Savannah River Site Ingestion Pathway Methodology Manual for Airborne Radioactive Releases

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SRS

SAVANNAH RIVER SITE

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ABSTRACT

This manual documents a recommended methodology for determining the ingestion pathway consequences of hypothetical *accidental* airborne radiological releases from facilities at the Savannah River Site. Both particulate and tritiated radioactive contaminants are addressed. Other approaches should be applied for evaluation of routine releases.

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**Savannah River Site Ingestion Pathway Methodology Manual
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INTRODUCTION

For emergency planning and potential food interdiction decision-making, it may be desirable to assess the ingestion pathway consequences of hypothetical accidents at various nuclear facilities. The ingestion pathway consequences of a single accident at each of three facilities were assessed previously. This manual describes the recommended method to be applied for the Savannah River Site (SRS) to predict the impact of an accidental airborne release of radioactive material on the use of foodstuffs downwind of such a release.

Department of Energy (DOE) emergency management guidance (DOE 1997) establishes requirements for assessing the consequences of postulated accidents at DOE sites. These requirements are used as bases for the assessments described in this manual.

The new Food and Drug Administration (FDA) recommendations for the accidental radioactive contamination of human foods and animal feeds (FDA 1998) provide the basis for the evaluation of ingestion pathway consequences.

The overall approach used to evaluate the impact of an atmospheric release of radionuclides on the food chain may be divided into several steps that follow radioactive material through the environment and food chain to humans. Table 1 was adapted from NCRP-50, Environmental Radiation Measurements (NCRP 1976). This table illustrates the steps from release of radionuclides into the environment to the dose that results from human ingestion. It also identifies two physical quantities (identified by shaded areas following the pathway step) that could be measured and compared to limits.

The form of the radioactive material released into the air may be particulate, vapor, or gas. Particulates include most substances that may be released, such as transuranics. Tritium may be released into the air in the oxide form (e.g., HTO, DTO, and T_2O vapor) or as an elemental gas (HT, DT, and T_2). Fission products include noble gases and volatile iodines. Noble gases are not a concern for the ingestion pathway, since their incorporation into the food chain is minimal.

Volatile iodines may be of concern with criticality-related accidents, or with postulated accidents involving spent fuel of very short cooling times. Since the fuel processed at SRS has generally undergone a significant cooling period and most radioiodines are short-lived, radioiodines are not expected to be major contributors to dose from ingestion. The exception may be the long-lived radionuclide, I-129, which may be a significant contributor to dose and whose impact should be evaluated if it is a significant constituent of a source term.

Table 1. Illustrative pathway for internal radiation exposure from airborne radionuclide effluent (adapted from NCRP 1976)

Pathway Step	Variable	Product of Variables
Source	Source term (Q)	Radioactive material released (Bq)
		Q
Dispersion	Dispersion (χ/Q)	Time-integrated airborne concentration (Bq s m^{-3})
		$Q(\chi/Q)$
Cumulative Deposition	Deposition velocity (V_d)	Radioactive material per unit area (Bq m^{-2})
		$Q(\chi/Q) V_d$
(Comparison basis for particulates: deposition)		
Environmental and Biological Transfer	Transfer factor (T_r)	Radioactive material per unit mass of environmental or biological medium (Bq kg^{-1})
		$Q(\chi/Q) V_d T_r$
(Comparison basis for tritium: concentration in food)		
Human Intake	Intake rate (I)	Radioactive material intake per unit time (Bq s^{-1})
		$Q(\chi/Q) V_d T_r I$
Human Absorbed Dose Rate	Intake rate to absorbed dose rate conversion factor (k)	Absorbed dose per unit time (rad s^{-1})
		$Q(\chi/Q) V_d T_r I k$

The first pathway step describes the amount of material released to the environment. Nuclide-specific source terms are adapted from authorization basis documents and emergency preparedness hazards assessments (EPHAs) evaluating the immediate dose from plume passage. For consequence analyses when **inhalation** pathways are the primary concern, the respirable (aerodynamic diameters less than 10 microns) airborne release is used. For consequences involving the **ingestion** pathways, it is more appropriate to use the total (the sum of the respirable and nonrespirable) airborne release.

