef production.

In the analyses (EPA/SANDIA, SANDIA, SAMPLED SANDIA) presented in this report, a unit curie source was input to the liquid phase of the surface water over 10,000 years (i.e., 10^{-4} Ci/yr) and the interchange between the surface water and the soil compartments of the Pathways Model determined the soil concentration. The calculations performed by the Pathways Model resulted in an input of 2.3E-3 Ci to the soil over the 10,000 year period. In addition, the fractional partitioning of land use (assumed by EPA) was not incorporated in this analysis.

Second, the EPA analysis considered a population detriment that was based on a linear relationship of population to the flow rate in a river for the water based pathways and was linearly proportional to the area of land for the land based pathways. In the approach used by EPA, it is important to note

that the area (A) canceled out of the equation for the land based ingestion calculation, which eliminated the linear relationship between area and population.

The Risk Assessment Methodology used for this analysis was based on the risk to an average individual and was converted to a population risk by relating the river flow rate to the population density (persons/ℓ) assumed by EPA to estimate the population for the water based pathways. For the land based pathways the density (persons/m^2) defined by EPA was multiplied by the area considered in the reference site analysis (Cranwell et al., 1982). The land area was defined as 40 km x 2 km on both sides of a river (160 km^2), that was assumed to fall within the flood plain of the river and to provide food (crops, beef and milk) for the population. With this approach, the population is a linear function of the assumed area and doubling the area will result in a doubling of the population.

The three calculational methods for the EPA/SANDIA, SANDIA and SAMPLED SANDIA Analyses are detailed in Chapters 2-4, respectively. Chapter 5 is a summary of the results calculated in this analysis.

2.0 Description of the EPA/SANDIA Analysis

The EPA/SANDIA Analysis used the Environmental Pathways Model developed at Sandia (Helton and Kaestner, 1981) and the input parameters used by EPA in their analysis. The input parameters included concentration ratios, human and animal consumption rates, dose conversion factors and risk estimates. These calculations were designed to estimate the health effects per curie release by employing the Risk Assessment Methodology developed at SNL and the EPA input parameters.

The Pathways Model (Helton and Kaestner, 1981) was used to estimate the radionuclide concentrations in the surface water and soil compartments following a 10^{-4} curie/year release into the surface water for a 10,000 year period. For the simplified analysis presented in this report, a system consisting of two compartments, soil and surface water, was used. For this situation, the mathematical formulation for each radionuclide considered is a system of two differential equations of the following form:

$$\begin{aligned} dx_1/dt &= h_1 - (\lambda + k_{21})\, x_1 + k_{12}\, x_2 \\ dx_2/dt &= h_2 + k_{21}\, x_1 - (\lambda + k_{02} + k_{12})\, x_2 \end{aligned} \qquad (1)$$

where x_i is the amount (units: Ci) of radionuclide in compartment i (1 ~ soil, 2 ~ surface water), h_i is the rate of radionuclide input (units: Ci/yr) to compartment i, and λ

is the decay constant (units: yr^{-1}) for the radionuclide under consideration. The k_{ij} is the rate constant for movement from compartment j to compartment i, where i = 0 denotes a flow from compartment j to an area outside the modeled system. Each coefficient, k_{ij}, is of the following form:

$$k_{ij} = \frac{(1 - S_j)RW_{ij}}{VW_j} + \frac{S_j\, RS_{ij}}{MS_j} , \qquad (2)$$

where VW_j denotes the volume of water in compartment j (units: ℓ), MS_j denotes the mass of solids in compartment j (units: kg), RW_{ij} denotes the rate at which water flows from compartment j to compartment i (units: ℓ/yr), and RS_{ij} denotes the rate at which solid material flows from compartment j to compartment i (units: kg/yr). Further, the unitless quantity S_j represents the effects of radionuclides partitioning in compartment j and is defined by

$$S_j = \frac{Kd_j MS_j}{Kd_j MS_j + VW_j} , \qquad (3)$$

where Kd_j is the distribution coefficient in compartment j for the radionuclide under consideration (units: ℓ/kg). The nonzero values for the VW_j, MS_j, RW_{ij} and RS_{ij} for the site described in this section are given in Table 2.1.

The system of equations in (1) can be reformulated in matrix notation as

$$dx/dt = h + Kx, \qquad (4)$$

where

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} , \; h = \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} \text{ and } K = \begin{bmatrix} -(\lambda + k_{21}) & k_{12} \\ k_{21} & -(\lambda + k_{02} + k_{12}) \end{bmatrix} \qquad (5)$$

For this analysis h_1 was assumed to be 10^{-4} curies/yr and h_2 was assumed to be 0. As the system under consideration is completely open, the equations represented in (1) and (2) have a unique asymptotic solution, sx, where

$$sx = -K^{-1} h. \qquad (6)$$

For the analysis presented in this report, the asymptotic solutions indicated in (6) were used instead of time-dependent solutions. Variables R_1 to R_4 were used to introduce variance in the exchange rate between subzones and may be sampled from a user-specified range. For this analysis, a mid-point value (see Table 2.1) was assumed.

Table 2.1

Environmental Transport Input Parameters
(Helton and Kaestner, 1981)

Surface Water:

VW_2	= Volume of Water	2.2×10^{10} ℓ
MS_2	= Mass of Solid	$6.8 \times 10^5 \left(\frac{R_4}{R_1}\right)$ kg
RS_{12}	= Rate of mass outflow to soil subzone	1.1×10^{11} (R_3) kg/y
RW_{02}	= Rate of water outflow to surface water in next zone	1.9×10^{13} (R_1) ℓ/y
RS_{02}	= Rate of solid outflow to surface in next zone	5.9×10^8 (R_4) kg/y
RW_{12}	= Rate of water outflow to soil subzone	4.0×10^{10} (R_2) ℓ/y

Soil:

VW_1	= Volume of water	2.0×10^{10} ℓ
MS_1	= Mass of solid	1.1×10^{11} kg
RW_{21}	= Rate of water outflow to surface water	4.0×10^{10} (R_2) ℓ/y
RS_{21}	= Rate of mass outflow to surface water	0.0 (kg/y)

Assumed Values:

$R_1 = 1.0$
$R_2 = 1.0$
$R_3 = 10^{-3}$
$R_4 = 9.0$

Variables to introduce variation in the subzones indicated above. Variations were not considered in the EPA/SANDIA or the SANDIA analyses, therefore these variables were assigned the point values given in this table.

Also for this analysis, the radionuclides were assumed to be released to the liquid phase of the surface water. Further, no adsorption onto the solid particulate phase of the surface water was considered. This would represent a situation where there are no Kd effects in the water. In an alternative scenario that considers river flooding, particulates are carried onto the surrounding land mass and contribute a large radionuclide burden to the soil. This analysis placed the radionuclide solely in the liquid phase of the surface water, as assumed by the EPA. However, the distribution coefficient, Kd, was taken into account in the radionuclide concentration in the soil subzone. The point values for the Kd values for the radionuclides that were used in this analysis and also by the EPA are given in Table 2.2. The EPA data (unless otherwise specified) were obtained from personal communication with J. M. Smith, EPA, Montgomery, Alabama. Since the initial work in 1981, these EPA parameters and the environmental calculations have been published in Smith, et al., 1982.

In the analysis presented in this section, a unit curie source was input to the liquid phase of the water over 10,000 years and the interchanges between the surface water and the soil compartments of the Pathways Model determined the soil concentration. The results of the Pathways analysis are given in Table 2.3 for the surface water and soil compartments. These radionuclide concentrations were used to calculate the health effects (cancer deaths) per curie release. The calculations of the cumulative health effects over time, T, may be summarized by the following general equation

$$RSK_{ij} = Q_{ij} * (\sum_{k} DF_{ijk} * HE_{jk}) * POP_{j} * T \qquad (7)$$

where

RSK_{ij} = health effects (cancer deaths) per curie release of radionuclide i via pathway j (ingestion, inhalation or external)

Q_{ij} = quantity intake per year (via ingestion or inhalation) or exposure (external) to radionuclide i via pathway j (Ci/y)

DF_{ijk} = dose conversion factor to calculate the dose commitment to organ k from radionuclide i via pathway j (rem/Ci)

Table 2.2

Distribution Coefficients (Kd)
Assumed by EPA

Radionuclide	Kd Value (cm^3/gm)
Am241	2000
Am243	2000
Cs135	200
Cs137	200
I129	0
Np239	15
Pu239	2000
Pu240	2000
Pu242	2000
Sr90	20
Tc99	0
Sn126	250

Table 2.3

Radionuclide Concentrations in the Surface Water and Soil From the Pathways Analysis

Radionuclide	Surface Water (Ci/ℓ)	Soil (Ci/kg)
Am241	5.26E-18	1.13E-15
Am243	5.26E-18	7.02E-15
Cs135	5.26E-18	1.05E-15
Cs137	5.26E-18	7.66E-17
I129	5.26E-18	9.57E-19
NP237	5.26E-18	7.99E-17
PU239	5.26E-18	9.10E-15
PU240	5.26E-18	6.54E-15
PU242	5.26E-18	1.04E-14
SR90	5.26E-18	4.56E-17
TC99	5.26E-18	9.57E-19
SN126	5.26E-18	1.31E-15

HE_{jk} = health effects conversion factor to estimate the potential fatal cancers from the dose commitment to organ k via pathway j $\left(\frac{\text{health effects}}{\text{rem}}\right)$

POP_j = population exposed to the dose commitment from pathway j (persons)

T = time interval of the calculation. For this analysis (and EPA) the time interval was assumed to be 10,000 years.

The three pathways included in this analysis were the ingestion (includes several subpathways), inhalation and external exposure. The calculations of health effects per curie release for each of these pathways are detailed in subsections 2.1, 2.2 and 2.3, respectively.

2.1 Ingestion

The ingestion pathway consists of intake of radionuclides from various subpathways including drinking water, fish, plants, milk and meat. The calculations for these subpathways used the following components: (1) dose factors and health estimates (2) population at risk and (3) quantity intake. Each component is discussed below with reference to the various subpathways.

2.1.1 Dose Factors and Health Effects Estimates

The dose conversion factors and the health effects estimates per rem of exposure were taken from Table 2.4. For each radionuclide, the product of the ingestion dose commitment factors and health effects conversion factors were summed over all organs. The summation was used to calculate the health effects from all of the subpathways. The dose conversion factors used by EPA represent a 50-year dose commitment (rem) to an individual which results from the initial intake of one curie of the radionuclide.

