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Methodology for Estimating Ingestion Dose for Emergency Response at SRS

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Abstract

At the Savannah River Site (SRS), emergency response models estimate dose for inhalation and ground shine pathways. A methodology has been developed to incorporate ingestion doses into the emergency response models. The methodology follows a two-phase approach. The first phase estimates site-specific derived response levels (DRLs) which can be compared with predicted ground-level concentrations to determine if intervention is needed to protect the public. This phase uses accepted methods with little deviation from recommended guidance. The second phase uses site-specific data to estimate a "best estimate" dose to offsite individuals from ingestion of foodstuffs. While this method deviates from recommended guidance, it is technically defensibly and more realistic. As guidance is updated, these methods also will need to be updated.

Keywords: Emergency Response, Dose, Atmospheric Releases

1. Introduction

At the Savannah River Site (SRS), emergency response computer models are used to estimate dose following releases of radioactive materials to the environment. The current model used for atmospheric releases is PUFF-PLUME (Garrett and Murphy 1981), which uses real-time data to track either instantaneous (puff) or continuous (plume) releases. PUFF-PLUME calculates downwind air and ground concentrations and their associated doses from inhalation and ground shine pathways. Using Food and Drug Administration (FDA) guidance (USFDA 1998), recommendations are made to estimate derived response levels. These levels can be compared with PUFF-PLUME output to determine if intervention needs to include restricting dietary intake of certain foods.

Methods recommended by FDA are rough approximations of complex processes and are conservative. Also, using the derived response level methodology does not give an estimation of the total dose received as a result of all pathways. A more realistic, site-specific ingestion dose model is recommended for use with PUFF-PLUME. The Federal Radiological Monitoring and Assessment Center (FRMAC) has developed a draft manual for assessing environmental data during a radiological emergency. When this document becomes final, changes may need to be made to the methodologies contained within this report.

2. Background

In 1982 the FDA (USEPA 1982) issued recommended dose levels to protect the public called Protective Action Guides (PAGs). PAGs were defined as "projected dose commitment values to individuals in the general population that warrant protective action following a release of radioactive material." This guidance is applicable to accidents where radiation dose could be received as a result of consumption of contaminated food (USFDA 1998). The recommended PAGs are 500 mrem committed effective dose equivalent, or 5000 mrem committed dose equivalent to individual tissues and organs, whichever is more limiting.

Using the PAGs discussed above, a concentration in food can be back calculated using defined assumptions. This concentration, referred to as the derived intervention level (DIL), "corresponds to the concentration in food present throughout the relevant period of time that, in the absence of an intervention, could lead to an individual receiving a radiation dose equal to the PAG" (USFDA 1998).

3. Derived Intervention Levels

The basic formula for the DIL is

$$DIL = \frac{PAG}{f * FI * DCF} \quad (1)$$

where

DIL	derived intervention level (pCi/kg)
PAG	protective action guide (mrem)
f	fraction of food or water assumed to be contaminated (unitless)
FI	quantity of food or water consumed in an appropriate period of time (kg)

DCF	dose conversion factor—radiation dose received per unit activity ingested (mrem/pCi)

Within USFDA (1998), DILs are reported for the following radionuclide groups: Sr-90, I-131, Cs-134+Cs-137, Pu-238+Pu-239+Am-241, and Ru-103+Ru-106. Also contained within the Appendices are DILs for several other isotopes. Using the methodologies contained within USFDA (1998) DILs were estimated for all radionuclides cited in the document. DILs for additional radionuclides contained within PUFF-PLUME could not be estimated because of the lack of age-specific dose conversion factors. DILs were calculated on an individual basis and if more than one radionuclide is released, the appropriate fraction of DILs could be summed to determine if intervention is necessary.

Some differences are seen when comparing the DILs published in USFDA (1998) and those presented here, which is primarily due to rounding. Calculations contained within the USFDA (1998) document contain rounding at several intermediate steps and the calculations performed here do not. The estimated DILs are shown in Table 1. The methods to determine the DILs are shown in detail in Appendix A.

Using the DILs, derived response levels (DRLs) were calculated to represent the deposition concentration upon a given environmental media (i.e. soil)—or for the special case of tritium, the air concentration—that would lead to exceeding the DIL (USEPA 1991). When multiple radionuclides are involved, summing the ratios of the environmental concentrations of each nuclide to its respective DRL is appropriate to verify that the sum is equal to or less than unity (USEPA 1991).

Table 1. Derived Intervention Levels

Radionuclide	DIL (pCi/kg)
H-3	5.9E+06
Sr-89	3.9E+04
Sr-90	4.3E+03
Nb-95	3.3E+05
I 129	1.5E+03
I-131	4.5E+03
I-133	1.9E+05
Cs-134	2.5E+04
Cs-137	3.7E+04
Ru-103	2.0E+05
Ru-106	1.2E+04
Ce-144	1.3E+04
Np-237	1.1E+02
Np-239	8.6E+05

Pu-238	6.7E+01
Pu-239	6.0E+01
Pu-241	3.3E+03
Am-241	5.4E+01
Cm 244	4.3E+01
Cs Group	3.1E+04
Pu+Am Group	6.0E+01
Ru Group	•

• The individual concentrations of Ru-103 and Ru-106 are divided by their respective DILs and summed. The sum must be less than one. [(Ru-103 Conc/2.0E+05+Ru-106/1.2E+04)<1]

4. Derivation of Derived Response Levels

The equations for the DRLs vary based on type of food. The primary food classes referred to by the USFDA (1998) are produce, grain, dairy, eggs, meat, fish, and beverage (including water). At SRS the food classes that are expected to have the major impact on dose are milk, meat, fish, grain, produce, and beverage. Referring to Hamby (1991a), eggs and poultry ingestion are excluded because chickens within 50 miles of SRS are typically housed in covered shelters and eat feed that is not produced locally. Pork is also excluded since hogs typically do not forage and are also fed commercial feeds. Contamination of drinking water is not expected to be a major pathway, due to mixing in the streams and rivers and deposition of particulates into the sediment, however, the pathway is included as a precaution.