The dispersion pathway step transports the release to downwind locations. The atmospheric dispersion model chosen for a particular application depends on the problem that needs to be solved. For determining ingestion pathway consequences, a simple straight-line Gaussian model is sufficient. The background for this decision is provided in *Selection of Models for Ingestion Pathway and Relocation* (Thompson 1999a). A summary of the points considered in this decision is presented here.

The model should be consistent with guidance for emergency planning use. It should be among, or be consistent with, those models that will actually be used or available following a release, should allow the user to modify dispersion and deposition parameters to site-specific values, and

should also have adequate documentation. The capabilities of a complex dispersion model may impose undue data development demands, without providing commensurate improvements in the quality of results. Additionally, for relatively flat terrain such as that characterizing the region around SRS, complex terrain models yield little added value. For these and other reasons, a simple Gaussian model is justified.

The cumulative deposition pathway step quantifies the amount of contaminant deposited on the ground (or directly on foodstuffs in some cases). To assess this effect, the concept of a deposition velocity is employed. The deposition velocity is defined to be the flux to ground divided by the air pollutant concentration (Randerson 1984). Deposition velocities can range from ~0.0 to 10 cm s^{-1}. High deposition velocities result in more deposition close to the release point, but deplete the plume more rapidly. Small deposition velocities result in less deposition for a given airborne concentration, but may result in a greater contaminant concentration farther from the release point since the plume is depleted less rapidly. The deposition "footprint" is a complex function of deposition velocity, wind velocity, activity released, and atmospheric stability class.

Environmental and biological transfer factors relate the concentration of radionuclides in one compartment of the pathway to another. Although in Table 1 only one aggregated transfer factor is shown (T_r), radioactive contaminants may pass through multiple compartments to reach humans. Transfer between any two adjacent compartments would be described by an individual transfer factor, and the aggregated value obtained by taking the product of the individual factors. When available, site-specific individual and aggregated transfer factors are used. Otherwise, values from other sources, as detailed later, are used. The product of the nuclide-specific aggregated transfer factor (in m^2 kg^{-1} or m^2 L^{-1}) for a given pathway and nuclide-specific deposition (Bq m^{-2}) gives the expected concentration of the nuclide in the foodstuff (in Bq kg^{-1} or Bq L^{-1}).

The aggregated transfer factor is a measure of the concentration in a particular food via a specific food pathway that results from the deposition of radionuclides. If the expected concentration in food is small per unit deposition, the aggregated transfer factor will be small. Foods with higher expected concentrations have larger aggregated transfer factors. A comparison of the aggregated transfer factors for various foodstuffs and pathways shows which pathways result in the highest concentrations in food for a given deposition.

The product of variables after applying environmental and biological transfer factors (the radioactive material per unit mass of environmental or biological medium) may be compared to Derived Intervention Levels (DILs) for food in FDA 1998. The intake rate and dose rate conversion factor in the last two rows of Table 1 are incorporated in the derivation of the DIL for each group of nuclides. The approach for tritium differs from this one because most tritium models calculate food concentrations directly. The computed tritium concentrations in food may be compared directly to DILs derived using FDA methodology.

Notwithstanding the most recent FDA guidance, it must be recognized that current DOE guidance in DOE G 151.1-1, Vol. 2, Section B.2.1, Radiological Protective Action Criteria (DOE 1997) cites the old FDA guidance. Since the new FDA guidelines were issued recently, it is

presumed that DOE guidance will be revised to reference the new guidelines. The new FDA guidelines appear to be much more restrictive than the old guidelines. Therefore, the new FDA DILs are recommended for use as evaluation guidelines for the ingestion pathways. Discussions with DOE, the Environmental Protection Agency (EPA), and the Nuclear Regulatory Commission (NRC) have indicated the intent to use the new guidelines.

An alternative to comparing food concentrations with a DIL is to compare deposition levels with a Derived Response Level (DRL). A DRL is the deposition that results in a concentration of a DIL in a foodstuff. Since deposition values (but not food concentrations) are calculated in HOTSPOT, comparison using DRLs allows convenient use of this relatively simple dispersion code. Therefore, deposition is used to evaluate ingestion pathway consequences for particulates.

