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Methodology for Calculation of Radiation Doses in the Environs from Nuclear Fuel Cycle Facilities

J. K. Soldat

August 1976

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Battelle

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IN THE ENVIRONS FROM NUCLEAR FUEL CYCLE FACILITIES

J. K. Soldat

August 1976

BATTELLE
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METHODOLOGY FOR CALCULATION OF RADIATION DOSES IN THE ENVIRONS FROM NUCLEAR FUEL CYCLE FACILITIES^(a)

by
J. K. Soldat

INTRODUCTION

Comparison of the impacts of various fuel cycle alternatives includes the evaluation of the radiological impacts. Methodology for such evaluation is discussed in this report.

To evaluate the radiological impacts of fuel cycle alternatives, exposure to man must first be identified. The pathways of consequence by which man can be exposed to radiation from a nuclear facility are illustrated in Figure 1. The exposure pathways can be grouped into those associated with gaseous effluents, those associated with liquid effluents, and those involving exposure to direct radiation from the facility or from transportation of radioactive materials to or from the facility. These exposure pathways are arranged by group in Table 1. Calculations for each pathway are then

TABLE 1. Pathways of Exposure to Man

Water Pathways

External

Water immersion and water surface
Exposure to shoreline

Internal

Ingestion of water
Ingestion of aquatic foods
Ingestion of irrigated food crops
Ingestion of products from animals fed irrigated foods

Air Pathways

External

Air submersion
Exposure to deposited materials

Internal

Inhalation
Transpiration of tritium oxide
Ingestion of food crops
Ingestion of animal products

Direct Radiation Pathways

External

Direct radiation from the facility
Exposure during transport of fuels and solid wastes

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made for those selected organs which could potentially receive the highest radiation dose. Some of the programs developed at Pacific Northwest Laboratories (PNL) for calculating radiation doses from radionuclides in the environment are described in Table 2.

FIGURE 1. Exposure Pathways to Man

TABLE 2. Programs for Calculating Radiation Doses

Program	Item Calculated	Organ Doses Calculated	Reference
ARRRG	Individual and population doses from ingested water	Annual dose to total body, GI-LLI, ^(a) thyroid, bone, liver, kidney	BNWL-1754(1)
	Individual and population doses from aquatic foods (fish, crustacea, molluscs, plants)	Annual dose to total body, GI-LLI, thyroid, bone, liver, kidney	
	Individual and population doses from sediment exposure (shoreline)	Annual dose to skin, total body ^(b)	
	Individual and population doses from swimming and boating	Annual dose to skin, total body ^(b)	
FOOD	Concentrations in produce, milk, eggs, meat from aerial deposition or irrigation at specified location	---	BNWL-SA-5523(2)
	Individual doses from ingestion of farm products ^(c)	Annual dose to total body, GI-LLI, thyroid, bone, liver, lung, kidney	
VITTLIS ^(d)	Concentrations on soil from aerial deposition or irrigation at specified locations	---	---
	Individual doses from exposure to soil ^(c)	Annual dose and dose commitment to skin, total body ^(b)	
	Concentrations in produce, milk, eggs, meat from aerial deposition or irrigation at specified location	---	
	Individual doses from ingestion of farm products ^(c)	Annual dose to total body, GI-LLI, thyroid, bone, liver, lung, kidney	
GRONK	Annual average atmospheric dilution factors (Ci/m^3 per Ci/sec released) versus distance and direction from the source ($\bar{x}/Q'$)	---	BNWL-1754(1)
	Individual doses from exposure to half-infinite cloud of effluents, versus distance and direction from the source	Annual dose to skin, total body	
	Integrated man-rem doses to total population within 50 miles	Annual dose to total body	
	Doses to child and adult from inhalation, and consumption of milk and leafy vegetables	Annual dose to thyroid	
GAUCHE	Individual doses from air submersion at a specified location	Annual dose and dose commitment to skin and total body	---
	Individual doses from inhalation and tritium transpiration at a specified location ^(c)	Annual dose and dose commitment to total body, GI-LLI, thyroid, bone, liver, kidney	
	Doses to child and adult from inhalation, and consumption of milk and leafy vegetables, at any specified $\bar{x}/Q'$	Annual dose to thyroid	

(a) GI-LLI means gastrointestinal tract-lower large intestine.

(b) For these pathways, the calculated total-body dose is also listed under organs other than skin on the printout and is added into the total dose to these organs.

(c) Population doses can be calculated by using population weighted average input data.

(d) VITTLIS also calculates the same internal doses as does FOOD, plus dose commitments.

DOSE TO MAN -- BASIC CONSIDERATIONS

The fundamental equation for calculation of radiation dose from the pathways described is

$$R_{ipr} = C_{ip} U_p D_{ipr} \quad (1)$$

where R_{ipr} = dose rate to organ r from nuclide i via pathway p,
 C_{ip} = concentration of nuclide i in the medium of pathway p,
 U_p = usage: the exposure or intake rate associated with pathway p,
 D_{ipr} = dose factor: a number specific to a given nuclide i, pathway p, and organ r which can be used to calculate radiation dose rate from exposure to a given radionuclide concentration or radionuclide intake.

Equations tailored to each specific exposure pathway are derived from Equation (1). The principal difference between pathways is the manner in which the radionuclide concentrations are calculated. The three terms on the right of Equation (1) are discussed in the following subsections.

Concentrations of Nuclides in Environmental Media, C_{ip}

Concentrations of nuclides in air, water, soil or food are calculated as intermediate steps in the computer programs. Concentrations in water, in aquatic foods, and on shoreline sediment are calculated from the radionuclide release rates, the effluent flow rate, the mixing and dilution in the receiving waters, and bioaccumulation factors for aquatic foods. Concentrations in air and on vegetation from aerial deposition are generated from radionuclide release rates and from equations for atmospheric dispersion.

Concentrations of nuclides in irrigated farm produce are calculated from concentrations of radionuclides in the irrigation water, irrigation rate, facility lifetime (determines long-term soil buildup), and decay time between nuclide release and produce consumption.

Usages, U_p

Usage refers to duration of exposure to external sources of radiation and to intake rates of ingested water and food. For pathways other than air submersion, the usage depends on the specific situation. Since noble gases are the principal contributors to air submersion dose, the assumption is made that the air concentrations of radionuclides are essentially the same indoors as outdoors. Thus, no shielding and occupancy factors are applied, and 8766 hr/yr is used for the air submersion pathway.

In the absence of site-specific data the generic usages and exposure times given in References 1 and 3 can be used to calculate individual adult doses. For population dose calculations the usages of the average adult are multiplied by the size of the population.