The methodology for derivation of DRLs for tritium is different than for all other radionuclides. All calculations of DRL take no credit for hold-up time or reduction in concentration due to preparation of food. Measures such as these could be implemented to reduce dose. DRLs are shown in Table 3 for all pathways.

4.1 Contamination of Vegetables and Grain

When radionuclides are deposited on the ground, produce is affected in two ways. One is by direct uptake through the leaves of the plant and the other is via root uptake of the contamination within the soil. The DRL for produce contaminated externally through the leaves is calculated using the following equation for all radionuclides other than tritium:

$$DRL_{veg-ext} = \frac{DIL * Y}{r} \quad (2)$$

where

$DRL_{veg-ext}$	derived response level (pCi/m^2)

DIL	derived intervention level ➔ see Table 1 (pCi/kg)
Y	vegetable productivity ➔ 2 kg/m^2 (USNRC 1977)
r	retention factor ➔ 0.2 for all radionuclides except radioiodines (1.0) (USNRC 1977)

The DRL for internal contamination of vegetables and grain is calculated using the following equation:

$$DRL_{veg-int} = \frac{DIL * P}{B} \quad (3)$$

where

P	surface soil density - 240 kg/m^2 (USNRC 1977)
B	element specific soil/plant uptake ratio (see Table 2)

Tritium oxide (HTO) is assumed to exchange readily with the moisture within the plant. The DRL for tritium, therefore, refers to the tritium in the atmosphere and not the amount deposited on the ground. The DRL for HTO in vegetation is estimated using the following equation.

$$DRL_{veg-H-3} = \frac{DIL * H * CF}{0.75 * 0.54} \quad (4)$$

DRL	derived response level (for H-3 pCi/m^3)
H	absolute humidity at the time of the accident (11 g/m^3 annual average for SRS can be used if no other available) (Hamby 1990)
CF	conversion factor 10^{-3} kg/g
0.75	fraction of plant mass that is water (USNRC 1977)
0.54	concentration ratio of plant tritium to atmospheric tritium (Hamby and Bauer 1994)

Table 2. Transfer Data for Various Media (USNRC 1977)

	Soil/Plant	Milk	Meat	Fish
	unitless	d/L	d/kg	(L/kg)
H-3	4.8E+00	1.0E-02	1.2E-02	9.0E-01
Sr-89	1.7E-02	8.0E-04	6.0E-04	3.0E+01

Sr-90	1.7E-02	8.0E-04	6.0E-04	3.0E+01
Nb-95	9.4E-03	2.5E-03	2.8E-01	3.0E+04
I 129	2.0E-02	6.0E-03	2.9E-03	1.5E+01
I-131	2.0E-02	6.0E-03	2.9E-03	1.5E+01
I-133	2.0E-02	6.0E-03	2.9E-03	1.5E+01
Cs-134	1.0E-02	1.2E-02	4.0E-03	2.0E+03
Cs-137	1.0E-02	1.2E-02	4.0E-03	2.0E+03
Ru-103	5.0E-02	1.0E-06	4.0E-01	1.0E+01
Ru-106	5.0E-02	1.0E-06	4.0E-01	1.0E+01
Ce-144	2.5E-03	1.0E-04	1.2E-03	1.0E+00
Np-237	2.5E-03	5.0E-06	1.2E-03	1.0E+01
Np-239	2.5E-03	5.0E-06	2.0E-04	1.0E+01
Pu-238	2.5E-04	2.0E-06	1.4E-05	3.5E+00
Pu-239	2.5E-04	2.0E-06	1.4E-05	3.5E+00
Pu-241	2.5E-04	2.0E-06	1.4E-05	3.5E+00
Am-241	2.5E-04	5.0E-06	2.5E-04	2.5E+01
Cm 244	2.5E-03	5.0E-06	2.5E-03	2.5E+01

4.2 Contamination of Milk and Beef

Cow's milk and beef can become contaminated when they ingest grass that has been contaminated with radionuclides. The equation for beef and milk is similar:

$$DRL_m = \frac{DIL * Y}{f_m * Q_f * r} \quad (5)$$

where

Y	agricultural productivity = 1.8 kg/m^2 (Hamby 1991a)
f_m	element specific feed transfer factor [milk (d/L), beef (d/kg) = see Table 2]
Q_r	cattle feed rate = adjusted for time on pasture [milk (52 kg/d*0.56), beef (36 kg/d*0.75)] (Hamby 1991a)
r	retention factor = 0.2 for all radionuclides except radioiodines (1.0) (USNRC 1977)

For the purpose of this calculation, the density of milk is assumed to be the same as water ($1 g/cm^3$).

For tritium, the DRL for milk and beef is estimated using the following equation:

$$DRL_{m-H-3} = \frac{DIL * H * CF}{0.75 * 0.54 * f_m * Q_f} \quad (6)$$

Where all terms have been previously defined.

4.3 Contamination of Fish

The DRL for ingestion of contaminated fish is estimated using the following equation:

$$DRL_{fish} = \frac{DIL * \rho * d}{B_f} \quad (7)$$

where

p	density of the water ($1000 kg/m^3$)
d	depth of the water for farm ponds (1 meter assumed)
B_f	concentration factor for fish- see Table 2

Contamination of fish from tritium following an atmospheric release is not expected to be an important pathway since tritium does not readily deposit on the surface of water unless it rains. Even if a rain event occurs during an accident the water would be highly diluted with uncontaminated water resulting in a low concentration. Also, the bioaccumulation factor for tritium in fish is low. Considering this, methods for estimating DRLs associated with ingestion of fish contaminated with tritium are not presented.