2.1.2 Population at Risk

EPA used the flow rate of the world's rivers and the world population to estimate the population that can be supported by a given river flow rate. This ratio, of the flow rate to the world population, was applied to the flow rate of the river considered in this analysis (1.9E13ℓ/yr) to define the population for the drinking water. A resulting population of 6.3E6 persons was used for the EPA/SANDIA calculations. EPA also related the world's average fish consumption rate (10^{10} kg/yr) to the world's river flow rate (3E16 ℓ/yr) to estimate the

Table 2.4

HEALTH EFFECTS CONVERSION FACTORS, HEALTH EFFECTS/MAN REM
(FATAL CANCERS FOR ALL ORGANS EXCEPT OVARIES AND TESTES. GENETIC EFFECTS TO FIRST GENERATION FOR OVARIES AND TESTES)

BONE	RED MARROW	LUNGS	LIVER	GI-LLI WALL	THYROID	KIDNEYS	OTHERORGAN	OVARIES	TESTES
1.000E-05	4.000E-05	4.000E-05	1.000E-05	2.000E-05	1.000E-06	1.000E-05	7.000E-05	2.000E-05	2.000E-05

NUCLIDE DEPENDENT INPUT DATA

NUCLIDE PATHWAY — DOSE COMMITMENT FACTORS
(INHALATION AND INGESTION=REM/CI INTAKE; AIR SUBMERSION=REM/Y PER CI/M**3; GROUND CONTAMINATION=REM/Y PER CI/M**2)

		ORGAN									
		BONE	RED MARROW	LUNGS	LIVER	GI-LLI WALL	THYROID	KIDNEYS	OTHERORGAN	OVARIES	TESTES
C-14	INHAL1	8.460E+00	2.420E+01	6.180E+00	8.880E+00	7.220E+00	6.480E+00	7.920E+00	1.410E+01	5.290E+00	5.420E+00
	INHAL2	8.460E+00	2.420E+01	6.180E+00	8.880E+00	7.220E+00	6.480E+00	7.920E+00	1.410E+01	5.290E+00	5.420E+00
	INGEST	1.170E+03	3.380E+03	8.490E+02	1.230E+03	1.460E+03	8.890E+02	1.060E+03	1.920E+03	7.360E+02	7.230E+02
	EXT AIR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	EXT GND	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NI-59	INHAL1	1.290E+04	2.150E+03	8.470E+03	4.983E+03	7.120E+02	2.150E+03	2.150E+03	2.150E+03	2.150E+03	2.150E+03
	INHAL2	1.290E+04	2.150E+03	8.470E+03	4.980E+03	3.560E+02	2.150E+03	2.150E+03	2.150E+03	2.150E+03	2.150E+03
	INGEST	9.670E+03	1.610E+03	1.610E+03	3.320E+03	9.700E+02	1.610E+03	1.610E+03	1.610E+03	1.610E+03	1.610E+03
	EXT AIR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	EXT GND	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SR-90	INHAL1	3.210E+05	1.210E+05	8.540E+06	1.930E+04	9.310E+05	3.740E+03	3.740E+03	1.510E+05	3.740E+03	3.730E+03
	INHAL2	3.000E+06	1.100E+06	4.920E+04	1.490E+04	5.500E+04	1.540E+04	1.540E+04	2.410E+05	1.540E+04	1.540E+04
	INGEST	1.200E+06	4.300E+05	1.570E-02	5.710E+03	1.980E+05	5.990E+03	5.990E+03	9.500E+04	5.990E+03	5.990E+03
	EXT AIR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	EXT GND	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ZR-93	INHAL1	1.470E+03	1.750E+03	5.850E+04	2.930E+03	7.170E+03	1.600E+03	1.360E+03	2.500E+03	1.040E+03	1.470E+02
	INHAL2	4.120E+03	2.460E+03	3.080E+04	2.110E+03	6.980E+03	1.320E+03	1.320E+03	2.130E+03	1.460E+03	4.950E+02
	INGEST	1.970E+02	3.340E+02	3.900E+01	1.430E+02	1.750E+04	1.690E+01	1.990E+02	2.470E+02	1.360E+03	1.340E+02
	EXT AIR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	EXT GND	1.780E+04	1.780E+04	1.780E+04	1.780E+04	1.780E+04	1.780E+04	1.780E+04	1.780E+04	1.780E+04	1.780E+04
TC-99	INHAL1	2.420E+02	2.150E+02	5.220E+04	4.210E+02	1.660E+03	9.460E+03	3.070E+02	8.870E+02	2.120E+02	2.120E+02
	INHAL2	2.420E+02	2.150E+02	5.220E+04	4.210E+02	1.660E+03	9.460E+03	3.070E+02	8.870E+02	2.120E+02	2.120E+02
	INGEST	3.610E+02	3.220E+02	0.0	6.280E+02	3.200E+03	1.410E+04	4.580E+02	2.140E+02	3.170E+02	3.170E+02
	EXT AIR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	EXT GND	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Taken from Smith, et al., 1982

Table 2.4 (continued)

		ORGAN									
		BONE	RED MARROW	LUNGS	LIVER	GI-LLI WALL	THYROID	KIDNEYS	OTHERORGAN	OVARIES	TESTES
SN-126	INHAL1	1.580E+05	1.580E+05	1.270E+06	4.190E+03	7.600E+04	1.230E+03	6.160E+03	6.160E+03	6.160E+03	6.160E+03
	INHAL2	1.580E+05	1.580E+05	1.270E+06	4.190E+03	7.600E+04	1.230E+03	6.160E+03	6.160E+03	6.160E+03	6.160E+03
	INGEST	8.570E+04	8.570E+04	3.110E+03	1.690E+03	1.180E+05	4.990E+02	2.830E+03	2.820E+03	2.820E+03	2.820E+03
	EXT AIR	1.150E+07	1.150E+07	1.150E+07	1.150E+07	1.150E+07	1.150E+07	1.150E+07	1.150E+07	1.150E+07	1.150E+07
	EXT GND	2.090E+05	2.090E+05	2.090E+05	2.090E+05	2.090E+05	2.090E+05	2.090E+05	2.090E+05	2.090E+05	2.090E+05
I-129	INHAL1	5.790E+02	6.050E+02	7.880E+02	4.660E+02	4.280E+01	5.000E+06	4.490E+02	2.050E+03	3.780E+02	3.570E+02
	INHAL2	5.790E+02	6.050E+02	7.880E+02	4.660E+02	4.280E+01	5.000E+06	4.490E+02	2.050E+03	3.780E+02	3.570E+02
	INGEST	9.020E+02	9.420E+02	1.790E+02	7.240E+02	6.700E+01	7.800E+05	7.020E+02	3.180E+03	5.920E+02	5.580E+02
	EXT AIR	1.450E+05	1.310E+05	4.850E+04	3.600E+04	1.150E+04	1.010E+05	5.380E+04	9.540E+04	3.400E+04	1.310E+05
	EXT GND	8.730E+03	7.870E+03	2.910E+03	2.160E+03	6.900E+02	6.040E+03	3.230E+03	5.730E+03	2.040E+03	7.880E+03
CS-135	INHAL1	7.470E+03	7.470E+03	6.400E+02	7.470E+03	8.510E+01	7.480E+03	7.470E+03	4.400E+03	7.470E+03	7.470E+03
	INHAL2	7.470E+03	7.470E+03	6.400E+02	7.470E+03	8.510E+01	7.480E+03	7.470E+03	4.400E+03	7.470E+03	7.470E+03
	INGEST	1.120E+04	1.120E+04	0.0	1.120E+04	5.350E+02	1.130E+04	1.120E+04	6.610E+03	1.120E+04	1.120E+04
	EXT AIR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	EXT GND	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CS-137	INHAL1	4.540E+04	4.910E+04	1.620E+04	5.230E+04	1.600E+04	4.470E+04	5.130E+04	3.260E+04	5.000E+04	4.440E+04
	INHAL2	4.540E+04	4.910E+04	1.620E+04	5.230E+04	1.600E+04	4.470E+04	5.130E+04	3.260E+04	5.000E+04	4.440E+04
	INGEST	6.820E+04	7.380E+04	1.990E+04	7.870E+04	2.590E+04	6.720E+04	7.730E+04	4.910E+04	7.540E+04	6.680E+04
	EXT AIR	4.660E+06	4.450E+06	3.600E+06	3.180E+06	2.750E+06	4.020E+06	3.380E+06	3.810E+06	1.390E+06	4.240E+06
	EXT GND	8.290E+04	7.920E+04	6.400E+04	5.650E+04	4.900E+04	7.150E+04	6.030E+04	6.790E+04	2.490E+04	7.550E+04
SM-151	INHAL1	5.100E+02	2.090E+02	6.780E+04	1.900E+03	3.040E+03	1.920E+01	5.540E+02	1.090E+03	1.470E+01	1.070E+01
	INHAL2	4.910E+03	1.940E+03	1.590E+04	1.890E+04	2.810E+03	1.040E+02	5.380E+03	1.190E+03	1.050E+02	1.030E+02
	INGEST	4.910E+00	3.200E+00	1.050E-01	1.730E+01	5.850E+03	1.030E-01	5.520E+00	2.340E+01	5.660E+00	5.360E-01
	EXT AIR	2.440E+01	2.130E+01	4.240E+00	2.350E+00	2.920E+00	9.060E+00	7.020E+00	3.070E+01	3.920E+00	3.860E+01
	EXT GND	4.590E+00	4.000E+00	7.960E-01	4.410E-01	5.480E-01	1.700E+00	1.320E+00	5.780E+00	7.360E-01	7.300E+00
RA-226	INHAL1	1.100E+07	9.800E+05	2.810E+07	3.400E+05	1.000E+05	3.400E+05	3.490E+05	4.600E+06	3.400E+05	3.400E+05
	INHAL2	1.100E+07	9.800E+05	2.810E+07	3.400E+05	1.000E+05	3.400E+05	3.490E+05	4.600E+06	3.400E+05	3.400E+05
	INGEST	6.320E+07	2.140E+06	2.710E+02	1.870E+06	8.160E+05	8.010E+05	5.790E+06	7.790E+06	8.060E+05	8.010E+05
	EXT AIR	1.500E+07	1.390E+07	1.270E+07	1.120E+07	1.030E+07	1.280E+07	1.060E+07	1.180E+07	9.900E+06	1.130E+07
	EXT GND	2.520E+05	2.340E+05	2.070E+05	1.850E+05	1.690E+05	2.120E+05	1.750E+05	2.210E+05	1.630E+05	1.890E+05
U-234	INHAL1	2.000E+07	8.100E+05	2.730E+08	5.900E+05	5.480E+04	5.900E+05	8.700E+05	9.800E+06	5.900E+05	5.900E+05
	INHAL2	5.900E+07	2.400E+06	2.800E+07	1.700E+06	4.790E+04	1.700E+06	2.500E+06	5.500E+06	1.700E+06	1.700E+06
	INGEST	2.000E+07	8.000E+05	8.230E+02	5.800E+05	8.860E+04	5.800E+05	8.500E+05	1.700E+06	5.800E+05	5.800E+05
	EXT AIR	2.940E+03	2.640E+03	1.030E+03	7.640E+02	8.560E+02	1.280E+03	8.130E+02	2.490E+03	6.640E+02	2.090E+03
	EXT GND	5.630E+02	5.050E+02	1.970E+02	1.460E+02	1.640E+02	2.460E+02	1.560E+02	4.780E+02	1.270E+02	4.000E+02
NP-237	INHAL1	9.040E+08	3.010E+08	2.900E+08	4.020E+08	1.380E+05	3.000E+06	5.200E+07	8.500E+07	1.800E+06	5.800E+06
	INHAL2	2.240E+09	7.470E+08	3.000E+07	9.910E+08	1.260E+05	7.400E+06	1.280E+08	1.900E+08	4.600E+06	1.400E+07
	INGEST	1.900E+07	6.200E+06	8.870E+02	8.200E+06	1.460E+05	6.080E+04	1.100E+06	1.600E+06	3.900E+04	1.200E+05
	EXT AIR	3.270E+06	3.030E+06	1.790E+06	1.560E+06	1.130E+06	2.150E+06	1.500E+06	2.050E+06	1.020E+06	2.410E+06
	EXT GND	7.250E+04	6.720E+04	3.970E+04	3.460E+04	2.500E+04	4.470E+04	3.340E+04	4.570E+04	2.270E+04	5.350E+04