Dose Factors, D_{ipr}

Equations for calculating internal dose factors were previously published.^(4,5) They were derived originally from those given by the International Commission on Radiological Protection⁽⁶⁾ for body burden and maximum permissible concentration. For this study, effective decay energies for the radionuclides are calculated from the ICRP model, which assumes all of the radionuclide is at the center of a spherical organ with an appropriate effective radius. Where data is lacking, metabolic parameters for the Standard Man⁽⁶⁾ are used for other ages as well. Internal dose factors have units of mrem/yr per pCi/yr intake via ingestion or inhalation, and represent the first year's dose from one year chronic intake.

Internal dose commitment factors have units of mrem over 50 yr per pCi taken in during the first year and include the dose during the year of intake. (Periods other than 50 years can be used for the dose commitment calculations.)

For calculating external dose factors from air submersion or water immersion, the penetrating power of the radiation emitted determines

whether it contributes to skin dose only, or to both skin and total-body dose. Beta and gamma radiation which can penetrate 7×10^{-3} cm of tissue is considered to contribute to skin dose; that which can penetrate 5 cm of tissue is considered to contribute to total-body dose (and dose to internal organs). The dose factors for air submersion and water immersion are derived by assuming that the contaminated medium is an infinite volume compared to the range of the emitted radiations. Under this assumption the energy emitted per gram of medium equals the energy absorbed per gram of medium. Corrections must be applied for differences in energy absorption between tissue and air or water, physical geometry of the specific exposure situation and the conversion from MeV per disintegration per gram to rem. The resulting dose factors have units of mrem/hr per pCi/m³ of air or mrem/hr per pCi/l of water. There is no further external dose commitment from air or water after the year of exposure.

Material deposited from the air or from irrigation water onto the ground represents a fairly large, nearly uniform, thin sheet of contamination. The factors for converting surface contamination in pCi/m² to gamma dose at 1 m above a uniformly contaminated plane are described in References 1, 4 and 5. Dose factors for exposure to soil (or river sediment) have units of mrem/hr per pCi/m² of surface. A dose commitment could be calculated for soil exposure by accounting for the contamination remaining on the surface after the year of deposition is over. This capability exists in the VITTLS program. Dose factors have been generated for nearly 200 radionuclides (Table 3) and are periodically recalculated using the latest available decay schemes. Also, first-year dose and 50-year dose commitment factors have been calculated for adults for a single (acute) intake of the radionuclides via ingestion and inhalation. However, these have not been entered into the routine dose calculation programs.

The standard format proposed by the U.S. Nuclear Regulatory Commission is a 50-year internal dose commitment from a 1-year chronic intake, plus a 1-year external dose from air submersion, swimming, contaminated soil, etc.

TABLE 3. Nuclides for Which Dose Factors
Are Currently Available

^3H	^{84}Br	^{101}Tc	^{132}I	^{147}Pm	$^{232\&d}\text{Th}$
^{10}Be	^{85}Br	$^{103\&d}\text{Ru}$	^{133}I	$^{148\text{m}\&d}\text{Pm}$	$^{234\&d}\text{Th}$
^{14}C	$^{83\text{m}}\text{Kr}$	$^{105\&d}\text{Ru}$	^{134}I	^{148}Pm	$^{231\&d}\text{Pa}$
^{13}N	$^{85\text{m}}\text{Kr}$	$^{106\&d}\text{Ru}$	$^{135\&d}\text{I}$	^{149}Pm	^{233}Pa
^{18}F	^{85}Kr	^{105}Rh	$^{131\text{m}}\text{Xe}$	^{151}Pm	$^{232\&d}\text{U}$
^{22}Na	^{87}Kr	^{107}Pd	$^{133\text{m}}\text{Xe}$	^{151}Sm	$^{233\&d}\text{U}$
^{24}Na	^{88}Kr	^{109}Pd	^{133}Xe	^{153}Sm	^{234}U
^{32}P	^{89}Kr	$^{110\text{m}\&d}\text{Ag}$	$^{135\text{m}}\text{Xe}$	^{152}Eu	$^{235\&d}\text{U}$
^{33}P	^{86}Rb	^{111}Ag	^{135}Xe	^{154}Eu	^{236}U
^{39}Ar	^{87}Rb	$^{113\text{m}}\text{Cd}$	^{137}Xe	^{155}Eu	^{237}U
^{41}Ar	^{88}Rb	$^{115\text{m}}\text{Cd}$	^{138}Xe	^{156}Eu	$^{238\&d}\text{U}$
^{41}Ca	$^{89\&d}\text{Rb}$	^{123}Sn	$^{134\text{m}}\text{Cs}$	^{160}Tb	$^{237\&d}\text{Np}$
^{46}Sc	$^{89\&d}\text{Sr}$	$^{125\&d}\text{Sn}$	^{134}Cs	$^{166\text{m}}\text{Ho}$	^{238}Np
^{51}Cr	$^{90\&d}\text{Sr}$	$^{126\&d}\text{Sn}$	^{135}Cs	^{181}W	^{239}Np
^{54}Mn	$^{91\&d}\text{Sr}$	^{124}Sb	^{136}Cs	^{185}W	^{238}Pu
^{56}Mn	$^{92\&d}\text{Sr}$	$^{125\&d}\text{Sb}$	$^{137\&d}\text{Cs}$	^{187}W	^{239}Pu
^{55}Fe	^{90}Y	^{126}Sb	^{138}Cs	$^{210\&d}\text{Pb}$	^{240}Pu
^{59}Fe	$^{91\text{m}\&d}\text{Y}$	^{127}Sb	$^{139\&d}\text{Cs}$	$^{210\&d}\text{Bi}$	$^{241\&d}\text{Pu}$
^{57}Co	^{91}Y	$^{125\text{m}}\text{Te}$	^{139}Ba	^{210}Po	^{242}Pu
^{58}Co	^{92}Y	$^{127\text{m}\&d}\text{Te}$	$^{140\&d}\text{Ba}$	$^{222\&d}\text{Rn}$	^{244}Pu
^{60}Co	^{93}Y	^{127}Te	^{141}Ba	$^{223\&d}\text{Ra}$	^{241}Am
^{59}Ni	$^{93\&d}\text{Zr}$	$^{129\text{m}\&d}\text{Te}$	^{142}Ba	$^{224\&d}\text{Ra}$	$^{242\text{m}}\text{Am}$
^{63}Ni	$^{95\&d}\text{Zr}$	^{129}Te	^{140}La	$^{225\&d}\text{Ra}$	^{243}Am
^{65}Ni	$^{97\&d}\text{Zr}$	$^{131\text{m}\&d}\text{Te}$	^{141}La	$^{226\&d}\text{Ra}$	^{242}Cm
^{64}Cu	$^{93\text{m}}\text{Nb}$	$^{131\&d}\text{Te}$	^{142}La	$^{228\&d}\text{Ra}$	^{243}Cm
^{65}Zn	^{95}Nb	$^{132\&d}\text{Te}$	^{141}Ce	^{225}Ac	^{244}Cm
$^{69\text{m}}\text{Zn}$	^{97}Nb	$^{133\text{m}\&d}\text{Te}$	$^{143\&d}\text{Ce}$	$^{227\&d}\text{Ac}$	^{245}Cm
^{69}Zn	^{93}Mo	^{134}Te	$^{144\&d}\text{Ce}$	$^{227\&d}\text{Th}$	^{246}Cm
^{79}Se	$^{99\&d}\text{Mo}$	^{129}I	^{143}Pr	$^{228\&d}\text{Th}$	$^{247\&d}\text{Cm}$
^{82}Br	$^{99\text{m}}\text{Tc}$	^{130}I	^{144}Pr	^{229}Th	^{248}Cm
$^{83\&d}\text{Br}$	^{99}Tc	$^{131\&d}\text{I}$	^{147}Nd	$^{230\&d}\text{Th}$	^{252}Cf

This type of dose calculation is planned for the current study although the first year internal dose will be added since the existing programs generate these doses automatically.