4.4 Contamination of Water/Beverages

The DRL for the contamination of water is calculated using the following equation:

$$DRL_{water} = DIL * \rho * d \quad (8)$$

All terms have been defined above. This equation is conservative in that it assumes that whatever deposits on the surface of the water uniformly mixes throughout the water and is available for ingestion. This does not take into account deposition onto the sediments

Contamination of water from tritium is not expected to be a major contributor to dose for reasons discussed in Section 4.3.

Table 3. Derived Response Levels

		Produce	Produce				
	DIL	External	Internal	Beef	Milk	Fish	Beverage
	pCi/kg	pCi/m^2	pCi/ m^2	pCi/ m^2	pCi/ m^2	pCi/ m^2	pCi/ m^2
H-3	5.9E+06	NC	1.8E+05	5.5E+05	6.2E+05	NC	NC
Sr-89	3.9E+04	3.9E+05	5.5E+08	8.7E+06	6.0E+06	1.3E+06	3.9E+07
Sr-90	4.3E+03	4.3E+04	6.1E+07	9.6E+05	6.6E+05	1.4E+05	4.3E+06
Nb-95	3.3E+05	3.3E+06	8.4E+09	1.6E+05	1.6E+07	1.1E+04	3.3E+08
I 129	1.5E+03	3.0E+03	1.8E+07	6.9E+04	3.1E+04	1.0E+05	1.5E+06
I-131	4.5E+03	9.0E+03	5.4E+07	2.1E+05	9.3E+04	3.0E+05	4.5E+06
I-133	1.9E+05	3.8E+05	2.3E+09	8.7E+06	3.9E+06	1.3E+07	1.9E+08
Cs-134	2.5E+04	2.5E+05	6.0E+08	8.3E+05	2.6E+05	1.3E+04	2.5E+07
Cs-137	3.7E+04	3.7E+05	8.9E+08	1.2E+06	3.8E+05	1.9E+04	3.7E+07
Ru-103	2.0E+05	2.0E+06	9.6E+08	6.7E+04	2.5E+10	2.0E+07	2.0E+08
Ru-106	1.2E+04	1.2E+05	5.8E+07	4.0E+03	1.5E+09	1.2E+06	1.2E+07
Ce-144	1.3E+04	1.3E+05	1.2E+09	1.4E+06	1.6E+07	1.3E+07	1.3E+07
Np-237	1.1E+02	1.1E+03	1.1E+07	1.2E+04	2.7E+06	1.1E+04	1.1E+05
Np-239	8.6E+05	8.6E+06	8.3E+10	5.7E+08	2.1E+10	8.6E+07	8.6E+08
Pu-238	6.7E+01	6.7E+02	6.5E+07	6.4E+05	4.2E+06	1.9E+04	6.7E+04
Pu-239	6.0E+01	6.0E+02	5.8E+07	5.7E+05	3.7E+06	1.7E+04	6.0E+04
Pu-241	3.3E+03	3.3E+04	3.2E+09	3.1E+07	2.0E+08	9.4E+05	3.3E+06
Am-241	5.4E+01	5.4E+02	5.2E+07	2.9E+04	1.3E+06	2.2E+03	5.4E+04
Cm 244	4.3E+01	4.3E+02	4.1E+06	2.3E+03	1.1E+06	1.7E+03	4.3E+04
Cs-Group	3.1E+04	3.1E+05	7.4E+08	1.0E+06	3.2E+05	1.6E+04	3.1E+07
Pu+Am Group	6.0E+01	6.0E+02	5.8E+07	5.7E+05	3.7E+06	1.7E+04	6.0E+04

NC ◆ not calculated

[1] Same used for grain

5. Ingestion Dose Methodology

The estimation of DILs and DRLs are conservative. More realistic doses can be estimated by applying site-specific methods. One of the main conservatisms in the DIL/DRL methodology is the assumption that the concentration in the foodstuff remains the same over the assumed period of ingestion (1 year). This assumption is highly conservative due to reduction in contaminants via decay from both weathering and radioactive processes. The following methods are proposed to estimate a more realistic ingestion dose following an accidental release of radioactive contaminants. Many of these estimates are seasonally dependent and professional judgement should be used to discount certain pathways based on timing of release.

Modeling such as this is a rough approximation of a complex process and the results should be treated as crude approximations at best. Where possible, environmental monitoring should be utilized to determine concentrations in a given media and then estimate dose. These methods should also be routinely revisited for potential revision pending new research.

5.1 Ingestion of vegetables

There are two main categories of vegetables: green leafy and other. The category of green leafy vegetables includes leafy vegetables grown above the ground with the assumption that the primary contamination pathway is direct deposition of radioactive contaminants on the leaves. This primarily includes different types of lettuce, spinach, and other green leafy vegetables. The category of other vegetables includes everything that does not fall into the leafy vegetable category, which includes vegetables grown both above and below the ground. The primary method of contamination for this type of vegetable is root uptake. Depending on what season of the year that the accident occurs there may be justification for excluding the other vegetable pathway dose.

The EPA Report on Food Ingestion Factors (USEPA 1997) includes a chapter on home-produced food items, which will serve as the main reference for the home-produced food consumption values. The dose from ingestion of vegetables is seasonally dependent. For conservatism, the accident is assumed to occur during the growing season.