Table 2.4 (continued)

		ORGAN									
		BONE	RED MARROW	LUNGS	LIVER	GI-LLI WALL	THYROID	KIDNEYS	OTHERORGAN	OVARIES	TESTES
PU-238	INHAL1	7.910E+08	2.640E+08	3.090E+08	3.550E+08	6.200E+04	2.600E+06	4.600E+07	7.600E+07	1.600E+06	5.000E+06
	INHAL2	2.030E+09	6.770E+08	3.200E+07	9.070E+08	5.510E+04	6.600E+06	1.170E+08	1.730E+08	4.100E+06	1.300E+07
	INGEST	5.000E+05	1.700E+05	7.890E-02	2.200E+05	1.100E+05	1.640E+03	2.910E+04	4.320E+04	1.030E+03	3.200E+03
	EXT AIR	1.260E+03	1.090E+03	3.020E+02	1.330E+02	4.450E+02	2.460E+02	1.770E+02	1.660E+03	1.860E+02	1.320E+03
	EXT GND	2.470E+02	2.140E+02	5.920E+01	2.600E+01	8.710E+01	4.810E+01	3.460E+01	3.250E+02	3.540E+01	2.580E+02
PU-239	INHAL1	9.120E+08	3.040E+08	2.940E+08	4.040E+08	5.780E+04	3.000E+06	5.200E+07	8.600E+07	1.800E+06	5.800E+06
	INHAL2	2.280E+09	7.610E+08	3.000E+07	1.000E+09	5.130E+04	7.400E+06	1.300E+08	1.920E+08	4.600E+06	1.500E+07
	INGEST	5.700E+05	1.900E+05	6.090E-02	2.500E+05	9.860E+04	1.850E+03	3.220E+04	4.820E+04	1.150E+03	3.600E+03
	EXT AIR	6.410E+02	5.610E+02	1.710E+02	9.380E+01	1.900E+02	1.890E+02	1.230E+02	7.220E+02	1.170E+02	6.110E+02
	EXT GND	1.220E+02	1.070E+02	3.240E+01	1.780E+01	3.600E+01	3.590E+01	2.330E+01	1.370E+02	2.210E+01	1.160E+02
PU-240	INHAL1	9.130E+08	3.040E+08	2.950E+08	4.050E+08	5.820E+04	3.000E+06	5.200E+07	8.600E+07	1.800E+06	5.800E+06
	INHAL2	2.280E+09	7.600E+08	3.100E+07	1.010E+09	5.170E+04	7.400E+06	1.300E+08	1.940E+08	4.600E+06	1.500E+07
	INGEST	5.700E+05	1.900E+05	8.320E-02	2.500E+05	9.930E+04	1.840E+03	3.220E+04	4.830E+04	1.150E+03	3.600E+03
	EXT AIR	1.160E+03	1.000E+03	2.890E+02	1.400E+02	3.950E+02	2.530E+02	1.780E+02	1.460E+03	1.800E+02	1.170E+03
	EXT GND	2.250E+02	1.960E+02	5.640E+01	2.720E+01	7.790E+01	4.930E+01	3.470E+01	2.850E+02	3.520E+01	2.280E+02
AM-241	INHAL1	9.430E+08	3.140E+08	3.130E+08	4.190E+08	6.520E+04	3.100E+06	5.400E+07	8.900E+07	1.900E+06	6.000E+06
	INHAL2	2.350E+09	7.830E+08	3.200E+07	1.040E+09	6.110E+04	7.700E+06	1.340E+08	1.990E+08	4.800E+06	1.500E+07
	INGEST	1.900E+07	6.400E+06	1.270E+02	8.500E+06	1.100E+05	6.320E+04	1.100E+06	1.600E+06	3.940E+04	1.200E+05
	EXT AIR	2.720E+05	2.480E+05	1.010E+05	8.300E+04	5.680E+04	1.380E+05	8.800E+04	1.440E+05	8.510E+04	1.260E+05
	EXT GND	1.420E+04	1.300E+04	5.300E+03	4.330E+03	2.960E+03	7.210E+03	4.590E+03	7.500E+03	4.440E+03	6.570E+03
PU-242	INHAL1	8.690E+08	2.890E+08	2.800E+08	3.850E+08	5.510E+04	2.800E+06	5.000E+07	8.200E+07	1.800E+06	5.500E+06
	INHAL2	2.170E+09	7.220E+08	2.900E+07	9.560E+08	4.900E+04	7.100E+06	1.230E+08	1.840E+08	4.400E+06	1.400E+07
	INGEST	5.400E+05	1.800E+05	1.600E-01	2.400E+05	9.400E+04	1.760E+03	3.060E+04	4.600E+04	1.090E+03	3.420E+03
	EXT AIR	1.040E+03	8.930E+02	2.360E+02	9.370E+01	3.650E+02	1.770E+02	1.320E+02	1.390E+03	1.510E+02	1.100E+03
	EXT GND	2.030E+02	1.750E+02	4.630E+01	1.840E+01	7.160E+01	3.470E+01	2.590E+01	2.720E+02	2.970E+01	2.170E+02
AM-243	INHAL1	9.430E+08	1.560E+09	3.030E+08	4.210E+08	3.220E+05	3.100E+06	5.400E+07	8.900E+07	1.900E+06	6.000E+06
	INHAL2	2.340E+09	3.870E+09	3.100E+07	1.040E+09	1.500E+05	7.700E+06	1.340E+08	1.990E+08	4.800E+06	1.500E+07
	INGEST	1.900E+07	3.200E+07	9.640E+02	8.500E+06	1.490E+05	6.340E+04	1.100E+06	1.600E+06	4.070E+04	1.200E+05
	EXT AIR	2.170E+06	2.010E+06	1.060E+06	9.140E+05	6.490E+05	1.330E+06	8.970E+05	1.290E+06	6.760E+05	1.410E+06
	EXT GND	5.290E+04	4.880E+04	2.630E+04	2.260E+04	1.610E+04	3.280E+04	2.210E+04	3.150E+04	1.650E+04	3.480E+04

population intake of fish (3.3E-7 kg per person/ℓ). The EPA estimate of 3.3E-7 kg per person/ℓ is the same as assuming a 1 kg/yr fish intake. Therefore, for the EPA/SANDIA calculations a 1 kg/yr consumption of fish and the same population used for the drinking water calculations (6.3E6 persons) were assumed.

The population for the land-based ingestion intakes was calculated by multiplying the density (persons/m^2) provided by EPA for the three subpathways by the area considered in the hypothetical reference site analysis (160 km^2) (Cranwell, et al., 1982). The populations used in these subpathway calculations were

CROP

$$160\ km^2 * 1.0E\text{-}3 \frac{person}{m^2} = 1.6E5\ persons$$

MILK

$$160\ km^2 * 1.5E\text{-}3 \frac{person}{m^2} = 2.4E5\ persons$$

BEEF

$$160\ km^2 * 2.1E\text{-}4 \frac{person}{m^2} = 3.4E4\ persons\ .$$

2.1.3 Quantity Intake of Radionuclides

The quantity intake of a radionuclide is dependent upon the concentration of the radionuclide in the food source and the rate of intake or consumption. The EPA/SANDIA calculations utilized the equations for each subpathway available in the Pathways Model and substituted the appropriate EPA parameter values. In some cases, the modeling approaches differed between EPA and the Pathways Model, and in these cases, the input parameters were selected from those used in the reference site analysis (Cranwell, et al., 1982). The EPA point values used in the analysis are given with each equation and are summarized in Tables 2.5 and 2.6. The radionuclide dependent concentration ratios were taken from a computer output provided by J. M. Smith, EPA, and are given in Table 2.7 (recently published in Smith, et al., 1982). The equations for the various ingestion subpathways are defined in Sections 2.1.3.1 to 2.1.3.5.

Table 2.5

Ingestion, Inhalation and External Exposure Rates Assumed by EPA

Ingestion Rates	
Water Consumption by Humans	6.03E02 ℓ/yr
Plant Consumption by Humans	1.94E02 kg/yr
Milk Consumption by Humans	1.12E02 ℓ/yr
Beef Consumption by Humans	8.5E01 kg/yr
Fish Consumption by Humans	1.0E00 kg/yr
Inhalation Rate	
Average Air Consumption by Humans	8.40E03m^3/y
Annual External Exposure	
Submersion in Air	1/3 year
Groundshine from Soil*	1/3 year

*An effective depth of 0.15m was assumed for soil by EPA.

Table 2.6

Crop and Animal Parameters
Assumed by EPA

Animal Consumption Rates	
Plant Consumption by Dairy Cows	5.0E01 kg/day
Plant Consumption by Beef Cows	5.0E01 kg/day
Sprinkler Irrigation for Crops	
Irrigation Rate	3.0E02 $\ell/m^2/y$*
Retention Fraction	2.5E-01*
Standing Crop	7.16E-01 kg/m^2
Rate Constant for Weathering (λ_ω)	1.8E01y^{-1} (13.75 day half-life)
Irrigation Time (τ)	1.7E-1 y
$e^{-\lambda\omega\tau}$	4.65E-2
Sprinkler Irrigation for Pasture	
Irrigation Rate	3.0E02 $\ell/m^2/y$*
Retention Fraction	2.5E-01*
Standing Crop	2.8E-01 kg/m^2
Rate Constant for Weathering (λ_ω)	1.8E01 y^{-1} (13.75 day half-life)
Irrigation Time (τ)	1.7E-1 y
$e^{-\lambda\omega\tau}$	4.65E-2

*These parameters were not defined in the EPA Analysis; therefore the values used in reference site analysis to demonstrate the SNL Risk Assessment Methodology were substituted for the calculation.