Other more complicated dose commitments can be calculated but the time and expense may not warrant such calculations. For example, the accumulated dose could be calculated for a person living for 50 years in the vicinity of the nuclear facility, who is exposed continuously during the facility lifetime (30 to 40 years for a reactor or reprocessing plant) and is also exposed to residual contamination in soil as well as the food grown in that soil after the facility shuts down; a total exposure time of 50 years.

All of the previous discussion applies generally to the doses received by a maximally exposed individual in the vicinity of a nuclear facility or the population residing within a reasonable distance (50 miles or 80 km) of a nuclear facility. In addition to these local dose calculations, regional (U.S.) and worldwide radiation doses must also be calculated.

U.S. REGIONAL AND WORLDWIDE DOSES

A unified, versatile computer code does not exist for calculating U.S. regional and worldwide doses for the variety of radionuclides potentially released from the different parts of the nuclear fuel cycle. Therefore, gross estimates have been made for individual nuclides such as ^3H , ^{14}C , ^{85}Kr , ^{129}I and the actinides.⁽⁷⁻¹¹⁾ These have generally been very conservative (that is, have overestimated the magnitude of the doses), and as long as the results indicate the doses are insignificant such conservatism is not a serious defect. However, this has not always been the case.

Unfortunately, even though the calculation scheme for each nuclide may use a somewhat different mathematical model and assumptions, the resulting doses have been compared with each other to determine which nuclides are the major contributors and added together to determine the total potential population (man-rem) dose.

Worse, yet, the results are often converted to health effects as though the ratio between man-rem and health-effects was known and constant,

and was independent of dose rate and total dose. The NCRP is currently studying this particular issue and has strongly recommended that the conversion from population man-rem dose to health effects not be made.⁽¹²⁾

For these reasons, it is advisable not to calculate any health effects in the current project. In addition, the diversity of methodology for estimating doses from different nuclides dictates that worldwide dose calculations not be made and the U.S. doses be calculated with extreme caution, if at all.

TRANSPORTATION DOSES

For purposes of the current study accidental releases of radionuclides are not being considered. Therefore, calculation of doses from transportation of radioactive materials will be restricted to external exposure. Methods defined in WASH-1238⁽¹³⁾ can be used to calculate external doses to transportation workers and the public from truck and rail shipments of raw materials, fuel (new, irradiated or recycled) or waste (low-level or solidified high-level). Parameters needed to perform the calculations include type and number of shipments, mode of transport, distances shipped and population density along the route. The latter two items can be defined for general regions of the country without knowledge of the exact locations of origin and destination.

COMPOSITE RADIATION DOSES

Quantitative comparison of the combined radiation dose from various fuel cycle options is required for the current project. This can be accomplished if the entire set of dose calculation programs do not have to be rerun and summed for each fuel cycle alteration. To circumvent this problem, a combined total dose to a specific organ of a particular category of person per unit nuclide release to air, water, or ground from a specific type of facility can be generated. This combined dose conversion factor can then be stored in the master computer library.

For example, the doses to the bone of the maximum individual adult near the boundary of a fuels reprocessing plant from a release rate of 1 Ci/yr of ^{90}Sr to the air can be calculated for inhalation, air submersion, exposure to contaminated ground, and consumption of produce, milk, eggs and meat contaminated via aerial deposition. These doses can then be summed into a combined dose conversion factor per unit release of ^{90}Sr to the air.

A similar combined dose conversion factor incorporating all potential aquatic pathways can also be generated for a release rate of 1 Ci/yr ^{90}Sr to surface water.

Dose conversion factors for other nuclides could also be generated. To determine the overall total dose to bone of a maximum individual adult the individual release rates of the various radionuclides to air (and water) would be multiplied by the proper dose conversion factors and summed by a computer program. New release rates resulting from alterations in the fuel cycle could then be used with appropriate dose conversion factors to calculate new doses without recalculation of all the individual pathway doses.

Modifications to the programs listed in Table 2 to permit automatic summation of the doses from appropriate groups of pathways should be possible without serious difficulty. Such a scheme has already proven feasible on a limited scale for a combination of the programs ARRRG and FOOD.

APPENDIX A DETAILED DOSE EQUATIONS

DOSE TO MAN -- LIQUID PATHWAYS

A computer program ARRRG calculates radiation doses to man from liquid effluent release via the pathways of drinking water, aquatic foods, and aquatic recreation. The mathematical model is described below.

DRINKING WATER

The dose rate from ingestion of water is calculated by

$$R_{pr} = 1119 \sum_{i=1}^n \frac{Q_i N_i}{F} M_p e^{-\lambda_i t_p} U_p D_{ipr} \quad (1)$$

where

R_{pr} = dose rate to organ r from all of the nuclides i via pathway p (mrem/yr)

N_i = reconcentration factor

Q_i = release rate of nuclide i (Ci/yr)

F = flow rate of the liquid effluent (ft³/sec)

M_p = mixing ratio at the point of exposure (or the point of withdrawal of drinking water or the point of harvest of aquatic food)

t_p = transit time required for nuclides to reach the point of exposure. For internal dose, t_p is the total time elapsed between release of the nuclides and ingestion of food or water (hr).

λ_i = radiological decay constant of nuclide i (hr⁻¹)

1119 = a constant which converts from (Ci/yr)/(ft³/sec) to pCi/l

The terms $\frac{Q_i N_i}{F}$ in Equation (1) of this appendix define the concentration of nuclide i in the effluent at the point of discharge. The expression $\frac{Q_i N_i}{F} M_p \exp(-\lambda_i t_p)$ yields the concentration at the time that the water is consumed. This latter concentration is the term C_{ip} in Equation (1) of the main text, page 4.