Leafy vegetables can be produced year round in the south. Leafy vegetables are assumed to be harvested continually for the 30-day period following the accident. Following the 30-day period, consumption of contaminated leafy vegetables is assumed to end. This assumption was made on the basis that canning and freezing of leafy vegetables is very limited.

Leafy green vegetables become contaminated primarily by direct deposition onto the leaves of the plant. The leafy vegetable ingestion dose is estimated by the following equation:

$$Dose_{Leafy} = \frac{DEP * r * DCF * I_{Leafy} * f_w * CF}{Y} \int_0^{30} e^{-\lambda_e t} \quad (9)$$

where

DEP	deposition concentration for radionuclide (pCi/m^2)
r	retention fraction (0.2 for all radionuclides except iodine, for which 1 was used) (unitless)
DCF	ingestion dose conversion factor (rem/μCi) (USDOE 1988)
I_{Leafy}	intake of leafy vegetables (0.058kg/d) (USEPA 1997)

f_w	fraction of contaminant remaining after washing/preparation (0.5 for leafy vegetables) (Marx and Simpkins 1998)
CF	conversion factor (10^{-6} uCi/pCi)
λ_t	decay constant including both decay (radionuclide dependent) and weathering (4.95E-02 d^{-1}) (d^{-1})
Y	agricultural productivity (0.7 kg/m^2) (Hamby 1991a)

Unlike leafy vegetables, other vegetables have a growing season that is typically centered on the summer months with most plantings occurring between March and May and harvest taking place between June and September.

For other vegetables, the assumption is made that harvesting occurs continually for 30 days post-accident. That harvest is assumed to be consumed over the thirty-day period as well as being canned or frozen during the thirty-day period for later consumption throughout the year. The portion that is canned or frozen is assumed to be harvested at a constant rate over the 30-day period.

The equation to estimate the dose from intake of other vegetables is represented by the following two-part equation that handles decay of the current consumption and the canned/frozen portions separately:

$$Dose_{veg} = DEP * DCF * f_w * CF \left\{ \left(\frac{B \int_0^{30} e^{-\lambda_t t}}{P} + \frac{r \int_0^{30} e^{-\lambda_t t}}{Y_v} \right) * \left[I_{v-30} + \frac{I_{v-335}}{30} * \int_{30}^{365} e^{-\lambda_t t} \right] \right\} \quad (10)$$

where

f_w	fraction remaining after preparation (0.1 for other vegetables) (Marx and Simpkins 1998)
CF	conversion factor (1E-06 pCi/μCi)
B	soil/plant uptake ratio (See Table 2)
P	surface soil density (240 kg/m^2) (USNRC 1977)
I_{v-30}	intake of vegetables over 30-day harvest period (0.385 kg/d) (USEPA 1997)
I_{v-335}	intake of canned or frozen vegetables over remainder of year (0.321 kg/d) (USEPA 1997)

This model does not include contamination of subsequent crops grown after the deposition of the plume. However, subsequent crops are expected to contribute dose that is minimal when compared to the crops growing during the accident. Also, based on timing of release, this pathway may be discounted.

5.1.1 Ingestion of Vegetables-Tritium

Tritium oxide (HTO) concentrations in produce are calculated differently than particulates due to the ready exchange of HTO with moisture within the plants. The transfer of HTO between plants and the atmosphere can vary with temperature, inorganic content, and transfer resistance. Uptake of

atmospheric HTO by leaves is rapid, reaching equilibrium levels in less than thirty minutes (Anspaugh et al. 1973). Studies at SRS indicate a site applicable uptake coefficient of 0.54 (Hamby and Bauer 1994). The concentration of tritiated water in the plant is directly dependent upon the concentration of tritiated water in the atmosphere using the following equation:

$$C_T^V = \frac{CONC \bullet 0.75 \bullet 0.54}{H} \quad (11)$$

where

C^V_T	concentration in vegetation, μCi/g
CONC	atmospheric concentration, μCi/m^3
0.75	fraction of plant mass that is water (USNRC 1977)
0.54	concentration ratio of plant tritium to atmospheric tritium (Hamby and Bauer 1994)
H	absolute humidity at the time of the accident (annual average: 11 g/m^3 for SRS used if no other data available) (Hamby 1990)

For an actual release, the absolute humidity at the time of the release should be entered or at the very least, a seasonally appropriate value should be used.

Once the concentration in the vegetation is determined, the remainder of the calculation is similar to that of other radionuclides. The exceptions are: the integral half-life of tritiated water in plants is assumed to be 1-day (Anspaugh et al. 1973) and no removal of contaminants is assumed to occur during preparation and processing since the contamination is not surficial. For tritium, the dose from ingestion of leafy vegetables is as follows:

$$Dose_{veg} = \frac{CONC * DCF * CF * 0.75 * 0.54 * I_{leafy}}{H} \int_0^{30} e^{-\lambda_w t} \quad (12)$$

where

CONC	HTO concentration in air (pCi/m^3)
0.75	fraction of plant assumed to be water
0.54	tritium uptake coefficient
H	absolute humidity (11 g/m^3 assumed if no other data available)
λ_w	weathering rate for tritium in vegetable water (1 d^{-1})

For ingestion of other vegetables the following equation is used to estimate dose following a release of tritium:

$$Dose_{veg} = \frac{CONC*DCF*CF*0.75*0.54}{H}\left\{\left(\int_0^{30} e^{-\lambda_w t}\right)*\left[I_{v-30} + \frac{I_{v-335}}{30}*\int_{30}^{365} e^{-\lambda_i t}\right]\right\} \quad (13)$$

All terms have been previously defined.