Table 2.7

Concentration Ratios Assumed by EPA

	FISH/WATER (Ci/kg per Ci/ℓ)	CROP/SOIL (dimensionless)	PASTURE (FEED)/SOIL (dimensionless)	MILK/FEED $\left(\frac{day \cdot kg}{kg \cdot \ell}\right)$	BEEF/FEED $\left(\frac{day \cdot kg}{kg \cdot kg}\right)$
Am241	2.5E1	0.11E-2	0.74E-2	0.36E-4	0.16E-5
Am243	2.5E1	0.22E-3	0.15E-2	0.36E-4	0.16E-5
CS135	4.0E2	0.10E-5	0.17E-4	0.56E-2	0.14E-1
CS137	4.0E2	0.85E-2	0.14E0	0.56E-2	0.14E-1
I129	1.5E1	0.19E-7	0.68E-7	0.99E-2	0.70E-2
NP237	1.0E1	0.16E-7	0.65E-7	0.50E-5	0.20E-3
Pu239	3.5E2	0.59E-4	0.36E-3	0.53E-7	0.19E-7
Pu240	3.5E2	0.19E-3	0.12E-2	0.53E-7	0.19E-7
Pu242	3.5E2	0.40E-5	0.24E-4	0.45E-7	0.41E-6
SR90	5.0E0	0.21E0	0.86E0	0.24E-2	0.30E-3
TC99	1.5E1	0.14E-5	0.28E-3	0.99E-2	0.87E-2
SN126	3.0E3	0.77E-5	0.31E-4	0.12E-2	0.80E-1

2.1.3.1 Drinking Water

$$\begin{pmatrix}\text{amt of nuclide}\\ \text{intake per year}\end{pmatrix} = \begin{pmatrix}\text{nuclide conc}\\ \text{in surface water}\end{pmatrix} * \begin{pmatrix}\text{rate of water}\\ \text{ingestion}\end{pmatrix}$$

$$Ci/y = (Ci/\ell) * (603\ell/y)$$

2.1.3.2 Fish

$$\begin{pmatrix}\text{amt of nuclide}\\ \text{intake per year}\end{pmatrix} = \begin{pmatrix}\text{nuclide conc in}\\ \text{surface water}\end{pmatrix} * \begin{pmatrix}\text{conc}\\ \text{ratio}\end{pmatrix} * \begin{pmatrix}\text{rate of fish}\\ \text{ingestion}\end{pmatrix}$$

$$Ci/y = (Ci/\ell) * (\ell/kg) * (1.0\ kg/y)$$

where

$$\text{conc ratio} = \frac{\text{conc of nuclide in fish}}{\text{conc of nuclide in water}}$$

2.1.3.3 Crops

$$\begin{pmatrix}\text{amt of nuclide}\\ \text{intake per year}\end{pmatrix} = \begin{pmatrix}\text{nuclide conc}\\ \text{in crops}\end{pmatrix} * \begin{pmatrix}\text{rate of crop}\\ \text{ingestion}\end{pmatrix}$$

$$Ci/y = (Ci/kg) * (194\ kg/y)$$

$$\begin{pmatrix}\text{nuclide conc}\\ \text{in crops}\end{pmatrix} = \begin{pmatrix}\text{nuclide conc}\\ \text{in soil}\end{pmatrix} * \begin{pmatrix}\text{conc}\\ \text{ratio}\end{pmatrix} + \begin{pmatrix}\text{conc due to}\\ \text{sprinkler irrigation}\end{pmatrix}$$

$$Ci/kg = (Ci/kg) * (\text{dimensionless}) + (Ci/kg)$$

where

$$\text{conc ratio} = \frac{\text{conc of nuclide in crops}}{\text{conc of nuclide in soil}}$$

$$\begin{pmatrix}\text{nuclide conc due to}\\ \text{sprinkler irrigation}\end{pmatrix} = \frac{1}{\text{rate constant for weathering}}\left(\frac{\begin{pmatrix}\text{retention}\\ \text{fraction}\end{pmatrix} * \begin{pmatrix}\text{nuclide conc in}\\ \text{surface water}\end{pmatrix} * \begin{pmatrix}\text{irrigation}\\ \text{rate}\end{pmatrix}}{\text{standing crop}}\right)\left(1-e^{-\lambda_\omega t}\right)$$

$$Ci/kg = \left(\frac{1}{18.05\ y^{-1}}\right)\left(\frac{0.25 * (Ci/\ell) * 300\ \ell/m^2/y}{0.716\ kg/m^2}\right)\left(0.9535\right)$$

2.1.3.4 Milk

$$\begin{pmatrix}\text{amt of nuclide}\\ \text{intake per year}\end{pmatrix} = \begin{pmatrix}\text{nuclide conc}\\ \text{in milk}\end{pmatrix} * \begin{pmatrix}\text{rate of milk}\\ \text{ingestion}\end{pmatrix}$$

$$Ci/y = (Ci/\ell) * (112\ell/y)$$

$$\text{nuclide conc in milk} = \left(\text{nuclide conc in dairy feed}\right) * \left(\text{conc ratio}\right) * \left(\text{consumption rate of contaminated feed}\right)$$

$$Ci/\ell = (Ci/kg) * \left(\frac{day \cdot kg}{kg \cdot \ell}\right) * \left(50\ \frac{kg}{day}\right)$$

where

$$\text{conc ratio} = \frac{\text{conc of nuclide in milk}}{\text{intake of nuclide per day}}$$

$$\text{nuclide conc in } \underline{\text{dairy}} \text{ and } \underline{\text{beef}} \text{ feed} = \left(\text{nuclide conc in soil}\right) * \left(\text{conc ratio}\right) + \left(\text{nuclide conc due to sprinkling pasture}\right)$$

$$\frac{Ci}{kg} = (Ci/kg) * (\text{dimensionless}) + (Ci/kg)$$

where

$$\text{conc ratio} = \frac{\text{conc of nuclide in pasture}}{\text{conc of nuclide in soil}}$$

$$\text{nuclide conc due to sprinkling pasture} = \frac{1}{\text{rate constant for weathering}}\left(\frac{\text{retention fraction} * \text{nuclide conc in surface water} * \text{irrigation rate}}{\text{standing crop}}\right)\left(1-e^{-\lambda_\omega t}\right)$$

$$Ci/kg = \left(\frac{1}{18.05\ y^{-1}}\right)\left(\frac{0.25 * (Ci/\ell) * 300\ \ell/m^2/y}{0.28\ kg/m^2}\right)(0.9535)$$

2.1.3.5 Beef

$$\text{amt of nuclide intake per year} = \left(\text{nuclide conc in beef}\right) * \left(\text{rate of beef ingestion}\right)$$

$$Ci/y = (Ci/kg) * (85\ kg/y)$$

$$\text{nuclide conc in beef} = \left(\text{nuclide conc in beef feed}\right) * \left(\text{conc ratio}\right) * \left(\text{consumption rate of contaminated feed}\right)$$

$$Ci/kg = \left(\frac{Ci}{kg}\right) * \left(\frac{day \cdot kg}{kg \cdot kg}\right) * (50\ kg/day)$$

where

$$\text{conc ratio} = \frac{\text{conc of nuclide in beef}}{\text{intake of nuclide per day}}$$

nuclide conc in beef feed = calculated the same as dairy feed (See 2.1.3.4)

2.2 Inhalation

The inhalation pathway considers inhaled radionuclides that are resuspended from the soil. The EPA obtained suspended radionuclide concentrations through multiplication of surface radionuclides concentration (expressed in Ci/m^2) by a resuspension factor of $10^{-9}m^{-1}$ (Smith, et al., 1982). In contrast, in this analysis the suspended radionuclide concentration was obtained by multiplying the soil concentration (Ci/kg) by an assumed concentration of suspended material in air of 3.5E-9 kg/m^3. The latter concentration of suspended material was taken from the listing of various soil types in the CRC Handbook of Environmental Control, Volume 1 (Bond and Straud, 1973).

2.2.1 Dose Factors and Health Effects Estimates

The dose conversion factors (rem/Ci) for the inhalation pathway were taken from Table 2.4 and were multiplied by the appropriate health effects estimates for the organs considered. INHAL1 dose factors are for insoluble (Y class) material retained in the lung for long biological half-times, while INHAL2 dose factors are for more soluble (W class) inhaled material and result in more dose to the other body organs. For this comparative calculation, the INHAL2 dose commitment factors were multiplied by the health effects estimators and summed over all organs for each radionuclide considered.

2.2.2 Population at Risk

The population at risk for the inhalation pathway was calculated by multiplying the population density (6.7E-5 persons/m^2) provided by EPA and the area considered in the reference site analysis (160 km^2). The area dependent population of 1.1E4 persons was used for these calculations.

2.2.3 Quantity Intake of Radionuclides

$$\text{amt of nuclide intake per year} = \begin{pmatrix}\text{nuclide conc}\\ \text{in soil}\end{pmatrix} * \begin{pmatrix}\text{conc of}\\ \text{suspended}\\ \text{material}\\ \text{in air}\end{pmatrix} * \begin{pmatrix}\text{average}\\ \text{breathing}\\ \text{rate}\end{pmatrix}$$

$$Ci/y = (Ci/kg) * (3.5E\text{-}9\ kg/m^3) * (8400 m^3/y).$$

2.3 External Exposure

EPA considered external exposure from contaminated soil and air in their analysis. The soil concentrations calculated by the Pathways Model (see Table 2.3) were used to estimate the external exposure for this comparison analysis. The approach detailed in Subsection 2.2 for calculating the radionuclide concentration in the air was used to estimate the air concentrations for the air submersion exposure calculations. An assumed exposure time of 1/3 year was multiplied by the soil concentration and the air concentration to estimate the exposure level.

2.3.1 Dose Factors and Health Effects Estimates

The dose conversion factors for the air exposure pathway and for the soil exposure pathway were multiplied by the appropriate health effects estimates (Table 2.4) and were summed over all organs for each radionuclide.

2.3.2 Population at Risk

The population density of (6.7E-5 persons/m^2) provided by EPA was multiplied by the area of 160 km^2 considered in the reference site analysis. Again, the area dependent population of 1.1E4 persons was used for the calculation of air and soil exposure.