AQUATIC FOODS

Concentrations of radionuclides in aquatic foods are directly related to the concentrations of the nuclides in water. Equilibrium ratios between the two concentrations, called bioaccumulation factors in this report, were taken from References 14 and 15 and are listed in Table A-1. The equation to calculate internal dose rate from consumption of aquatic food is

$$R_{pr} = 1119 \sum_{i=1}^n \frac{Q_i N_i}{F} M_p B_{ip} e^{-\lambda_i t_p} U_p D_{ipr} \quad (2)$$

where B_{ip} is the bioaccumulation factor for nuclide i via pathway p (pCi/kg per pCi/l).

SHORELINE DEPOSITS

The calculation of sediment load, transport and concentrations of radionuclides associated with suspended and deposited materials is a complex problem. One approach to this problem was used in the Year 2000 Study.⁽⁵⁾ For the program ARRRG, a simplified scheme for obtaining an order of magnitude estimate of the concentration of shoreline sediments was developed. The concentration of nuclide i in the sediment can be estimated from

$$S_i = K \frac{A_i (1 - e^{-\lambda_i t_s})}{\lambda_i} \quad (3)$$

where

S_i = concentration of nuclide i in sediment (pCi/kg)

A_i = concentration of the nuclide i in the water adjacent to the sediment (pCi/l)

K = assumed constant in units of l/kg-d

T_s = total time the sediment is exposed to the contaminated water, nominally taken to be the operating lifetime of the facility (hr)

TABLE A-1. Bioaccumulation Factors (pCi/kg per pCi/l)

Element	Salt Water Factors				Fresh Water Factors			
	Fish	Crus.	Moll.	Algae	Fish	Crus.	Moll.	Algae
H	1	1	1	1	0.9	0.9	0.9	0.9
Be	1,000	10,000	10,000	10,000	2	10	10	20
C	1	1	1	1	4,600	9,100	9,100	4,600
N(a)	0	0	0	0	0	0	0	0
F	4	4	4	1	10	100	100	2
Na	1	1	1	1	100	200	200	500
P	10,000	10,000	10,000	100,000	100,000	20,000	20,000	500,000
Ar	1	1	1	1	1	1	1	1
Ca	10	10	10	1	40	330	330	130
Sc	100	300	300	1,000	2	1,000	1,000	10,000
Cr	100	1,000	1,000	1,000	20	2,000	2,000	4,000
Mn	3,000	10,000	50,000	10,000	400	90,000	90,000	10,000
Fe	1,000	4,000	20,000	6,000	100	3,200	3,200	1,000
Co	100	10,000	300	100	50	200	200	200
Ni	500	100	100	100	100	100	100	50
Cu	1,000	5,000	5,000	1,000	50	400	400	2,000
Zn	5,000	5,000	50,000	1,000	2,000	10,000	10,000	20,000
Se	10	10	10	100	170	170	170	1,000
Br	3	10	10	100	420	330	330	50
Kr	1	1	1	1	1	1	1	1
Rb	30	50	10	10	2,000	1,000	1,000	1,000
Sr	1	1	1	20	30	100	100	500
Y	30	100	100	300	25	1,000	1,000	5,000
Zr	30	100	100	1,000	3	6	6	1,000
Nb	100	200	200	100	30,000	100	100	800
Mo	10	100	100	100	10	10	10	1,000
Tc	10	100	100	1,000	15	5	5	40
Ru	3	100	100	1,000	10	300	300	2,000
Rh	10	100	100	100	10	300	300	200
Pd	10	100	100	100	10	300	300	200
Ag	1,000	5,000	5,000	1,000	2	770	770	200
Cd	100	3,000	10,000	10,000	200	2,000	2,000	1,000
Sn	3	3	3	10	3,000	1,000	1,000	100
Sb	1,000	1,000	1,000	10,000	1	10	10	1,500
Te	10	10	100	1,000	400	75	75	100
I	20	100	100	10,000	15	5	5	40
Xe	1	1	1	1	1	1	1	1
Cs	30	50	10	10	2,000	100	100	500
Ba	3	3	3	100	4	200	200	500
La	30	100	100	300	25	1,000	1,000	5,000
Ce	30	100	100	300	1	1,000	1,000	4,000
Pr	100	1,000	1,000	1,000	25	1,000	1,000	5,000
Nd	100	1,000	1,000	1,000	25	1,000	1,000	5,000
Pm	100	1,000	1,000	1,000	25	1,000	1,000	5,000
Sm	100	1,000	1,000	1,000	25	1,000	1,000	5,000
Eu	100	1,000	1,000	1,000	25	1,000	1,000	5,000
Tb	100	1,000	1,000	1,000	25	1,000	1,000	5,000
Ho	100	1,000	1,000	1,000	25	1,000	1,000	5,000
W	10	10	10	100	1,200	10	10	1,200
Pb	300	1,000	1,000	5,000	100	100	100	200
Bi	15	1,000	1,000	10,000	15	10	10	1,500
Bo	300	5,000	5,000	2,000	500	20,000	20,000	2,000
Rn	1	1	1	1	57	1	1	1
Ra	50	100	100	100	50	250	250	2,500
Ac	25	1,000	1,000	5,000	25	1,000	1,000	5,000
Th	10,000	2,000	2,000	3,000	30	500	500	1,500
Pa	10	10	10	6	11	110	110	1,100
U	10	10	10	67	2	60	60	
Np	10	10	10	6	10	400	400	300
Pu	3	200	200	1,000	3	100	100	350
Am	25	1,000	1,000	5,000	25	1,000	1,000	5,000
Cm	25	1,000	1,000	5,000	25	1,000	1,000	5,000
Cf	25	1,000	1,000	5,000	25	1,000	1,000	5,000

(a) The values for nitrogen (0) were selected because N-13 has a half life of only 9.6 minutes.

In the original evaluation of the equation, λ_i was chosen to be the radiological decay constant, although the true value should include an unknown "environmental" removal constant. If the presence of a radionuclide in water and sediment is controlled primarily by radioactive equilibrium with its parent nuclide, then the water concentration and half-life of the parent should be used in the equation.

The relationship was tested and the value of K derived from radionuclide concentrations measured in water and sediment samples collected over a period of several years in the Columbia River between Richland, Washington and the river mouth and in Tillamook Bay, Oregon, 75 km (47 miles) south of the river mouth.^(16,17) Since the primary use of the equation is to facilitate estimates of the exposure rate from gamma emitters 1 m above the sediment, an effective surface contamination was devised. This surface contamination level was taken to be all of the nuclides contained within the top 2.5 cm (1 in.) of sediment.^(a) The dose contribution from the radionuclides below 2.5 cm in depth was ignored. The resulting equation is

$$S_i' = 100 T_i A_i W (1 - e^{-\lambda_i t_s}) \quad (4)$$

where

S_i' = "effective" surface contamination (pCi/m²)
 T_i = radiological half-life of nuclide i (d)
 W = shore width factor (unitless)

Shore width factors were derived from data given in Figure 3.1(5) of Reference 18 and are summarized in Table A-2.