METHOD

ALLOWABLE CONCENTRATIONS OF RADIONUCLIDES IN FOODSTUFFS

The Food and Drug Administration (FDA) Derived Intervention Levels (DILs) are limits on the concentrations permitted in human food distributed in commerce to prevent consumption of undesirable amounts of radionuclides and apply in the first year after an accident (FDA 1998). The DIL corresponds to the concentration in food present throughout the relevant period of time that, in the absence of any intervention, could lead to an individual receiving a radiation dose equal to the Protective Action Guide (PAG). The PAGs for the ingestion pathway are 0.5 rem committed effective dose equivalent or 5 rem committed dose equivalent to an individual tissue or organ, whichever is most limiting.

FDA (1998) places selected radionuclides into five primary groups, each with common characteristics. These groups are:

- Sr-90
- I-131
- Cs-134 + Cs-137
- Pu-238 + Pu-239 + Am-241
- Ru-103 + Ru-106

The five radionuclide groups are not sufficient to cover accidents at all types of facilities or locations. Appendix E of FDA (1998) presents DILs for 15 additional radionuclides. DILs for tritiated water (HTO) and organically bound tritium (OBT) were derived using methodology consistent with FDA (1998) and are listed in Table 2 (Tharakan 1999).

Table 2. Calculated DILs for HTO and OBT

Radionuclide / Group	DIL (Ci/g)
HTO	5.9E-09
OBT	2.4E-09

ANALYSIS OF THE IMPACTS FROM ACCIDENTS - PARTICULATES AND NON-TRITIUM VOLATILE SPECIES

Inputs needed for calculation of ingestion pathway impacts for particulates and non-tritium vapors are a source term, dispersion/deposition parameters, and environmental transfer factors. In the following discussion, references to particulates should be understood to apply to both particulates and non-tritium vapors.

Source Term Data for Particulates

Source term data will normally be available from authorization basis documents or EPHAs. Caution must be exercised when gathering source term data, since authorization basis documents and EPHAs usually present *respirable* releases, rather than *total* (respirable plus nonrespirable) releases. Division of the respirable source term by the respirable fraction (RF) term will give the total release.

The total release from an accident scenario may involve multiple release points and initiators (fire, spill, debris, etc.). Releases must be evaluated on a nuclide-specific basis, not using Pu equivalent or any similar construct. The source term may be derived to achieve the maximum release or a most likely release depending on the intent of the final calculation.

Specific Pathways and Environmental Transfer Factors for Particulates

The pathways considered for this analysis are only those that involve ingestion of foodstuffs (either liquid or solid). The food groups listed in FDA 1998 (Table D-2) are evaluated, with further breakdown when the transfer factors are available. The food intake values used in the DIL determinations were national (versus regional) values.

The following is a suggested list of dietary components:
    Dairy
    Egg contents
    Meat
        Beef
        Veal
        Sheep
        Lamb
        Pork
        Poultry
    Fish
    Produce – direct deposition
    Produce – root uptake
    Produce – soil adhesion
    Grain – direct deposition
    Grain – root uptake
    Grain – soil adhesion
    Beverage (including water)

Relationship of Contamination Level in Food to Deposition

Environmental transfer factors are used to relate deposition of radionuclides (calculated using atmospheric dispersion computer programs) to concentrations in food (for comparison to DILs set by FDA in its 1998 guidance). The general relationship between the concentration of radionuclide i in a foodstuff ($_iC_{food}$) and deposition ($_iD$) is

$$_iC_{food} = {}_iT \times {}_iD \, ,\tag{1}$$

where $_iC_{food}$ has units of becquerels (Bq) per kilogram (wet weight), radionuclide-specific deposition $_iD$ has units of Bq per square meter, and $_iT$ is an aggregated transfer factor in square meters per kilogram. The aggregated transfer factor $_iT$ is often the product of many individual factors, each describing transfer from one environmental compartment to another. For example, an aggregated transfer factor describes the radionuclide concentration in milk resulting from fresh deposition of radionuclides on the surface of a field. An individual transfer factor in this pathway is one relating the radionuclide intake of a cow to the concentration of that radionuclide in milk.