2.3.3 Exposure Level

2.3.3.1 Contaminated Soil

$$\text{Exposure Level} = \begin{pmatrix}\text{nuclide conc}\\ \text{in soil}\end{pmatrix} * \begin{pmatrix}\text{soil}\\ \text{density}\end{pmatrix} * \begin{pmatrix}\text{effective}\\ \text{depth}\end{pmatrix} * \begin{pmatrix}\text{exposure}\\ \text{time}\end{pmatrix}$$

$$\begin{pmatrix}Ci \cdot y\\ m^2\end{pmatrix} = \begin{pmatrix}Ci\\ kg\end{pmatrix} * \begin{pmatrix}2.8E3\ kg\\ m^3\end{pmatrix} * (.15m) * \begin{pmatrix}1\\ 3\end{pmatrix} y$$

2.3.3.2 Contaminated Air

$$\text{Exposure Level} = \begin{pmatrix}\text{nuclide conc}\\ \text{in soil}\end{pmatrix} * \begin{pmatrix}\text{conc of}\\ \text{suspended}\\ \text{material}\\ \text{in air}\end{pmatrix} * \begin{pmatrix}\text{exposure}\\ \text{time}\end{pmatrix}$$

$$\left(\frac{Ci \cdot y}{m^3}\right) = \left(\frac{Ci}{kg}\right) * \left(\frac{3.5E\text{-}9kg}{m^3}\right) * \left(\frac{1}{3}\ y\right)$$

3.0 Description of the SANDIA Analysis

The SANDIA health effects per curie release values were calculated using the modeling approaches and input parameters presented in the Pathways Model (Helton and Kaestner, 1981) and the Dosimetry and Health Effects Model (Runkle, et al., 1981). The two compartment system of the Pathways Model, described in Chapter 2, was used in this analysis. The input parameters (distribution coefficients (Kd) and variables to vary flow between subzones) to the Pathways Model were assumed to be the point values presented in Table 2.1. The dose conversion factors (70 year intake/70 year dose commitment), concentration ratios, environmental parameters and health effects estimates from the Risk Assessment Methodology (Cranwell, et al., 1982) were used to calculate the SANDIA health effects per curie values. The average individual risk estimates were converted to population risk by multiplying the density values assumed by EPA (in persons/m^2) and the area considered in the reference site analysis for the land-based pathways. The population estimates for drinking water and fish intake were based on a linear relationship of world population to the river flow rate of the world's rivers and the flow rate of the river considered in the reference site analysis. The equations used in the calculations for the ingestion, inhalation and external exposures are given in Table 3.1. The input parameters that were used in the calculations are given in Tables 3.2-3.8. The dose conversion factors used in the Risk Assessment Methodology consider a 70 year chronic intake and estimate a 70 year dose commitment. The 70 year dose commitment is essentially equivalent to the 50 year dose commitment (considered by EPA), however, the 70 year chronic intake must be adjusted to account for the ~143 generation that can occur in 10,000 years. Therefore, the health effects estimates were divided by a factor of 70 for estimating the health effects per curie release values.

Many of the parameters used in the SANDIA Analysis are different from those preesented in the EPA analysis and may be the source of some of the differences between the SANDIA and EPA health effects per curie values. For example, in the

Table 3.1

Basic Equations for Calculating Radionuclide Concentrations for Various Pathways

WATER BASED

(1) Drinking Water Intake (Ci/yr)=Water Consumption (370 ℓ/yr) *Water Treatment Factor (1.0) * Water Conc. (Ci/ℓ)

(2) Fish (kg/yr) = Fish Consumption (6.9 kg/yr) *Water/Fish Conc. Factor (CF)[a] *Water Conc. (Ci/ℓ)

LAND WITHOUT IRRIGATION

(3) Plant Conc. (Ci/kg) = Soil/Plant CF[a] *Soil Conc. (Ci/kg)

(4) Plant Intake (Ci/yr) = Plant Consumption (190.0 kg/yr) * Plant Conc. (Ci/kg)

(5) Milk Intake (Ci/yr) = [Dairy Cow Consumption of Plants (50 kg/day) * Plant Conc. (Ci/kg) + Dairy Cow Drinking Rate Per Day (60.0 ℓ/day) * Water Conc. (Ci/ℓ)] * Milk/Diet CF[a] * Milk Consumption Rate (110.0 ℓ/yr)

(6) Meat Intake (Ci/yr) = [Beef Cattle Consumption of Plants (50 kg/day) * Plant Conc. (Ci/kg) + Beef Cattle Drinking Rate Per Day (500 ℓ/day) * Water Conc. (Ci/ℓ)] * Beef/Diet CF[a] * Meat Consumption Rate (95.0 kg/yr)

LAND WITH IRRIGATION

(7) Deposition Rate (Ci/kg-yr)=Retained Fraction on Plant (.25) * Water Conc. (Ci/ℓ) * [Rate Irrigation (300 l/m^2-yr)/Plant Density (5.2 kg/m^2)]

(8) Rate Constant for Weathering (yr^{-1}) = ln2/.0384 yr (14 Day Half Life)

(9) Plant Conc. (Ci/kg) = [Soil/Plant CF[a] *Soil Conc. (Ci/kg)] + [(Deposition Rate (Ci/kg)/Weathering Rate (yr^{-1})] * {1 - [Exp -ln2/.0384 * Irrigation Time (.17 yr)]}

Plant, Beef, Milk Consumptions with Irrigation are Calculated Using Formulas 4-6 and the Plant Conc. (9).

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[a]See Table 3.2 These concentration factors are radionuclide dependent.

Table 3.1 (Continued)

INHALATION

(10) Air Conc. (Ci/m^3) = Soil Conc. (Ci/kg)
* Concentration of Suspended Material in the Air ($3.5E-9\ kg/m^3$)

(11) Inhalation (Ci/yr) = Air Conc. (Ci/m^3)

* Breathing Rate ($8000\ m^3/yr$)

EXTERNAL

(12) Air Submersion = (6.13E5 hrs (Lifetime Exposure))
* Air Conc. (Ci/m^3)

(13) Soil Exposure = [2.04E5 hrs (1/3 year Exposure for 70 years)

* Soil Conc. (Ci/kg) * Soil Density ($2.8E3\ kg/m^3$)

* Soil Depth (.025m)]

(14) Sediment Exposure = [1.05E3 hrs (15 hrs/yr for 70 years)

* Sediment Conc. (Ci/kg) * Sediment Density ($2.6E3 kg/m^3$)

* Sediment Depth (.025m)]

(15) Water Immersion = (1.06E3 hrs (15 hrs/yr for 70 years)

* Water Conc. (Ci/ℓ) * $1000\ ℓ/m^3$)

Table 3.2

Concentration Ratios for Human and Animal Food Sources
(Used in Reference Site Analysis)

Radionuclide	FISH/WATER (Ci/kg per Ci/ℓ)	CROP/SOIL PASTURE/SOIL (dimensionless)	MILK/FEED (day • kg/kg • ℓ)	BEEF/FEED (day • kg/kg • kg)
AM	2.5E01	2.5E-04	5.0E-06	2.0E-04
CS	2.0E03	1.0E-02	1.2E-02	4.0E-03
I	1.5E01	2.0E-02	6.0E-03	2.9E-03
NP	1.0E01	2.5E-03	5.0E-06	2.0E-04
Pu	3.5E00	2.5E-04	2.0E-06	1.4E-05
SR	3.0E01	1.7E-02	8.0E-04	6.0E-04
TC	1.5E01	2.5E-01	2.5E-02	4.0E-01
SN	3.0E03	2.5E-03	2.5E-03	8.0E-02

*Taken from USNRC (1977)

Table 3.3

Ingestion, Inhalation and External Exposure Rates
for an Average Individual
(Used in Sandia Reference Site Analysis)

Ingestion Rates	
Water Consumption by Humans	3.7 E02 ℓ/yr
Plant Consumption by Humans	1.9 E02 kg/yr
Milk Consumption by Humans	1.1 E02 ℓ/yr
Beef Consumption by Humans	9.5 E01 kg/yr
Fish Consumption by Humans	6.9 E00 kg/yr
Inhalation Rate	
Average Air Consumption by Humans	8.0 E03 m^3/yr
External Exposure Rates	
Submersion in Air	8.7 E03 hr/yr
Groundshine from Soil	2.9 E03 hr/yr*

*An effective depth of 0.025 m was assumed for soil and sediment.

Taken from USNRC (1977) and USDOE (1979)

Table 3.4

Crop and Animal Parameters
(Used in Sandia Reference Site Analysis)

Animal Consumption Rates	
Plant Consumption by Dairy Cows	5.0EO1 kg/day
Water Consumption by Dairy Cows	6.0EO1 ℓ/day
Plant Consumption by Beef Cows	5.0EO1 kg/day
Water Consumption by Beef Cows	5.0EO1 ℓ/day
Sprinkler Irrigation of Crops and Pasture	
Irrigation Rate	3.0EO2 ℓ/m^2
Retention Fraction	2.5E-01
Standing Crop (Plant Density)	5.2EOO kg/m^2
Constant Rate of Weathering (λ_ω)	1.8EO1 yr^{-1} (14 day half life)
Irrigation Time (τ)	1.7E-01 yr
$e^{-\lambda_\omega \tau}$	4.65E-02

Table 3.5

Dose Conversion Factors - Ingestion
(rem/Ci)

(70-year intake/70-year dose commitment)

	TOTAL BODY	BONE	LUNG	GI TRACT
SR90	1.01E8	4.07E8	0.0	1.53E7
TC99	3.51E3	8.76E3	1.11E3	2.89E4
SN126	1.68E5	5.88E6	0.0	1.70E6
I129	6.41E5	2.29E5	0.0	3.11E4
CS135	5.55E5	1.35E6	1.42E5	2.95E4
CS137	4.96E6	5.53E6	8.51E5	1.48E5
NP237	2.77E6	6.80E7	0.0	5.56E6
Pu239	9.51E5	3.91E7	0.0	4.66E6
Pu240	9.50E5	3.91E7	0.0	4.75E6
Pu242	9.16E5	3.63E7	0.0	4.57E6
AM241	2.75E6	4.08E7	0.0	5.19E6
AM243	2.68E6	4.07E7	0.0	6.09E6

Taken from Runkle, et al., 1981.

Table 3.6

Dose Conversion Factors - Inhalation
(rem/Ci)

(70-year intake/70-year dose commitment)

	TOTAL BODY	BONE	LUNG	GI TRACT
SR90	1.35E8	2.17E9	8.67E7	6.31E6
TC99	3.51E3	8.76E3	7.32E6	5.28E5
SN126	9.39E5	2.35E7	8.47E7	1.11E6
I129	4.80E5	1.73E5	0.0	1.55E4
CS135	4.17E5	1.01E6	5.91E6	1.48E4
CS137	3.72E6	4.15E6	3.55E7	7.35E4
NP237	6.93E9	1.66E11	3.78E9	3.44E6
Pu239	7.93E9	3.26E11	1.22E10	2.89E6
Pu240	7.91E9	3.26E11	1.22E10	2.95E6
Pu242	7.63E9	3.02E11	1.18E10	2.83E6
AM241	6.86E9	1.03E11	4.39E9	3.22E6
AM243	6.70E9	1.03E11	4.16E9	3.78E6

Taken from Runkle, et al., 1981.