(a) Calculated by multiplying the concentration (pCi/kg) by a mass thickness (40 kg/m²).

TABLE A-2. Shore Width Factors for Use in Equations (4) and (5)

<u>Exposure Situation</u>	<u>Shore Width Factor, W</u>
Discharge canal bank	0.1
River shoreline	0.2
Lake shore	0.3
Nominal ocean site	0.5
Tidal basin	1.0
Organisms on surface or in burrow(a)	2.0

(a) Since the radionuclide concentration normally decreases with depth in the mud, the dose to a buried organism is probably no higher than that to one lying on the mud surface.

The combination of Equations (1) and (4) yields the equation below for the radiation dose from exposure to shoreline sediments.

$$\begin{aligned}
 R_{pr} &= \sum_{i=1}^n S_i' U_p D_{ipr} = 100 \sum_{i=1}^n T_i A_i W (1-e^{-\lambda_i t_s}) U_p D_{ipr} \\
 &= 111,900 \sum_{i=1}^n T_i \frac{Q_i N_i}{F} M_p e^{-\lambda_i t_p} W (1-e^{-\lambda_i t_s}) U_p D_{ipr} \quad (5)
 \end{aligned}$$

SWIMMING AND BOATING

The equation for external dose to the skin and total-body from swimming (water immersion) or boating (water surface) is

$$R_{pr} = 1119 \sum_{i=1}^n \frac{Q_i N_i}{F K_p} M_p e^{-\lambda_i t_p} U_p D_{ipr} \quad (6)$$

where K_p is a geometry correction factor equal to 1 for swimming and 2 for boating.

DOSE TO MAN -- GASEOUS PATHWAYS

The computer program GRONK calculates radiation doses to man from radio-nuclides released with gaseous effluents.

AIR SUBMERSION

The formulas used to calculate doses from air submersion are Equations (7) and (8) below (Reference 19, p. 113).

$$R_{pr}(x, \theta, d) = \sum_{i=1}^n \bar{x}_i U_p D_{ipr} \quad (7)$$

where

$R_{pr}(x, \theta, d)$ = external dose rate from all of the nuclides i via pathway p to organ r of a person located a point x meters from the source in a direction d , averaged over a sector width of θ radians (mrem/yr)

U_p = 8766 hr/yr for air submersion

D_{ipr} = dose factor for nuclide i via pathway p to organ r based on a half-infinite cloud geometry and corrected for the fractional penetration of beta and gamma radiations to the depth of 7×10^{-3} cm for skin and 5 cm for total body (mrem/hr per pCi/m³)

and

$$\bar{x}_i = \sum_{j=1}^J \left(\frac{2}{\pi} \right)^{1/2} \frac{(0.01 f_j) 10^{12} Q_i'}{(\sigma_z)_j \bar{u}_j \theta x} \left[\exp \left(- \frac{h^2}{2(\sigma_z)_j^2} \right) \right] \left[\exp \left(- \frac{\lambda_i x}{\bar{u}_j} \right) \right] \quad (8)$$

where

$\bar{x}_i$ = annual average concentration (pCi/m³) of nuclide i at point (x, θ, d)

f_j = percent of time wind blows in direction d under meteorological condition j

10^{12} = picocuries per curie

Q_i = release rate of nuclide i (Ci/sec)

θ = sector width = $2\pi/n$ radians, where the number of sectors n is normally 16

x = downwind distance (m)

$\bar{u}_j$ = average wind speed for meteorological condition j (m/sec)

$\frac{x}{\bar{u}_j}$ = travel time of released material to point (x, θ, d) under meteorological condition j (sec)

λ_i = radiological decay constant for nuclide i (sec^{-1})

h = height of effluent release (m)

$(\sigma_z)_j$ = standard deviation of vertical dispersion under meteorological condition j (m^2)

J = number of meteorological conditions ("stability classes")

The standard deviation of vertical dispersion may be derived for the Hanford (Fuquay-Simpson) four-stability-class method from equations given on pp. 141 and 392 of Reference 19, or from tables of σ_z versus x by Pasquill stability category on p. 409 of Reference 19. Both the Hanford and the Pasquill formats are programmed into GRONK since raw meteorology data may be given in either format, depending upon the particular system employed at the nuclear facility.

Equation (7) yields the yearly external dose to a person located at point (x, θ, d) . The population dose in man-rem/yr is determined by multiplying this dose by the population located within the sector of the annulus of concern. Values of the dose at the point (x, θ, d) are assumed to apply to all individuals located in that sector

DOSES FROM INHALATION

The equation used to calculate inhalation doses is given by:

$$R_{ipr}(x, \theta, d) = \sum_{i=1}^n 3.169 \times 10^4 D_{ipr} \bar{x}_i U_p \quad (9)$$

where

$R_{ipr}(x,\theta,d)$ = internal dose rate from n nuclides i via pathway p to organ r of a person located at a point x meters from the source in a direction d , averaged over a sector width of θ radians (mrem/yr)

3.169×10^4 = dimensional conversion constant (pCi/sec per Ci/yr)

D_{ipr} = dose factor for organ r from inhalation of nuclide i (mrem/yr per pCi/yr)

U_p = breathing rate (m^3 /yr)

Equation (9) yields the yearly internal radiation dose to an individual located at point (x,θ,d) . The population dose in man-rem/yr is determined by multiplying the dose to an individual by the population located within the sector of the annulus of interest. Values of the dose at the point (x,θ,d) are assumed to apply to all individuals located in that sector. The total population dose in a region can be obtained by summing the population doses within all of the sectors of the region.

DOSE TO MAN -- FOODS

The computer program FOOD is designed to calculate radiation doses to man from ingestion of foods, such as produce, milk, eggs and meat contaminated by radionuclides. These radionuclides may be deposited on vegetation and on the ground by water used for irrigation or directly from the air. A total of 14 food categories may be selected with corresponding consumption rates, growing periods and irrigation rates or atmospheric deposition assigned by the user. At present, doses to the total body, and six internal organs from 187 radionuclides may be calculated; dose summaries are displayed at the local terminal. Additional details on percent contribution to dose by nuclide and by food type are available from an auxiliary high-speed printer. This latter output also includes estimated radionuclide concentrations in soil, plants and animal products.

The program is designed to be compatible with files of releases and dose factors which are used by the program ARRRG.

The model presented for estimating the transfer of radionuclides (except for ^3H and ^{14}C) from irrigation water or from air to plants through both leaves and soil to food products was derived by Soldat (HEDL-TME-71-168)⁽⁵⁾ for a study of the potential doses to people from a nuclear power complex in the year 2000.

DEPOSITION ON FOOD PRODUCTS

The source of the radionuclide contamination of the foods may be either deposition with water used for sprinkler irrigation or deposition of airborne radionuclides. In the absence of specific data, sprinkler irrigation is normally assumed, rather than surface irrigation, because the aerial spray produced by the sprinkler leads to foliar deposition resulting in higher radionuclide concentrations in the plants (and animals consuming them) than would irrigation via furrows or drip. These latter systems can be simulated, if desired, by setting the factor for foliar retention in the program to zero.