A small aggregated transfer factor occurs when a relatively small amount of deposited material reaches the foodstuff of concern. A large aggregated transfer factor is associated with radionuclides that transport readily from deposition on the soil to a foodstuff.

References for Food Chain Parameters

The aggregated transfer factor is often calculated by modeling the sequential movement of radionuclides from deposition on the ground to incorporation in the foodstuff (i.e., as the product of individual transfer factors). Parameters may be found in several scientific and regulatory documents. Some parameters are found in Regulatory Guide (RG) 1.109, Rev.1 (NRC 1977). Although RG 1.109 is primarily intended for assessment of routine releases, some values are applicable to acute, accidental releases. An additional source of parameters is Department of Health and Human Services (HHS) Publication FDA 82-8196, Background for Protective Action Recommendations: Accidental Radioactive Contamination of Food and Animal Feeds (Shleien and Chiacchierini 1982) which is contained within EPA (1992). Generic values for parameters have also been published in more recent documents, including Radiological Assessment (Till and Meyer 1983); IAEA Technical Reports Series No. 364, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments (IAEA 1994); and NCRP 123, Screening Models for Releases of Radionuclides to Atmosphere, Surface Water, and Ground (NCRP 1996). Values specific to the Savannah River Site (SRS) for some parameters may be found in WSRC-RP-91-17, Land and Water Use Characteristics in the Vicinity of the Savannah River Site (Hamby 1991), and an associated Health Physics Journal article, Site-Specific Parameter Values for the Nuclear Regulatory Commission's Food Pathway Dose Model (Hamby 1992).

Derivation of Foodstuff-Specific Aggregated Transfer Factors

External contamination of produce from direct deposition

This pathway describes the external contamination of produce from deposition directly onto the edible portions of the plant. Contamination is present on the outer surfaces of the produce. This pathway is applicable to produce that is present in fields at the time the deposition occurs. There will be no contribution to contamination from this pathway for produce planted after plume passage (however, other pathways may be significant).

The relationship between the initial concentration in food $_iC_{produce, direct}$ from direct deposition of radionuclide i ($_iD$) on produce, following an acute release, is

$$_iC_{produce, direct} = (r/Y_v) \times {_iD} \tag{2}$$

No credit is taken for reduction in radionuclide concentration due to weathering.

The interception fraction r corrects for the difference in total amount of material deposited and that which deposits on edible portions of produce. The agricultural productivity, or yield, Y_v is the wet weight of produce growing per unit area. The SRS-specific yield (wet weight) for leafy vegetables, Y_v, is given as 0.7 kg m^{-2} per Hamby (1991), Table 2, page 13. The interception fraction, r, is 0.2 for particulates (RG 1.109 page 1.109-68). These values give an aggregated transfer factor for this pathway of

$$_iT_{produce, direct} = {_iC_{produce, direct}} / {_iD} = r/Y_v = 2.9 \times 10^{-1} \text{ m}^2 \text{ kg}^{-1} \tag{3}$$

This value of the transfer factor is applicable to any particulate radionuclide, since the transfer information conveyed through this term is independent of the environmental contaminant.

Coefficients and aggregated transfer factors are presented in Appendix A for many particulate radionuclides potentially found in postulated source terms from SRS facilities.

Internal contamination of produce from root uptake

This pathway models the root uptake of radionuclides by produce grown in contaminated soil. Radionuclides are drawn out of the soil and incorporated into the edible portions of the plant as it grows.

The soil-to-plant transfer factors, which are expressed as concentration ratios, $_iCR_{soil\ to\ plant,\ dry}$ (Bq per dry weight crop / Bq per dry weight soil) are presented in Table VI of IAEA (1994), pages 17 to 25. The category of mixed green vegetables is chosen. For vegetables, conversion of a concentration ratio based on dry weight to a ratio based on wet weight may be accomplished by dividing the dry weight concentration ratio by a factor of seven (the ratio of wet weight to dry weight), per IAEA (1994), page 26.