5.2 Ingestion of Milk

Milk can become contaminated when cows graze on pasture that has radionuclides deposited on it during plume passage. Milk cows in the region surrounding SRS obtain approximately 56% of their food from pasture grazing. Another 25% comes from stored grain or silage with the remaining 19% coming from commercial feed produced in other regions (Hamby 1991a).

During pasture grazing, dairy cows are often rotated to and from different pastures to maintain palatability of pasture. While this practice varies by season and from farm to farm, an average value of two weeks is assumed (Sullivan, DeClue, and Emmick 2000). With this in mind, there could be fresh grass available for the dairy cattle to eat for a long period of time after the deposition of contaminants. The dairy cattle are assumed to graze on grass that could be contaminated for one year. Due to the assumed 14 day weathering half life, however, the grass is virtually free of contamination after about three months.

For conservatism, stored grain or silage is assumed to be harvested on the day of the release and consumption is assumed to be delayed 90 days.

The following equation provides an estimate of dose from the milk pathway:

$$Dose_{Milk} = \frac{DEP*r*DCF*I_{Milk}*CF*F_i^m*Q_m}{Y}\left\{\int_0^{365} e^{-\lambda_w t}*0.56 + \int_{90}^{365} e^{-\lambda_i t}*0.25\right\}*e^{-\lambda_i t_h} \quad (14)$$

where

I_{Milk}	intake of home-produced milk (0.98 kg/d) (USEPA 1997)
R	retention fraction (0.2 for all radionuclides except iodine, for which 1 was used) (unitless)
F_i^m	element-specific feed transfer factor for milk cows (See Table 2)
Q_m	dairy cattle feed rate (52 kg/day) (Hamby 1991a)
Y	agricultural productivity (1.8 kg/m^2) (Hamby 1991a)
0.56	fraction of dairy cattle diet from pasture (Hamby 1991a)
0.25	fraction of dairy cattle diet from silage (Hamby 1991a)
t_h	hold-up time between milking and consumption (3 days) (Hamby 1991a)

5.2.1 Ingestion of Milk-Tritium

For tritium, the concentration in grass or silage is calculated as shown above in equation 11. Therefore, for tritium equation 14 above is modified as follows:

$$Dose_{Milk} = \frac{CONC * DCF * CF * 0.75 * 0.54 * I_{Milk} * CF * F_i^m * Q_m}{H} \left\{ \int_0^{365} e^{-\lambda_w t} * 0.56 + \int_{90}^{365} e^{-\lambda_r t} * 0.25 \right\} \quad (15)$$

Where all terms have been previously defined. The decay term for holdup between milking and consumption is not included since tritium has a long half life (12 years).

5.3 Ingestion of Beef

For ingestion of beef the equation used to estimate dose is similar to that of ingestion of milk. The equation is shown below again for ease in variable definition:

$$Dose_{Beef} = \frac{DEP * r * DCF * I_{Beef} * CF * F_i^b * Q_b}{Y} \left\{ \int_0^{365} e^{-\lambda_w t} * 0.75 + \int_{90}^{365} e^{-\lambda_r t} * 0.25 \right\} * e^{-\lambda_r t_h} \quad (16)$$

where

I_{Beef}	intake of home produced beef (0.172 kg/d) (USEPA 1997)
R	retention fraction (0.2 for all radionuclides except iodine, for which 1 was used) (unitless)
F_i^b	element-specific feed transfer factor for beef (See Table 2)
Q_b	beef cattle feed rate (36 kg/day) (Hamby 1991a)
Y	agricultural productivity (1.8 kg/m^2) (Hamby 1991a)
0.75	fraction of beef cattle diet from pasture (Hamby 1991a)
0.25	fraction of beef cattle diet from silage (Hamby 1991a)
t_h	holdup time from slaughter to consumption (4 days) (Hamby 1991a)

5.3.1 Ingestion of Beef-Tritium

The equation for estimating the dose from ingestion of beef contaminated with tritium is similar to that for milk except the fraction of year on pasture is higher (0.75) and the transfer factor is different.

$$Dose_{Beefk} = \frac{CONC * DCF * CF * 0.75 * 0.54 * I_{Beef} * CF * F_i^b * Q_b}{H} \left(\int_0^{365} e^{-\lambda_e t} * 0.75 + \int_{90}^{365} e^{-\lambda t} * 0.25 \right) * e^{-\lambda t_h} \quad (17)$$

Where all terms have been previously defined.

5.4 Ingestion of Fish

Due to time-constraints and the likelihood of certain radionuclides being released, cesium is the only radionuclide considered for this pathway. For an atmospheric release, fish can become contaminated when a plume passes over a pond. Once the radionuclide deposits on the surface, mixing within the body of water occurs and material begins to deposit onto the sediment. For cesium, 95% of the cesium is lost from the water within 4 days (Friend 1963). Given this, a factor of 0.05 is applied to account for the amount that remains in the water. This factor assumes that equilibrium is achieved between exchange of particulates from the sediment and the water and is maintained for a one-year period via absorption and desorption of the cesium.

The concentration in the fish is estimated using a bioaccumulation factor (L/kg) which represents the radionuclide concentration in fish (pCi/kg) due to submersion in water contaminated at a given concentration (pCi/L). Such bioaccumulation factors are estimated assuming equilibrium has been obtained with the fish and the water. The site-specific bioaccumulation factor for cesium in fish is 3000 L/kg (Hamby 1991b). For cesium the accumulated amount reaches a maximum at about 80 days after fallout (Forseth et al. 1991). Prior to equilibrium, a linear relationship is assumed and the bioaccumulation factor for cesium in fish is estimated by simply integrating over the one year period to derive an effective bioaccumulation factor. The equation used to estimate the dose from fish following an atmospheric release is as follows:

$$Dose_{fish} = \frac{0.05 * DEP * B_f * I_{fish} * DCF}{\rho * d} \quad (18)$$

where

0.05	fraction of cesium remaining in the water
B_f	integrated bioaccumulation factor for Cs-137 in fish 2670 L/kg
I_{fish}	intake of home-produced fish (102 kg/yr) (USEPA 1997)
ρ	density of the water (1000 kg/m^3)
d	depth of the water (1 meter assumed)

Doses for other radionuclides could be derived at a later date. As discussed in Section 4.3, contamination of fish from releases of tritium are not expected to be an important pathway.