DEPOSITION BY IRRIGATION WATER

The deposition rate d_i from irrigation water is defined by the relation

$$d_i = C_{iw} I \text{ (water deposition)} \quad (10)$$

where

d_i = deposition rate or flux ($\text{pCi}/\text{m}^2 \cdot \text{d}$) of radionuclide i

C_{iw} = concentration of radionuclide i in water used for irrigation
(pCi/ℓ)

I = irrigation rate ($\ell/\text{m}^2 \cdot \text{d}$). Amount of water sprinkled on unit area of field in 1 day.

DEPOSITION DIRECTLY FROM AIR

The deposition rate onto the foilage from airborne radionuclides is:

$$d_i = 86,400 \bar{x}_i V_{di} \text{ (air deposition)} \quad (11)$$

where

86,400 = dimensional conversion factor (sec/d)

V_{di} = deposition "velocity" of radionuclide i (m/sec)

$\bar{x}_i$ = annual average air concentration (pCi/m^3) of radionuclide i .

CONCENTRATION IN VEGETATION

The concentration of radioactive material in vegetation resulting from deposition onto the plant foliage and uptake from the soil of prior depositions on the ground is given by:

$$C_{iv} = d_i \left[\frac{r \tau_v (1 - e^{-\lambda_{Ei} t_e})}{Y_v \lambda_{Ei}} + \frac{B_{iv} (1 - e^{-\lambda_i t_b})}{P \lambda_i} \right] e^{-\lambda_i t_h} \quad (12)$$

where

C_{iv} = concentration of radionuclide i in edible portion of plant v
(pCi/kg)

- r = fraction of deposition retained on plant (dimensionless), taken to be 0.25.
- T_v = factor for the translocation of externally deposited radionuclide to edible parts of plants (dimensionless). For simplicity it is taken to be independent of radionuclide and set to 1 for leafy vegetables and fresh forage, and 0.1 for all other produce, including grain. (Reference 5 lists values of this parameter which vary with nuclide.)
- λ_i = radiological decay constant for radionuclide i (d^{-1}).
- λ_{Ei} = effective removal constant of radionuclide i from plant (d^{-1})
 $\lambda_{Ei} = \lambda_i + \lambda_w$, where λ_w = weathering removal constant = $0.693/14$ (d^{-1}).
- t_e = time of above ground exposure of crop to contamination during growing season (d).
- Y_v = plant yield [kg(wet weight)/ m^2].
- B_{iv} = concentration factor for plant uptake of nuclide i from soil [pCi/kg(wet weight) per pCi/kg (dry soil)].
- t_b = time for buildup of radionuclide in soil (d), can be 30 or 40 years if the source of the radionuclide is an operating nuclear facility.
- P = soil "surface density" [kg(dry soil)/ m^2]. Assuming a uniform mixing of all radionuclides in a plowlayer of 15-cm depth. P has a value of $224 \text{ kg}/m^2$.⁽⁵⁾
- t_h = holdup time (d). The time between harvest and consumption of the food.

The first term inside the brackets of Equation (12) relates to the concentration derived from direct foliar deposition during the growing season whereas the second term relates to uptake from soil and reflects the deposition throughout the time from start of deposition until harvest of the plant.

For a cow grazing on fresh forage, t_e in Equation (12) is set equal to 30 days, the typical time for a cow to return to a particular portion of a grazing site.

CONCENTRATION IN ANIMAL PRODUCTS

The radionuclide concentration in an animal product such as meat, milk or eggs is dependent on the amount of contaminated feed or forage eaten by the animal and its intake of contaminated water. The following equation describes this calculation.⁽⁵⁾

$$C_{ia} = S_{ia} \left[C_{iF} Q_F + C_{iaw} Q_{aw} \right] \quad (13)$$

where

C_{ia} = concentration in animal product (pCi/l) or (pCi/kg)

S_{ia} = transfer coefficient of radionuclide i from daily intake of animal to edible portion of animal product [pCi/l (milk) per pCi/d] or [pCi/kg (animal product) per pCi/d]

C_{iF} = concentration of nuclide i in feed or forage pCi/kg) calculated from Equation (1) above

Q_F = consumption rate of contaminated feed or forage by animal (kg/d)

C_{iaw} = concentration of nuclide i in water consumed by animals (pCi/l); assumed usually to be equal to C_{iw} , and

Q_{aw} = consumption rate of contaminated water by animal (l/d).

The second set of terms in the brackets in Equation (13) is omitted if the animal does not drink contaminated water. Animal consumption rates normally assumed are given in Table A-3.

TABLE A-3. Consumption Rates⁽¹⁾ of Feed and Water by Farm Animals

	Feed or Forage ^(a) (kg/day) Q_F	Water (l/day) Q_{aw}
Milk Cow	55 (fresh forage)	60
Beef Cattle	68 (dry feed)	50
Pig	4.2 (dry feed)	10
Poultry (chickens)	0.12 (dry feed)	0.3

(a) Equivalent fresh weight used to ensure proper calculation of radionuclide intake by animal.

Values for various plant concentration factors and animal product transfer coefficients for the elements considered are given in Table A-4. Plant concentration factors were taken originally from UCRL-50163, pt. IV⁽²⁰⁾ and supplemented with radionuclide data as explained in HERMES.⁽⁵⁾ Coefficients of transfer from feed to animal products for a limited number of radionuclides were available in the literature. For those for which data were lacking comparisons were made with the behavior of chemically similar elements in man⁽⁶⁾ and animals. In some instances, identified with an asterisk in Table A-4, the value was set to 9.9×10^{-4} . The most complete listing of transfer coefficients to be found is that for milk in Reference 20. The milk transfer coefficients given in this reference were intended to be maximum or "worst case" values. The authors imply, by reference to ^{131}I , that average values would be about one-half of their listed values. As a result the milk transfer values in Table A-4 for elements lacking specific radionuclide data are one-half of those found in Reference 20.

There are some experimental data available on the transfer of several radionuclides for chicken, eggs and meat.^(21,22) Some of these literature sources were referenced in HERMES.⁽⁵⁾ Unfortunately very little data is currently available on the transfer of radionuclides to beef and pork. Uncontrolled studies have been performed on the principal constituents of fallout ^{90}Sr , ^{131}I and ^{137}Cs ⁽⁵⁾ and the EPA National Environmental Research Center at Las Vegas has an on-going study of radionuclides in cattle and milk, which hopefully, will continue to generate data usable in our model.

