METHODOLOGY FOR ESTIMATING INGESTION DOSE FOR EMERGENCY RESPONSE AT SRS

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Abstract - At the Savannah River Site (SRS), emergency response computer models are used to estimate dose following releases of radioactive materials to the environment. Downwind air and ground concentrations and their associated doses from inhalation and ground shine pathways are estimated. The emergency response model (PUFF-PLUME) uses real-time data to track either instantaneous (puff) or continuous (plume) releases. A site-specific ingestion dose model was developed for use with PUFF-PLUME that includes the following ingestion dose pathways pertinent to the surrounding SRS area: milk, beef, water, and fish. The model is simplistic and can be used with existing code output.

INTRODUCTION

The Savannah River Site (SRS) processes and stores nuclear materials in support of the national defense and U.S. nuclear non-proliferation efforts. The site also develops and deploys technologies to improve the environment and treat nuclear and hazardous wastes from the Cold War. The SRS complex is located in South Carolina along the Savannah River and covers approximately 800 km^2.

SRS has a fully operational Weather Center, which can provide real-time modeling and assessment of the movement of radioactive releases. One such model used within the

Weather Center 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. Currently, air and ground concentrations predicted by PUFF-PLUME are compared with derived response levels (DRLs) recommended by the Food and Drug Administration (FDA) guidance (USFDA 1998), to determine if interdiction of food consumption for certain pathways is necessary. DRLs correspond to the concentration in a given environmental media that when propagated through the food chain, in the absence of intervention, would result in a person receiving a dose in excess of the protective action guides.

DRL methods recommended by FDA are rough approximations of complex processes and are very conservative in that radioactive decay or decay due to weathering from plant surfaces is not considered. Also, using the DRL methodology does not give an estimation of the total dose received as a result of all pathways but rather limits each individual consumption pathway based on certain dose limits. A more realistic, site-specific ingestion dose model is recommended for use with PUFF-PLUME.

Accident models incorporate ingestion models for predictive purposes (MACCS (Chanin 1997), GENII, (Napier 2002) but few, if any, do so for real time releases. One reason is the complexity of the growth cycle of plants in relation to when the release occurs. The ingestion model recommended here is simplistic yet not overly conservative.

INGESTION DOSE METHODOLOGY

The following methods are proposed to estimate an ingestion dose immediately following an accidental release of radioactive contaminants. Final decisions should still be based on derived response level methods as recommended by the FDA. An assumption is made that the release occurs during the growing season 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 from these concentrations. However, during the early stages following an accident, these dose methods provide decision-makers with an additional tool. Dose methods are discussed for the following ingestion pathways: vegetables, milk, beef, and water. These pathways are considered to be important at SRS based on agricultural practices.

Ingestion of vegetables

Two main categories of vegetables are considered here: 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 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 the season of the year in which the accident occurs, there may be justification for excluding the other vegetable pathway dose. Due to the warm climate surrounding SRS, leafy vegetables can be produced year-round.

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 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:

$$Dose_{Leafy} = \frac{DEP * r * DCF * I_{Leafy} * f_w *}{Y_L} \int_0^{30} e^{-\lambda_t t}$$

where

DEP deposition concentration for radionuclide (Bq m^{-2})

r retention fraction (0.2 for all radionuclides except iodine, for which 1 was used) (unitless)

DCF	ingestion dose conversion factor (Sv Bq^{-1}) (USDOE 1988)
I_{Leafy}	ingestion rate of leafy vegetables (0.058kg d^{-1}) (USEPA 1997)
f_w	fraction of contaminant remaining after washing/preparation (0.5 for leafy vegetables) (Simpkins, Marx, and Hamby 2000)
λ_t	decay constant including both decay (radionuclide dependent) and weathering (0.0495 d^{-1}) (d^{-1})
Y_L	productivity for leafy vegetables (0.7 kg m^{-2}) (Hamby 1991a)
t	time between harvest and consumption (d)

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:

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

where

f_w	fraction remaining after preparation (0.1 for other vegetables) (Simpkins, Marx, and Hamby 2000)
B	soil/plant uptake ratio (USNRC 1977)
P	surface soil density (240 kg m^{-2}) (USNRC 1977)
Y_V	productivity for other vegetables (0.7 kg m^{-2}) (Hamby 1991a)
I_{v-30}	ingestion rate of vegetables over 30-day harvest period (0.385 kg d^{-1}) (USEPA 1997)
I_{v-335}	ingestion rate of canned or frozen vegetables over remainder of year (0.321 kg d^{-1}) (USEPA 1997)
λ_I	radionuclide-specific decay constant (d^{-1})

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.

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:

$$C_T^V = \frac{CONC \bullet 0.75 \bullet 0.54}{H}$$

where

C_T^V	concentration in vegetation, Bq g^{-1}
CONC	atmospheric concentration, Bq 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:

$$Dose_{leafy} = \frac{CONC * DCF * 0.75 * 0.54 * I_{leafy}}{H} \int_0^{30} e^{-\lambda_w t}$$

where

λ_w disappearance 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:

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

All terms have been previously defined.

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:

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

where

I_{Milk}	ingestion rate of home-produced milk (0.98 L d^{-1}) (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 (d L^{-1}) (USNRC 1977)
Q_m	dairy cattle feed rate (52 kg d^{-1}) (Hamby 1991a)
Y	agricultural productivity of grass (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 d) (Hamby 1991a)

Ingestion of Milk-Tritium

For tritium, the concentration in grass or silage is calculated using the same method as for other vegetables. Incorporating this concentration equation into the milk dose equation shown above yields:

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

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).

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:

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

where

I_{Beef}	ingestion rate of home produced beef (0.172 kg d^{-1}) (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 (USNRC 1977))
Q_b	beef cattle feed rate (36 kg d^{-1}) (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)

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.

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

All terms have been previously defined.

Ingestion of Fish

Because of its high bioaccumulation factor in fish and the likelihood of certain radionuclides being released at SRS, ^{137}Cs 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^{-1}) which represents the radionuclide concentration in fish (Bq kg^{-1}) due to submersion in water contaminated at a given concentration (Bq L^{-1}). 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^{-1} (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:

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

where

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

Doses from other radionuclides could be derived in a similar manner.

Ingestion of Water

Ingestion of contaminated water following an atmospheric release 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 the 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

$$Dose_{water} = \frac{DEP * I_{water} * DCF * 0.3}{\rho * d}$$

where

0.3 fraction of water assumed to come from contaminated sources (USFDA 1998)

I_{water} water ingestion rate (475 L yr^{-1}) (USEPA 1997)

ρ density of water (1000 kg m^{-3})

d depth of 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 suspended in the air over the water and does not easily fallout except in the presence of rain.

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 from all pathways will be estimated.

CONCLUSIONS

Methods have been developed for estimating dose from ingestion of contaminated foodstuffs following an accidental release of radioactive materials to the atmosphere. Methods are simple and can be easily used in conjunction with existing code output to provide decision makers with an additional tool in the event of an unplanned release of radioactive materials. 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.

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