5.5 Ingestion of Water

Ingestion of contaminated water can occur when contaminants enter the public drinking system via surface water, runoff, or migration to the groundwater. Each of these processes is complex and modeling of the process would be dependent on radionuclide and the location of plume in relation to water sources. For instance, if the plume where to pass directly over the Savannah River upriver of the site, radionuclides could enter the drinking water system for Augusta, GA. However, the radionuclide concentration would be highly diluted by mixing with non-contaminated water prior to drinking. USFDA (1998) conservatively assumes that 30% of water consumption comes from contaminated sources and this value will be used here. For ingestion of water radiation dose is estimated for particulates using the following equation

$$Dose_{water} = \frac{DEP * I_{water} * DCF * 0.3}{\rho * d} \quad (19)$$

where

0.3	fraction of water assumed to come from contaminated sources (USFDA 1998)
I_{water}	water intake (475 L/yr) (USEPA 1997)
ρ	density of the water (1000 kg/m^3)
d	depth of the water (1 meter assumed)

These methods are conservative and refinements could be made using groundwater modeling.

Ingestion of tritium from drinking water is not expected to be a major pathway since tritium oxide (HTO) is suspending in the air over the water and does not easily fallout except perhaps in the presence of heavy rain.

5.6 Computer Model of Methods

These methods have been programmed into a Microsoft Excel © Spreadsheet. For dose estimates, the user only needs to enter the ground concentrations (air concentration for tritium) at the point of concern and the total dose will be estimated. This spreadsheet should be reviewed yearly and updated as needed.

6. Conclusions

Methods have been developed for estimating dose from ingestion of contaminated foodstuffs following an accidental release of radioactive materials to the atmosphere. Estimates are conservative in that the individual is assumed to consume the contaminated products for an entire year for all pathways. The more likely scenario is a person being exposed through one or two pathways as dictated by their current diet. Methodologies such as these are gross estimates at best and should be treated as such. As FDA Guidance is finalized, these methods should be reevaluated to determine their relevance.

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Appendix A. Derived Intervention Level (DIL) Estimation

Derived Intervention Level Estimation

Derived Intervention Levels (DILs) "correspond to the concentration in food present throughout the relevant period of time that, in the absence of an intervention, could lead to an individual receiving a radiation dose equal to the PAG" (USFDA 1998). The basic formula for the DIL is

$$DIL = \frac{PAG}{f*FI*DCF} \quad (1)$$

where

DIL	derived intervention level (Ci/kg)
PAG	protective action guide (mrem)
f	fraction of food assumed to be contaminated (unitless)
FI	quantity of food consumed in an appropriate period of time (kg)
DCF	dose conversion factor • radiation dose received per unit activity ingested (mrem/Ci)

The PAGs are 500 mrem committed effective dose equivalent or 5000 mrem committed dose equivalent to individual tissues or organs, whichever is more limiting. The fraction of food assumed to be contaminated is 0.3 for all radionuclides except for I-131 (infant diets 1.0) as recommended in USFDA (1998). The quantity of food consumed was taken also taken from USFDA (1998) with an original reference of USEPA (1984). These values are shown in Table A-1. Table A-2 shows the dose conversion factors used as taken from ICRP (1989). Comparing Tables A-1 and A-2 show that the age breakdowns do not agree. Where necessary, consumption data were averaged to provide an estimate for the appropriate age group.

Ingestion of food is typically assumed to occur for one year. This however, is not feasible for radionuclides such as I-131 which have a relatively short half life. For these radionuclides, the consumption period is assumed to be the period of time from deposition until the activity has decayed to 1% of its original value. This is calculated from the radioactive decay law and the results are shown in Table A-3.

The DILs are calculated using the above equation and the results are shown in Table A-4. Table A-5 shows the most limiting DIL by radionuclide and group as defined in USFDA (1998).

Table A-1. Annual Dietary Intakes (kg/yr)

	Age Group (yrs)									
Food Class	<1	1--4	5--9	10--14	15--19	20--24	25--29	30--39	40--59	60 & up
Dairy	208	153	180	186	167	112	98.2	86.4	80.8	90.6
(fresh milk)	99.3	123	163	167	148	96.5	79.4	66.8	61.7	70.2
Egg	1.8	7.2	6.2	7	9.1	10.3	10.2	11	11.4	10.5
Meat	16.5	33.7	46.9	58.4	69.2	71.2	72.6	73.1	70.7	56.3
Fish	0.3	2.5	4	4.9	6.1	6.8	7.6	7.1	8	6.3
Produce	56.6	59.9	82.3	96	97.1	91.4	99.1	102	115	121
Grain	20.4	57.6	79	90.6	89.4	77.3	78.4	73.7	70.2	67.1
Beverage	112	271	314	374	453	542	559	599	632	565
(tap water)	62.3	159	190	223	243	240	226	232	268	278
Misc.	2	9.3	13.3	14.8	13.9	10.9	11.9	12.5	13.3	13
Total Annual Intake	418	594	726	832	905	922	937	965	1001	930

Table A-2. Dose Conversion Factors (mSv/Bq) (multiply by 3.7 to get mrem/pCi)