TRITIUM AND CARBON-14 MODEL

The concentration of tritium or ^{14}C in environmental media (soil, plants and animal products) is assumed to have the same specific activity (pCi of nuclide per kg of stable element) as the contaminating medium (air or water). The fractional content of hydrogen or carbon in a plant or animal product is then used to compute the concentration of tritium or ^{14}C in the food product under consideration. Hydrogen content in both the

TABLE A-4. Plant Concentration Factors and Animal Product Transfer Coefficients

Element	Plant/Soil (Dimensionless) B_{iv}	Lqg/Feed (day/kg)	Milk/Grass (day/l)	Beef/Feed (day/kg)	Pork/Feed (day/kg)	Poultry/Feed (day/kg)
		S_{ia}				
Bc	4.7E-04	2.0E-02	2.0E-05	8.0E-04	1.0E-02	4.0E-01
N	7.5E+00	9.9E-04*	1.1E-02	9.9E-04	9.9E-04	9.9E-04
F	2.0E-02	9.9E-04	7.0E-03	2.0E-02	9.0E-02	9.9E-04
Na	5.0E-02	2.0E-01	4.0E-02	5.0E-02	1.0E-01	1.0E-02
P	5.0E+01	1.0E+01	1.2E-02	5.0E-02	5.4E-01	1.9E-01
Ca	4.0E-02	1.0E+00	8.0E-03	3.3E-03	3.3E-03	3.3E-03
Sc	1.1E-03	9.9E-04	2.5E-06	6.0E-03	1.0E-02	4.0E-03
Cr	2.5E-04	9.9E-04	1.1E-03	9.9E-04	9.9E-04	9.9E-04
Mn	3.0E-02	1.0E-01	1.0E-04	5.0E-03	2.0E-02	1.1E-01
Fe	4.0E-04	1.0E-01	6.0E-04	2.0E-02	5.0E-03	1.0E-03
Co	9.4E-03	1.0E-01	5.0E-04	1.0E-03	5.0E-03	1.0E-03
Ni	1.9E-02	1.0E-01	3.4E-03	1.0E-03	5.0E-03	1.0E-03
Cu	1.3E-01	2.0E-01	7.0E-03	1.0E-02	1.5E-02	2.0E-03
Zn	4.0E-01	4.0E-03	6.0E-03	5.0E-02	1.4E-01	2.0E-03
Se	1.3E+00	2.1E+00	2.3E-02	1.0E+00	4.5E-01	3.7E-01
Br	7.6E-01	1.6E+00	2.5E-02	2.0E-02	9.0E-02	4.0E-03
Rb	1.3E-01	3.0E-00	1.0E-02	1.5E-01	2.0E-01	2.0E+00
Sr	2.0E-01	4.0E-01	1.5E-03	3.0E-04	7.3E-03	9.0E-04
Y	2.5E-03	5.0E-04	5.0E-06	5.0E-03	5.0E-03	5.0E-04
Zr	1.7E-04	1.2E-03	2.5E-06	5.0E-04	1.0E-03	1.0E-04
Nb	9.4E-03	1.2E-03	1.2E-03	5.0E-04	1.0E-03	1.0E-04
Mo	1.3E-01	4.0E-01	4.0E-03	1.0E-02	2.0E-02	2.0E-03
Tc	2.5E-01	9.9E-04	1.2E-02	9.9E-04	9.9E-04	9.9E-04
Ru	1.0E-02	4.0E-03	5.0E-07	1.0E-03	5.0E-03	3.0E-04
Rh	1.3E+01	4.0E-03	5.0E-03	1.0E-03	5.0E-03	3.0E-04
Pd	5.0E+00	4.0E-03	5.0E-03	1.0E-03	5.0E-03	3.0E-04
Ag	1.5E-01	9.9E-04	2.5E-02	9.9E-04	9.9E-04	9.9E-04
Cd	3.0E-01	9.9E-04	6.2E-05	1.6E-02	1.6E-02	1.6E-02
Sn	2.5E-03	9.9E-04	1.3E-03	9.9E-04	9.9E-04	9.9E-04
Sb	1.1E-02	7.0E-02	7.5E-04	3.0E-03	7.0E-03	6.0E-03
Te	1.3E+00	4.0E-01	5.0E-04	5.0E-02	1.0E-02	1.0E-02
I	2.0E-02	1.6E+00	1.0E-02	2.0E-02	9.0E-02	4.0E-03
Cs	2.0E-03	6.0E-01	5.0E-03	3.0E-02	2.6E-01	4.5E+00
Ba	5.0E-03	4.0E-01	4.0E-04	5.0E-04	1.0E-02	5.0E-04
La	2.5E-03	2.0E-03	2.5E-06	5.0E-03	5.0E-03	4.0E-03
Ce	5.0E-04	3.0E-03	1.0E-05	1.0E-03	5.0E-03	6.0E-04
Pr	2.5E-03	4.0E-03	2.5E-06	5.0E-03	5.0E-03	1.0E-03
Nd	2.4E-03	2.0E-04	2.5E-06	5.0E-03	5.0E-03	4.0E-03
Pm	2.5E-03	7.0E-03	2.5E-06	5.0E-03	5.0E-03	1.0E-04
Sm	2.5E-03	7.0E-03	2.5E-06	5.0E-03	5.0E-03	4.0E-03
Eu	2.5E-03	7.0E-03	2.5E-06	5.0E-03	5.0E-03	4.0E-03
Tb	2.6E-03	7.0E-03	2.5E-06	5.0E-03	5.0E-03	4.0E-03
Ho	2.6E-03	7.0E-03	2.5E-06	5.0E-03	5.0E-03	4.0E-03
W	1.8E-02	9.9E-04	2.5E-04	9.9E-04	9.9E-04	9.9E-04
Pb	6.8E-02	9.9E-04	1.0E-05	9.9E-04	9.9E-04	9.9E-04
Bi	1.5E-01	9.9E-04	2.5E-04	9.9E-04	9.9E-04	9.9E-04
Po	9.0E-03	9.9E-04	1.2E-04	9.9E-04	9.9E-04	9.9E-04
Ra	1.4E-03	2.0E-05	2.0E-04	9.9E-04	9.9E-04	9.9E-04
Ac	2.5E-03	2.0E-03	2.5E-06	5.0E-03	1.0E-02	4.0E-03
Th	4.2E-03	2.0E-03	2.5E-06	5.0E-03	1.0E-02	4.0E-03
Pa	2.5E-03	2.0E-03	2.5E-06	5.0E-03	1.0E-02	4.0E-03
U	2.5E-03	3.4E-01	6.0E-04	5.0E-03	6.0E-04	1.2E-03
Np	2.5E-03	2.0E-03	2.5E-06	5.0E-03	1.0E-02	4.0E-03
Pu	2.5E-04	2.0E-03	2.5E-08	5.0E-03	1.0E-02	4.0E-03
Am	2.5E-04	2.0E-03	2.5E-06	5.0E-03	1.0E-02	4.0E-03
Cm	2.5E-03	2.0E-03	2.5E-06	5.0E-03	1.0E-02	4.0E-03
Cf	2.5E-03	2.0E-03	7.5E-07	5.0E-03	1.0E-02	4.0E-03

* Where value unknown, a default value of 9.9E-04 was used.

water and the nonwater (dry) portion of the food product is used to calculate the tritium concentration. It is assumed that plants obtain all their carbon from airborne carbon dioxide and that animals obtain all their carbon through ingestion of plants.