Table 3.7

Dose Conversion Factors - External

	TOTAL BODY	
	SOIL (rem/hr/Ci/m^2)	AIR (rem/hr/Ci/m^3)
SR90	0.0	2.40E-1
TC99	0.0	5.80E-2
SN126	9.00E0	1.32E4
I129	4.50E-1	1.80E1
CS135	0.0	2.80E-2
CS137	4.20E0	4.70E2
NP237	1.40E0	1.45E2
Pu239	7.90E-4	5.60E-2
Pu240	1.30E-3	6.50E-2
Pu242	1.10E-3	5.10E-2
AM241	1.80E-1	1.80E-1
AM243	1.30E0	1.40E2

Taken from Runkle, et al., 1981.

Table 3.8

Cancer Risk Estimates Used in the SANDIA Analysis

Type of Cancer	Individual Risk per rem*	Organ Dose Commitment Associated With This Cancer Type
Leukemia	2.9E-05	Bone
Lung	2.5E-05	Lung
GI Tract	1.9E-05	GI Tract
Breast	2.9E-05	Total Body
Bone	9.8E-06	Bone
All Other	3.6E-05	Total Body

*Based on a lifetime plateau period for the solid tumor cancers.

Taken from Runkle et al., 1981.

ingestion calculations for land-based food sources, the contributions from crop irrigation were taken into account in the SANDIA Analysis. Also, the intake of contaminated drinking water by the animals that provide milk and beef was considered. In contrast, the EPA considered only the intake of contaminated forage by the milk and beef producing animals.

4.0 Description of SAMPLED SANDIA Analysis

This set of calculations was performed to consider some of the uncertainty that results from variability in the input parameters. However, only a few of the parameters were varied and the uncertainties in many other aspects of the modeling effort were not addressed. In this analysis, the Pathways Model utilized a set of sampled input parameters selected by the Latin Hypercube sampling technique (Iman, et al., 1980). The distribution coefficients (Kd) and variables to adjust the flow rates between various subzones were sampled and the range, description and assigned distribution of each input parameter are defined in Table 4.1. The results of the analysis represent a 3σ variation in the input data for those variables with a log-normal or normal distribution assigned to their ranges. Those variables with a uniform or log-uniform distribution assigned were sampled over the entire range. Variables 1 to 4, that adjust the flow rates, are further described in Table 4.2. Fifteen runs of the computer code were made, each with a different sampled set of input variables. The output of each computer run (in the form of radionuclide concentration in the soil and surface water) was processed by the Dosimetry and Health Effects Computer Code, and health effects (cancer deaths) per curie release were calculated. The concentration ratios, dose conversion factors and risk estimates used in this analysis are described in Chapter 3.

The population for the water based pathways was based on the linear relationship between river flow rate and population described above. To estimate the population at risk for this calculation, the flow rate of the river was varied by the sampled variable (R_1) and the population was adjusted for each of the fifteen computer runs. The population for the land based and external pathways was based on the density defined by EPA and the area of the reference site of 160 km^2. These populations, which are area dependent, were kept constant for the fifteen computer runs for land based and external pathways.

As discussed in Chapter 3, the health effects per curie release were divided by 70 to account for the ~ 143 generations that can occur in a 10,000 year period.

Two types of calculations were performed depending on whether or not adsorption was allowed to influence the solid phase (particulates) of the surface water. For the first set

Table 4.1

Latin Hypercube Sample

TITLE-LHS PATH EPA

RANDOM SEED = 5114652675042517

NUMBER OF VARIABLES = 12 SAMPLE SIZE = 15

DISTRIBUTION AND RANGE ASSUMED FOR EACH VARIABLE

Variable	Distribution Assumed	Range			
1	Uniform	.250	to	2.00	Scale Factor Rivr Dischrg
2	Log Uniform	1.000E-02	to	1.00	Scale Factor Water Xchng
3	Log Uniform	1.000E-04	to	1.000E-02	Scale Factor Solid Xchng
4	Uniform	3.00	to	15.0	Regional Erosion Rate
5	Log Normal	1.000E-02	to	2.500E+05	KD for CM(AM)
6	Log Normal	1.000E-02	to	1.000E+04	KD for Pu
7	Log Normal	1.000E-02	to	50.0	KD for NP
8	Log Normal	1.000E-02	to	1.000E+03	KD for TC
9	Log Normal	1.000E-02	to	3.000E+03	KD for SR
10	Log Normal	1.000E-02	to	1.000E+04	KD for CS
11	Log Normal	1.000E-02	to	1.000E+03	KD for I
12	Log Normal	1.000E-02	to	1.000E+03	KD for SN

Table 4.2

Variables Which Affect the Physical Description of the Surface Environment

R_1:	scale factor used to introduce variation in hydrologic properties. New values for water flow from the soil compartment to the ground-water compartment are obtained by multiplication with this factor. As the reference site was defined with an annual rainfall of 1 m, use of R_1 amounts, in a crude way, to varying the rainfall from .25 m to 2 m. This is only approximate, as the indicated rates do not move in a strictly linear manner with rainfall; however, it is felt that this provides a way of varying between wet and dry conditions. (Units: Unitless; Range: .25, 2.; Sampling Dist.: Uniform.)
R_2:	scale factor used to introduce variation in water movement between the soil compartment and the surface water compartment. New values for such movements are obtained by multiplication of the pore volume of the soil compartment by R_2. This variable is introduced to allow for variation in water movements which might result from runoff, irrigation or overbank flooding. (Units: yr^{-1}; Range: 10^{-2}, 10^{0}; Sampling Dist.: Log Uniform.)
R_3:	scale factor used to introduce variation in solid movement between the soil compartment and the surface water compartment. New values for such movements are obtained by multiplication of the mass of solids contained in a soil compartment by R_3. This variable is introduced to allow for variation in solid movements which might result from runoff, irrigation or overbank flooding. (Units: yr^{-1}; Range: 10^{-4}, 10^{-2}; Sampling Dist.: Log Uniform.)
R_4:	regional erosion rate. (Units: cm/1000 yr; Range: 3., 15.; Sampling Dist.: Uniform.)

of calculations, the radionuclides were input into the surface water with no adsorption onto the solid phase (particulates) of the water (i.e., Kd = 0 for all radionuclides in the water). However, the Kd influence in the soil compartment was considered. This technique is similar to the procedures used by EPA in their analysis and in the EPA/SANDIA and SANDIA calculations.

When flooding of a river occurs, the particulates suspended in the surface water may carry the adsorbed radionuclides onto the surrounding land mass. If adsorption of radionuclides onto solid phase of the surface water is ignored, there is a much smaller quantity of a radionuclide carried to the soil compartment by the surface water. In the second set of calculations, the radionuclides were allowed to adsorb onto the solid phase of the surface water as well as the liquid phase. The exchange to the soil compartment was influenced by the particulates suspended in the water, and the distribution coefficients (Kd) determined the partition of a radionuclide between the solid and liquid phases. The results of this analysis may simulate exchange that could occur with flooding and erosion or with irrigation and erosion.

5.0 Results and Discussion

The health effects per curie release for the individual pathways are given in Table 5.1. The EPA values were taken from the Health Effects per Curie Release Model and Subpathway Table provided to the author by the EPA. A slightly revised version of this table was published in Smith, et al., 1982. These values represent the health effects (deaths) per curie release. The EPA/SANDIA values were calculated using the procedures outlined in Chapter 2. This procedure utilized the Pathways Model and point Kd values provided by EPA to calculate the radionuclide concentrations in the soil and surface water. Other parameters (e.g., dose conversion factors, health effects estimates, etc.) from EPA were also used. The SANDIA values were calculated with Pathways Model and Dosimetry and Health Effects Model using the 70-year intake/ 70-year dose commitment factors, environmental parameters and risk estimates used in the reference site analysis. However, the same point Kd values from EPA (and used in the EPA/SANDIA calculations) were used in the analysis.

There is good agreement between the EPA and the EPA/SANDIA results for the drinking water and the fish pathways for most of the radionuclides. Marked differences are noted for the crop, milk and meat subpathways. EPA assumed that 0.5 curies were released to the soil over the 10,000-year interval and further assumed that 50% of the contaminated land was used for crop production for direct human consumption, 25% for milk

Table 5.1

Individual Pathways and Dosimetry and Health Effects Comparison Table
Expressed as Deaths Per Curie

		Drinking Water	Fish	Crop	Milk	Meat	Inhalation	External Soil	External Air
Am241	EPA	1.29E-1	3.7E-3	5.5E-1	8.2E-4	2.7E-6	2.2E-5	1.4E-5	2.9E-13
	EPA/Sandia	1.32E-1	5.45E-3	6.18E-3	2.62E-5	1.24E-7	3.03E-7	2.72E-5	4.34E-15
	Sandia	3.23E-3	1.51E-3	3.42E-5	1.84E-8	8.00E-8	2.27E-7	6.84E-7	1.02E-14
Am243	EPA	3.4E-1	1.2E-2	2.1E0	3.2E-3	1.5E-5	5.7E-5	7.3E-5	3.0E-12
	EPA/Sandia	1.06E-1	4.4E-3	5.03E-3	2.17E-5	1.03E-7	4.74E-6	7.01E-4	2.43E-13
	Sandia	3.25E-3	1.52E-3	4.62E-5	2.10E-8	9.28E-8	1.40E-6	3.08E-5	4.97E-13
Cs135	EPA	2.6E-4	1.7E-4	2.1E-3	9.9E-4	2.6E-4	2.4E-10	0	0
	EPA/Sandia	1.83E-4	1.21E-4	8.24E-6	5.11E-6	1.3E-6	3.01E-12	0.0	0.0
	Sandia	1.62E-4	6.02E-3	5.79E-6	4.33E-6	1.66E-7	1.01E-11	0.0	1.49E-17
Cs137	EPA	2.1E-3	1.3E-3	7.8E-3	2.1E-3	5.5E-4	1.9E-9	1.5E-4	8.4E-12
	EPA/Sandia	2.0E-3	1.33E-3	9.25E-5	6.42E-5	1.71E-5	1.71E-12	1.6E-5	7.53E-15
	Sandia	9.79E-4	3.65E-2	1.15E-5	1.40E-5	5.09E-7	4.42E-12	1.09E-6	1.82E-14
I129	EPA	1.6E-3	4.0E-5	6.4E-3	2.4E-3	1.8E-4	1.5E-9	1.1E-5	1.8E-13
	EPA/Sandia	1.63E-3	4.04E-5	7.32E-5	8.02E-5	6.03E-6	1.64E-14	1.48E-8	2.05E-18
	Sandia	8.95E-5	2.50E-5	8.89E-7	5.95E-7	3.12E-8	1.63E-15	1.45E-9	8.70E-18
Np237	EPA	1.3E-1	2.2E-3	4.6E-1	9.2E-5	3.9E-4	2.2E-5	1.0E-4	4.7E-12
	EPA/Sandia	1.3E-1	2.15E-3	5.84E-3	3.23E-6	1.38E-5	1.87E-8	3.76E-8	2.03E-8
	Sandia	5.08E-3	9.48E-4	5.28E-5	2.86E-8	1.25E-7	2.47E-8	3.77E-7	5.85E-15
Pu239	EPA	4.3E-3	2.5E-3	2.5E-2	5.4E-8	2.1E-9	3.1E-2	1.9E-7	1.0E-15
	EPA/Sandia	4.31E-3	2.5E-3	1.97E-4	1.19E-9	4.52E-11	2.37E-6	2.47E-6	1.09E-16
	Sandia	2.90E-3	1.89E-4	4.50E-5	7.83E-9	6.07E-9	5.42E-6	2.43E-8	2.58E-16
Pu240	EPA	4.3E-3	2.5E-3	2.4E-2	5.2E-8	2.0E-9	2.2E-5	3.8E-7	2.0E-15
	EPA/Sandia	3.31E-3	1.92E-3	1.55E-4	9.67E-10	3.70E-11	1.71E-6	3.48E-6	1.48E-16
	Sandia	2.90E-3	1.89E-4	4.03E-5	7.42E-9	5.73E-9	3.89E-6	2.87E-8	2.15E-16
Pu242	EPA	4.1E-3	2.4E-3	2.4E-2	4.4E-8	4.3E-8	2.1E-5	3.5E-7	1.8E-15
	EPA/Sandia	4.10E-3	2.38E-3	1.85E-4	9.22E-10	8.92E-10	2.58E-6	5.17E-6	2.16E-16
	Sandia	2.70E-3	1.76E-4	4.41E-5	7.48E-9	5.81E-9	5.76E-6	3.87E-8	2.69E-16
Sr90	EPA	8.0E-3	6.0E-5	1.0E-1	7.8E-3	1.0E-4	2.6E-8	0	0
	EPA/Sandia	7.99E-3	6.63E-5	4.78E-4	1.46E-4	1.95E-6	1.42E-11	0.0	0.0
	Sandia	3.94E-2	2.20E-2	4.65E-4	3.74E-5	3.07E-6	1.92E-10	0.0	5.53E-18
Tc99	EPA	2.4E-5	6.0E-7	1.9E-4	6.3E-5	5.8E-6	6.2E-10	0	0
	EPA/Sandia	2.39E-5	5.95E-7	1.08E-6	1.18E-6	1.10E-7	6.96E-15	0.0	0.0
	Sandia	2.02E-6	5.64E-7	2.11E-8	5.70E-8	9.93E-8	8.30E-15	0.0	2.80E-20
Sn126	EPA	1.4E-3	7.0E-3	6.7E-3	2.9E-4	2.1E-3	1.7E-8	4.6E-4	2.6E-11
	EPA/Sandia	1.38E-3	6.83E-3	6.19E-5	8.22E-6	5.82E-5	2.62E-10	8.54E-4	3.91E-13
	Sandia	4.72E-4	2.64E-2	8.49E-6	1.72E-6	6.14E-6	1.82E-10	3.98E-5	8.74E-12