	Age Group					
Radionuclide- Organ	**3 Months**	**1 Year**	**5 Years**	**10 Years**	**15 Years**	**Adult**
H-3	5.5E-08	4.1E-08	2.6E-08	1.9E-08	1.6E-08	1.6E-08
Sr-89 lower intestine	2.8E-05	1.4E-04	7.1E-05	4.8E-05	2.3E-05	2.1E-05
Sr-89	3.0E-05	1.5E-05	7.7E-06	5.2E-06	3.5E-06	2.2E-06
Sr-90 bone surface	1.0E-03	7.4E-04	3.9E-04	5.5E-04	1.2E-03	3.8E-04
Sr-90	1.3E-04	9.1E-05	4.1E-05	4.3E-05	6.7E-05	3.5E-05
Nb-95	5.2E-06	3.7E-06	2.1E-06	1.3E-06	8.6E-07	6.8E-07
I-129 thyroid	3.7E-03	4.3E-03	3.5E-03	3.8E-03	2.8E-03	2.1E-03
I 129	1.1E-04	1.3E-04	1.0E-04	1.1E-04	8.4E-05	6.4E-05
I-131-thyroid	3.7E-03	3.6E-03	2.1E-03	1.1E-03	6.9E-04	4.4E-04
I-131	1.1E-04	1.1E-04	6.3E-05	3.2E-05	2.1E-05	1.3E-05
I-133 thyroid	9.6E-04	8.6E-04	5.0E-04	2.3E-04	1.5E-04	8.3E-05
I-133	2.9E-05	2.6E-05	1.8E-05	7.0E-06	4.3E-06	2.5E-06
Cs-134	2.5E-05	1.5E-05	1.3E-05	1.4E-05	2.0E-05	1.9E-05
Cs-137	2.0E-05	1.1E-05	9.0E-06	9.8E-06	1.4E-05	1.3E-05
Ru-103	7.7E-06	5.1E-06	2.7E-06	1.7E-06	1.0E-06	8.1E-07
Ru-106	8.9E-05	5.3E-05	2.7E-05	1.6E-05	9.2E-06	7.5E-06
Ce-144 LLI	7.6E-04	4.9E-04	2.4E-04	1.5E-04	8.2E-05	6.6E-05
Ce-144	8.0E-05	4.3E-05	2.1E-05	1.3E-05	7.2E-06	5.8E-06
Np-237 bone surface	1.0E-01	8.9E-03	9.3E-03	9.9E-03	1.2E-02	1.2E-02
Np-237	5.5E-03	4.9E-04	4.3E-04	4.0E-04	4.7E-04	4.5E-04
Np-239 LLI	9.8E-05	6.4E-05	3.2E-05	1.9E-05	1.1E-05	8.8E-06
Np-239	9.6E-06	6.3E-06	3.2E-06	1.9E-06	1.1E-06	8.7E-07
Pu-238 bone surface	1.6E-01	1.6E-02	1.5E-02	1.5E-02	1.6E-02	1.7E-02
Pu-238	1.3E-02	1.2E-03	1.0E-03	8.8E-04	8.7E-04	8.8E-04
Pu-239 bone surface	1.8E-01	1.8E-02	1.8E-02	1.7E-02	1.9E-02	1.8E-02
Pu-239	1.4E-02	1.4E-03	1.1E-03	1.0E-03	9.8E-04	9.7E-04
Pu-241bone surface	3.3E-03	3.4E-04	3.5E-04	3.9E-04	3.9E-04	3.7E-04

Pu-241	2.2E-04	2.2E-05	2.1E-05	2.0E-05	2.0E-05	1.9E-05
Am-241 bone surface	2.0E-01	1.9E-02	1.9E-02	1.9E-02	2.1E-02	2.0E-02
Am-241	1.2E-02	1.2E-03	1.0E-03	9.0E-04	9.1E-04	8.9E-04
Cm-244 bone surface	2.5E-01	2.5E-02	1.6E-02	1.2E-02	9.9E-03	9.8E-03
Cm 244	1.4E-02	1.4E-03	9.2E-04	6.7E-04	5.9E-04	5.4E-04

Table A-3. Effective Days of Consumption Based on Decay

	Half Life	Days to 1% of Activity	Effective Days of Consumption per Year
	(days)		
H-3	4.49E+03	2.98E+04	365
Sr-89 lower intestine	5.05E+01	3.36E+02	336
Sr-89	5.05E+01	3.36E+02	336
Sr-90 bone surface	1.06E+04	7.03E+04	365
Sr-90	1.06E+04	7.03E+04	365
Nb-95	3.50E+01	2.32E+02	232
I-129 thyroid	5.84E+09	3.88E+10	365
I 129	5.84E+09	3.88E+10	365
I-131-thyroid	8.04E+00	5.34E+01	53
I-131	8.04E+00	5.34E+01	53
I-133 thyroid	8.67E-01	5.76E+00	6
I-133	8.67E-01	5.76E+00	6
Cs-134	2.07E+00	1.37E+01	14
Cs-137	1.10E+04	7.32E+04	365
Ru-103	3.92E+01	2.61E+02	261
Ru-106	3.72E+02	2.47E+03	365
Ce-144 LLI	2.84E+02	1.89E+03	365
Ce-144	2.84E+02	1.89E+03	365
Np-237 bone surf	7.81E+08	5.19E+09	365
Np-237	7.81E+08	5.19E+09	365