When ^{14}C is present only in the water used for irrigation it presently is difficult to model the transfer of this nuclide to vegetation, because plants acquire most of their carbon from the air. At this time we have not yet determined the transfer of carbon from the water to the air or soil. Therefore, we have conservatively assumed that plants obtain all their carbon from the irrigation water. Such an assumption could lead to plant concentrations which are high by about an order of magnitude or more. To date no operating nuclear facilities have been identified which specify releases of ^{14}C in their liquid effluents. However, this pathway could exist from migration of ^{14}C into ground water from long-term storage of nuclear wastes.

Table A-5 lists the parameters used in the computer program for tritium and ^{14}C . These values may be altered based on site-specific data.

The concentration of tritium in vegetation is:

$$C_{lv} = (C_{lw})(9)(F_{hv})^* \quad (14)$$

where

C_{lw} = concentration of tritium in the environmental water (pCi/l)

= concentration in irrigation water (for water release)

= pCi $^3\text{H}/\text{m}^3$ air: absolute humidity (l/m^3) (for airborne release)

1/9 = fraction of the mass of water which is hydrogen

F_{hv} = fraction of hydrogen in total vegetation (see Table A-5).

The concentration of tritium in the animal product is:

$$C_{la} = \left[\frac{C_{lf} Q_F + C_{law} Q_{aw}}{F_{hf} Q_F + Q_{aw}/9} \right] F_{ha} \quad (15)$$

TABLE A-5. Calculation of Fractions of Hydrogen and Carbon in Environmental Media, Vegetation, and Animal Products

Food or Fodder	Water f_w	Carbon (dry) f_c	Hydrogen (dry) f_h	Carbon ^(a) (wet) $F_{cv} \cdot F_{ca}$	Hydrogen ^(b) (wet) $F_{hv} \cdot F_{ha}$
Fresh Fruits, Vegetables and Grass	0.80	0.45	0.062	0.090	0.10
Grain and Stored Animal Feed	0.12	0.45	0.062	0.40	0.068
Eggs	0.75	0.60	0.092	0.15	0.11
Milk	0.88	0.58	0.083	0.070	0.11
Beef	0.60	0.60	0.094	0.24	0.10
Pork	0.50	0.66	0.10	0.33	0.11
Poultry	0.70	0.67	0.087	0.20	0.10

Absolute Humidity0.008 kg/m^3

Concentration of carbon in water2.0 x 10⁻⁵ $\text{kg}/\text{L}^{(c)}$

Concentration of carbon in air1.6 x 10⁻⁴ $\text{kg}/\text{m}^3^{(d)}$

(a) F_{cv} or $F_{ca} = f_c (1 - f_w)$

(b) F_{hv} or $F_{ha} = f_w/9 + f_h (1 - f_w)$

(c) Assumes a typical bicarbonate concentration of 100 mg/L

(d) Assumes a typical atmospheric CO_2 concentration of 320 ppm_v .

where

C_{1F} = concentration of tritium in feed or forage (pCi/kg) calculated by Equation (14) above, where now $C_{1F} = C_{1V}$.

F_{hf} = fraction of hydrogen in animal feed, where now $F_{hf} = F_{hv}$ (grain)

F_{ha} = fraction of hydrogen in animal product (see Table A-5)

C_{1aw} = concentration of tritium in animal drinking water (set to 9 unless there is a release to water).

Similarly, the concentration of ^{14}C in vegetation is:

$$C_{3v} = C_{3w} F_{cv}^* \quad (16)$$

where

C_{3w} = concentration of ^{14}C in the environmental median $\div$ by carbon concentration in that medium (pCi ^{14}C /kg C)
 = pCi ^{14}C /l $\div$ carbon concentration in irrigation water (kg/l) for water release
 = pCi ^{14}C /m³ $\div$ carbon concentration in air (kg/m³) for air release
 F_{cv} = fraction of carbon in total vegetation.

The concentration of ^{14}C in the animal product is:

$$C_{3a} = \left[\frac{C_{3F} Q_F + C_{3aw} Q_{aw}}{F_{cF} Q_F + F_{cw} Q_{aw}} \right] F_{ca} \quad (17)$$

For an air release $C_{3aw} = 0$ and since F_{cw} is very small compared to F_{cF} , Equation (17) reduces to:

$$C_{3a} = C_{3F} \left(\frac{F_{ca}}{F_{cF}} \right) \quad (18)$$

DOSE CALCULATIONS FOR MAN

The dose, R_{vr} , in mrem to a person consuming vegetation is:

$$R_{vr} = \sum_{i=1}^n C_{iv} U_v D_{ir} \quad (19)$$

Similarly the dose from consuming a particular animal product is:

* The subscript 1 refers to tritium which is the first nuclide in the isotope listing; similarly the subscript 3 in Equation (17) refers to ^{14}C .

$$R_{ar} = \sum_{i=1}^n C_{ia} U_a D_{ir} \quad (20)$$

where

U_v, U_a = annual consumption of contaminated vegetable or animal products in kg

D_{ir} = a factor which converts intake in pCi of nuclide i to dose in mrem to organ r .

DOSE CALCULATIONS FOR BIOTA

Since the program output lists the radionuclide concentrations in the final product from the consumption by animals of both contaminated feed and drinking water, the internal radiation dose to animals can be estimated in a manner analogous to calculation of internal dose to man. If the assumption were made that the concentration of the radionuclides in meat were similar to the average concentration in the whole animal, then the total body dose would be similar to that in the meat. The following equations can be used to calculate the dose rate in mrad/yr to an animal containing a constant concentration of a radionuclide.

$$R_c = \sum_{i=1}^n 18.7 \epsilon_{ia} C_{ia} \quad (21)$$

where

C_{ia} = concentration of nuclide in the animal (pCi/g)

ϵ_{ia} = effective absorbed energy of nuclide i in the animal (MeV/dis)

18.7 = conversion factor calculated as follows:

$$\begin{aligned} & (1.17 \times 10^6 \text{ dis}\cdot\text{yr}^{-1}\cdot\text{pCi}^{-1}) (1.6 \times 10^{-5} \text{ g}\cdot\text{mrad}\cdot\text{MeV}^{-1}) \\ & = 18.7 \frac{\text{dis}\cdot\text{g}\cdot\text{mrad}}{\text{pCi}\cdot\text{yr}\cdot\text{MeV}} \end{aligned}$$

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