production and 25% for beef production. The soil concentrations calculated by the Pathways Model used an asymptotic solution, dependent upon the flow rates between the soil and surface water subzones, and were based on a different input rate than the EPA analysis. The calculations performed by the Pathways Model resulted in an input of 2.3E-3 Ci to the soil over the 10,000 year period. Another contributor to the difference between the EPA and EPA/ SANDIA values is the different rate of input to the plants via sprinkler irrigation. For the calculations presented in this report, the input to plants by irrigation was 2.5E-7 Ci/yr, while EPA assumed a value of 5.0E-5 Ci/yr. This difference of greater than two orders of magnitude in the input rate is reflected in the results.

Generally, the SANDIA health effects per curie values are smaller than the EPA values for most of the paths and this difference appears to be due to differences in the input rates, concentration factors, dose conversion factors and exposure times used in the calculations. Again, the land based pathways are affected by differences in the input rates.

When the health effects per curie values from EPA and SANDIA are summed over subpathways 1-5 (includes drinking water, fish, crop, milk and meat) and 6-8 (includes inhalation, external soil and external air) the SANDIA values are lower in all cases (Table 5.2). Some values differ by factors of greater than 10^2; however, pathways 1-5 do not show as much variation as pathways 6-8. The risk of adverse health effects from pathways 6-8 is lower than the risk from pathways 1-5; therefore, the difference noted in pathways 6-8 is less significant. We have not attempted to account for all the differences; but the input rates, dose factors and concentration ratios used in the two analyses appear to account for the major differences.

The results of the SANDIA SAMPLED calculations (described in Chapter 4) are presented graphically in Figures 5.1 to 5.4. The Kd ranges and the R_1 to R_4 variables were sampled using the Latin Hypercube Sampling technique for this analysis. The populations for the various subpathways, defined in Sections 2.1.2; 2.2.2; and 2.3.2, were used in this analysis. The population for the drinking water and fish intakes were adjusted by the sampled variable, R1, to account for changes in the river flow. The population for land based pathways was held constant for all 15 calculations.

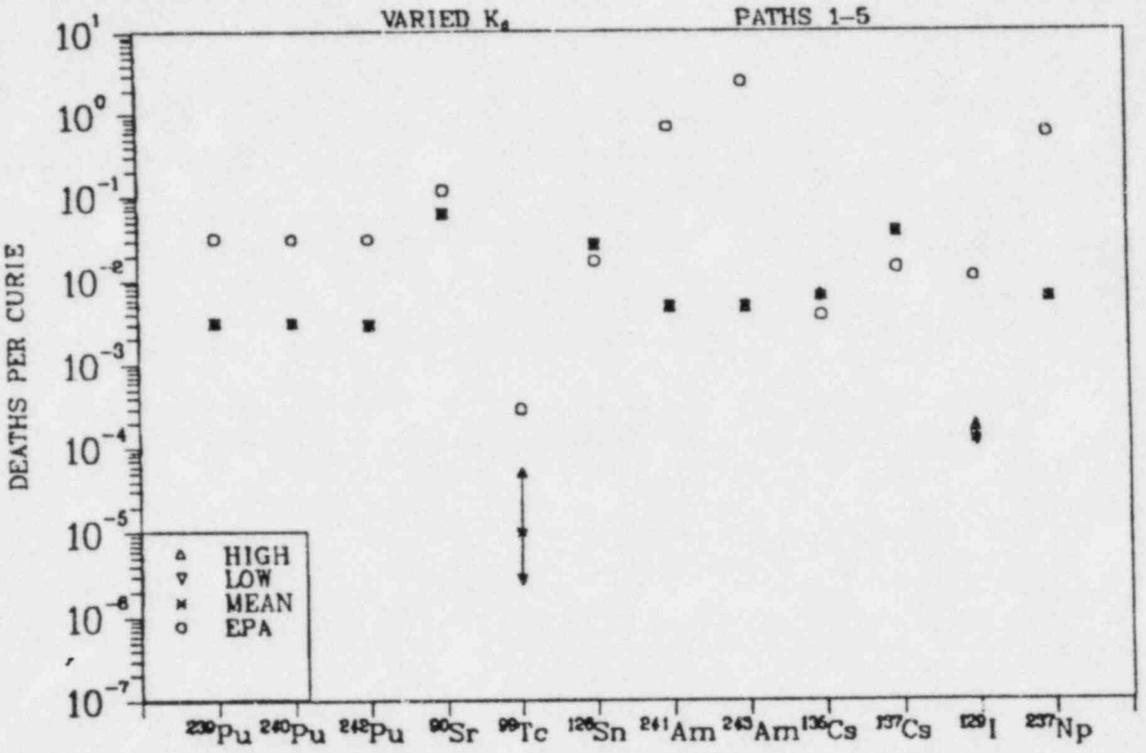
In Figures 5.1 and 5.2 the results are given for the case when there was no adsorption of the radionuclide onto the solid phase of the surface water. The subpathways 1 to 5 (Figure 5.1) and 6 to 8 (Figure 5.2) were summed and the mean, maximum and minimum values of the fifteen computer runs are presented

Table 5.2

Pathway and Dosimetry and Health Effects
Comparison Table

Health Effects Per Curie

Radionuclide		EPA Pathways 1-5	EPA Pathways 6-8
Am241	EPA	7.0E-1	2.0E-2
	Sandia	4.8E-3	9.1E-7
Am243	EPA	2.5E00	2.0E-1
	Sandia	4.8E-3	3.2E-5
Cs135	EPA	3.8E-3	1.1E-7
	Sandia	6.2E-3	1.0E-11
Cs137	EPA	1.4E-2	6.0E-3
	Sandia	3.8E-2	1.1E-6
I129	EPA	1.1E-2	9.2E-5
	Sandia	1.2E-4	1.5E-9
Np237	EPA	5.9E-1	2.5E-3
	Sandia	6.1E-3	4.0E-7
Pu239	EPA	3.2E-2	3.7E-2
	Sandia	3.1E-3	5.4E-6
Pu240	EPA	3.1E-2	3.5E-2
	Sandia	3.1E-3	3.9E-6
Pu242	EPA	3.1E-2	3.7E-2
	Sandia	2.9E-3	5.8E-6
Sr90	EPA	1.2E-1	7.9E-7
	Sandia	6.2E-2	1.9E-10
Tc99	EPA	2.9E-4	4.9E-10
	Sandia	2.8E-6	8.3E-15
Sn126	EPA	1.7E-2	1.0E-1
	Sandia	2.7E-2	4.0E-5

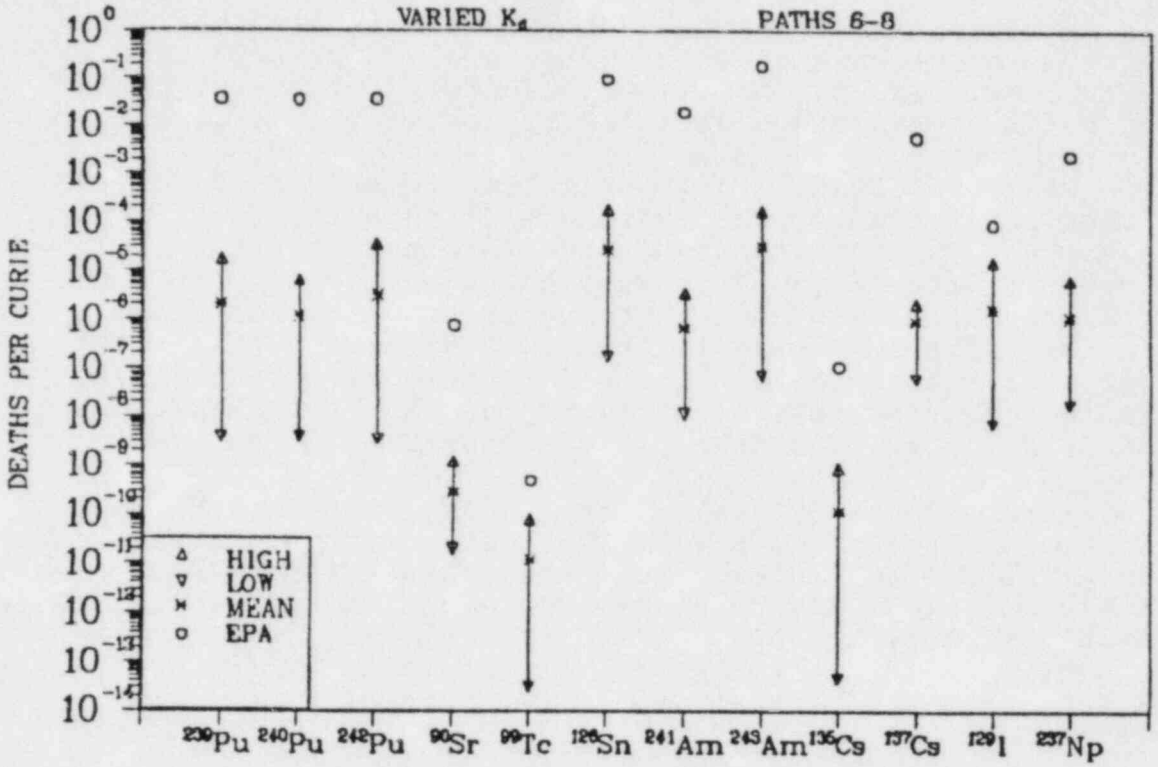


(1) VARIED K_d RANGES (LATIN HYPERCUBE SAMPLE)

(2) INPUT OF RADIONUCLIDE TO LIQUID PHASE OF SURFACE WATER

Figure 5.1.