Np-239 LLI	2.12E+00	1.41E+01	14
Np-239	2.12E+00	1.41E+01	14
Pu-238 bone surface	3.20E+04	2.13E+05	365
Pu-238	3.20E+04	2.13E+05	365
Pu-239 bone surface	8.80E+06	5.85E+07	365
Pu-239	8.80E+06	5.85E+07	365
Pu-241bone surface	5.24E+03	3.48E+04	365
Pu-241	5.24E+03	3.48E+04	365
Am-241 bone surface	1.58E+05	1.05E+06	365
Am-241	1.58E+05	1.05E+06	365
Cm-244 bone surface	6.61E+03	4.39E+04	365
Cm 244	6.61E+03	4.39E+04	365

Table A-4 Derived Intervention Level by Age Group

Radionuclide	PAG	DIL (pCi/kg)					
	mrem	3 Months	1 Year	5 Years	10 Years	15 Years	Adult
H-3	500	5.9E+06	6.5E+06	2.6E+07	3.0E+07	3.2E+07	3.0E+07
Sr-89 LLI	5000	4.2E+05	6.9E+04	1.0E+05	1.3E+05	2.5E+05	2.5E+05
Sr-89	500	3.9E+04	6.5E+04	9.6E+04	1.2E+05	1.6E+05	2.4E+05
Sr-90 bone	5000	1.1E+04	1.2E+04	1.8E+04	1.1E+04	4.3E+03	1.3E+04
Sr-90	500	8.3E+03	9.8E+03	1.7E+04	1.3E+04	7.7E+03	1.4E+04
Nb-95	500	3.3E+05	3.8E+05	5.1E+05	7.0E+05	9.5E+05	1.1E+06
I-129 thyr	5000	2.9E+03	2.1E+03	2.0E+03	1.5E+03	1.9E+03	2.3E+03
I 129	500	9.8E+03	6.8E+03	6.8E+03	5.3E+03	6.2E+03	7.5E+03
I-131-thyr	5000	5.3E+03	4.5E+03	2.0E+04	3.2E+04	4.6E+04	6.6E+04
I-131	500	1.8E+04	1.5E+04	6.6E+04	1.1E+05	1.5E+05	2.2E+05
I-133 thyr	5000	2.1E+05	1.9E+05	8.3E+05	1.5E+06	2.1E+06	3.5E+06
I-133	500	6.8E+05	6.2E+05	2.3E+06	5.0E+06	7.3E+06	1.2E+07
Cs-134	500	4.3E+04	5.9E+04	5.3E+04	4.1E+04	2.6E+04	2.5E+04
Cs-137	500	5.4E+04	8.1E+04	7.6E+04	5.9E+04	3.7E+04	3.7E+04

Ru-103	500	2.0E+05	2.4E+05	3.3E+05	4.4E+05	6.8E+05	7.7E+05
Ru-106	500	1.2E+04	1.7E+04	2.5E+04	3.6E+04	5.6E+04	6.4E+04
Ce-144 LLI	5000	1.4E+04	1.8E+04	2.8E+04	3.9E+04	6.3E+04	7.2E+04
Ce-144	500	1.3E+04	2.1E+04	3.3E+04	4.4E+04	7.2E+04	8.2E+04
Np-237 bone	5000	1.1E+02	1.0E+03	7.3E+02	5.8E+02	4.3E+02	4.0E+02
Np-237	500	2.0E+02	1.8E+03	1.6E+03	1.4E+03	1.1E+03	1.1E+03
Np-239 LLI	5000	8.6E+05	1.1E+06	4.9E+06	6.9E+06	1.1E+07	1.2E+07
Np-239	500	8.7E+05	1.1E+06	4.9E+06	6.9E+06	1.1E+07	1.3E+07
Pu-238 bone	5000	6.7E+01	5.6E+02	4.6E+02	3.9E+02	3.2E+02	2.8E+02
Pu-238	500	8.3E+01	7.4E+02	6.8E+02	6.6E+02	6.0E+02	5.4E+02
Pu-239 bone	5000	6.0E+01	4.9E+02	3.8E+02	3.4E+02	2.7E+02	2.7E+02
Pu-239	500	7.7E+01	6.4E+02	6.2E+02	5.8E+02	5.3E+02	4.9E+02
Pu-241 bone	5000	3.3E+03	2.6E+04	2.0E+04	1.5E+04	1.3E+04	1.3E+04
Pu-241	500	4.9E+03	4.0E+04	3.3E+04	2.9E+04	2.6E+04	2.5E+04
Am-241 bone	5000	5.4E+01	4.7E+02	3.6E+02	3.0E+02	2.5E+02	2.4E+02
Am-241	500	9.0E+01	7.4E+02	6.8E+02	6.4E+02	5.7E+02	5.4E+02
Cm-244 bone	5000	4.3E+01	3.6E+02	4.3E+02	4.8E+02	5.2E+02	4.9E+02
Cm 244	500	7.7E+01	6.4E+02	7.4E+02	8.6E+02	8.8E+02	8.8E+02

Table A-5. Derived Intervention Level by Radionuclide and Group

	DIL
	(pCi/kg)
H-3	5.9E+06
Sr-89	3.9E+04
Sr-90	4.3E+03
Nb-95	3.3E+05
I 129	1.5E+03
I-131	4.5E+03
I-133	1.9E+05

Cs-134	2.5E+04
Cs-137	3.7E+04
Ru-103	2.0E+05
Ru-106	1.2E+04
Ce-144	1.3E+04
Np-237	1.1E+02
Np-239	8.6E+05
Pu-238	6.7E+01
Pu-239	6.0E+01
Pu-241	3.3E+03
Am-241	5.4E+01
Cm 244	4.3E+01
Cs-Group	3.1E+04
Pu+Am Group	6.0E+01
Ru-Group	*

[1]The individual concentrations of Ru-103 and Ru-106 are divided by their respective DILs and summed. The sum must be less than one. [(Ru-103 Conc/2.0E+05+Ru-106/1.2E+04)<1]