Deaths per curie calculated with sampled Kd ranges and no adsorption onto solid phase of the surface water for Pathways 1-5.



(1) VARIED K_d RANGES (LATIN HYPERCUBE SAMPLE)

(2) INPUT OF RADIONUCLIDE TO LIQUID PHASE OF SURFACE WATER.

Figure 5.2.

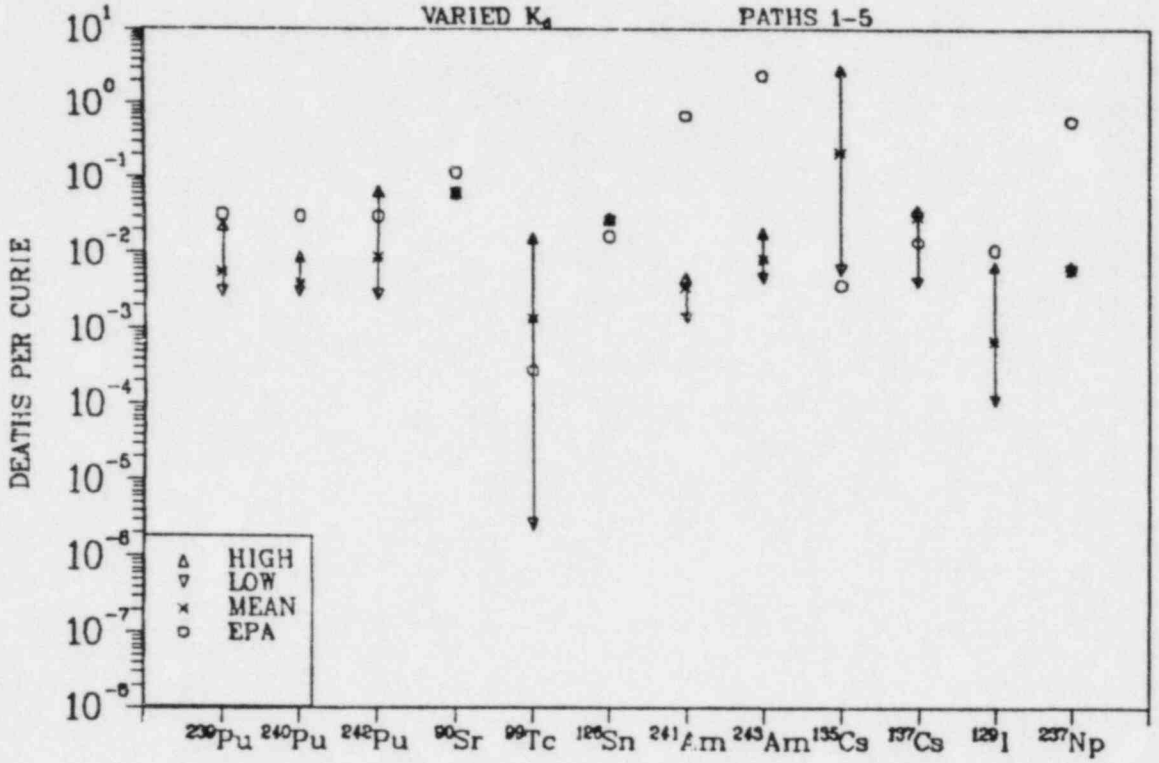
Deaths per curie calculated with sampled Kd ranges and no adsorption onto solid phase of the surface water for Pathways 6-8.

along with the point values from EPA. In general, the EPA values for pathways 1-5 are higher than the results calculated with the sampled values. The exceptions are ^{126}Sn, ^{135}Cs and ^{137}Cs. The sum of pathways 1-5 is dominated by the water based pathways and, since the populations are adjusted by the sampled variable R1, the results are clustered. If a constant population were assumed for the calculation and the flow rate were varied, the results would vary in an approximately linear fashion. That is, a one order of magnitude variation in the flow rate would result in a one order variation in the response. In pathways 6-8, there is more variability than in Paths 1-5; however the EPA values are always higher than the deaths per curie values calculated by the sampled values.

In Figures 5.3 and 5.4 the results are presented for the case when adsorption of the radionuclide onto the solid phase was assumed. The partitioning was determined by the distribution coefficients (Kd). This approach significantly affects the soil concentration and the resulting risk to the human population. For the analysis that considers adsorption, the EPA values for both the 1-5 and 6-8 pathways are generally within the range or only slightly higher than the results using the sampled ranges, for most radionuclides.

Of note are the EPA values for ^{241}Am, ^{243}Am and ^{237}Np for pathways 1-5 (Figure 5.3). The results of this analysis for ^{241}Am and ^{243}Am indicate that the release limits for these radionuclides may be overly conservative and may warrant a reexamination by the EPA. Also, the EPA release limit for ^{135}Cs would appear not to be restrictive enough from the results of this analysis and again may warrant some reconsideration.

Although these results certainly do not establish that the EPA release limits proposed in the Standard are overly conservative, <u>generally</u> they do suggest that the allowed release limits might be higher if the health effects per curie calculated in this analysis were used.

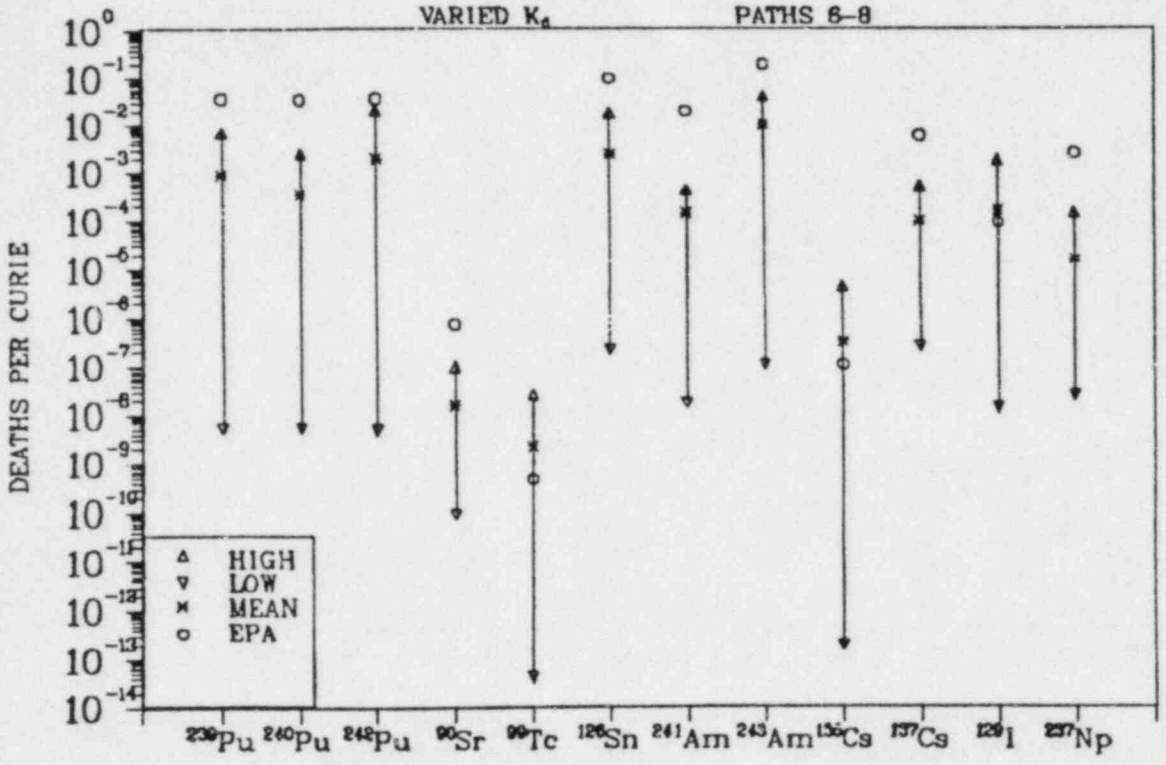


(1) VARIED K_d RANGES (LATIN HYPERCUBE SAMPLE)

(2) INPUT OF RADIONUCLIDE TO LIQUID AND SOLID PHASE OF SURFACE WATER

Figure 5.3.

Deaths per curie calculated with sampled Kd ranges and adsorption onto solid phase of the surface water for Pathways 1-5.



(1) VARIED K_d RANGES (LATIN HYPERCUBE SAMPLE)

(2) INPUT OF RADIONUCLIDE TO LIQUID AND SOLID PHASE OF SURFACE WATER

Figure 5.4.

Deaths per curie calculated with sampled Kd ranges and adsorption onto solid phase of the surface water for Pathways 6-8.

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Simple models are presented for the estimation of individual and population health effects for long-term radionuclide releases to the surface environment. In volume 5, models based on the use of asymptotic solutions to mixed cell models in conjunction with appropriate usage rates, dose factors, risk factors, and population estimates are demonstrated. These simple models may be useful in evaluating topics such as the potential importance of individual radionuclides, different release patterns or exposure pathways, and the relationship between individual and population exposures. Illustrative model calculations are compared with the calculated population exposures on which the Draft (#19) EPA Standard 40CFR191 is based. In Volume 6, simple models are employed to provide insights into the degree of conservatism in the health effects per curie value presented by the draft standard. No attempt is made to encompass all uncertainty in the input parameters use in the calculations, and some of the modeling assumptions used in this analysis are different from those of the EPA. Three sets of calculations of health effects (cancer deaths) per curie release are presented and discussed in terms of their potential implications upon the curie release limits of the EPA draft standard.

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