An additional step is necessary to convert soil concentration (activity per unit volume) to deposition on soil (activity per unit area). The concentration ratios in Table VI of IAEA (1994) are based on a soil depth of 0.20 m for crops and 0.10 m for pasture, per IAEA (1994), page 16. A default soil density of 1400 kg m^{-3} is used per IAEA (1994), page 29. The product of the soil density and soil depth gives the soil areal density. For crops, this is 280 kg m^{-2}. For comparison, RG 1.109, page 1.109-68, recommends a default soil areal concentration value of 240 kg m^{-2}, consistent with Till and Meyer (1983), page 5-29. This factor is the product of the soil density (1600 kg m^{-3}) and depth of the root zone (0.15 m). A value of 280 kg m^{-2} is used in conjunction with the concentration ratios from Table VI of IAEA (1994).

A deposition of $_iD$ Bq m^{-2} of a radionuclide results in a concentration of $(_iD / 280)$ Bq kg^{-1} in the soil of the root zone. The relationship between the deposition and food concentration due to uptake by leafy vegetables of radionuclide i from the soil is

$$_iC_{\text{soil uptake, produce}} = (_iCR_{\text{soil to plant, dry}}/7) \times (_iD / 280)$$
$$= (_iCR_{\text{soil to plant, dry}}) \times (_iD) / 1960 \qquad (4)$$

By rearranging Equation 1 and substituting, it can be shown that the aggregated transfer factor $(_iT_{\text{soil uptake, produce}})$ that relates deposition $(_iD)$ to the concentration of radionuclide i in leafy vegetables $(_iC_{\text{soil uptake, produce}})$ is

$$_iT_{\text{soil uptake, produce}} = {_iC_{\text{soil uptake, produce}}} / {_iD} = \{_iCR_{\text{soil to plant, dry}}/1960\} \text{ m}^2 \text{ kg}^{-1} \qquad (5)$$

Aggregated transfer factors will vary with soil-to-plant transfer factors $(_iCR_{\text{soil to plant, dry}})$ for different elements or chemical forms.

Coefficients and aggregated transfer factors are presented in Appendix B for many particulate radionuclides potentially found in postulated source terms from SRS facilities.

External contamination of leafy vegetables during harvest

Resuspension and soil adhesion are processes that result in external contamination of the food product during harvest. It may be significant after weathering has reduced the amount of material deposited initially on the plant to negligible levels. An estimate of external contamination of leafy vegetables is 10 grams of soil per kilogram (dry weight) harvested (IAEA (1994), Table VII, page 27). Washing or other processing may reduce this amount. It is necessary to express the soil adhesion fraction in terms of wet weight harvested. This adjustment may be made using the wet-to-dry weight ratio of seven. The relationship between the concentration in food and deposition for this pathway, assuming a soil areal density of 280 kg m^{-2}, is

$$_iC_{\text{adhesion, produce}} = (1 \text{ dry kg}/7 \text{ wet kg}) \times (10 \text{ g soil}/ 1000 \text{ g dry produce} \times (_iD/280) \qquad (6)$$

$$_iC_{\text{adhesion, produce}} = 5.1 \times 10^{-6} \text{ m}^2 \text{ kg}^{-1} \times {_iD} \qquad (7)$$

$$_iT_{\text{adhesion, produce}} = {}_iC_{\text{adhesion, produce}} / {}_iD = 5.1 \times 10^{-6} \text{ m}^2 \text{ kg}^{-1} \tag{8}$$

This value of the transfer factor is applicable to any particulate, since it is independent of radionuclide species.

Soil adhesion and root uptake represent long-term processes that may affect crops over several growing seasons. In contrast, the direct deposition pathway is significant only for crops present during cloud passage.

Coefficients and aggregated transfer factors are presented in Appendix C for many particulate radionuclides potentially found in postulated source terms from SRS facilities.

External contamination of grain

This pathway describes the external contamination of grain from deposition directly onto the edible portions of the plant. Contamination is present on the outer surfaces of the grain. This pathway is applicable to grain that is present in fields at the time the deposition occurs. There will be no contribution to contamination from this pathway for grain planted after the time of direct deposition (however, other pathways may be significant).

The relationship between direct deposition and food contamination (Bq kg^{-1} wet weight) for the consumption of externally contaminated grain may be calculated in a manner similar to that for produce. The crop yield (kg wet weight m^{-2}) and interception fraction are needed. A crop yield value is not given specifically for grain in RG 1.109 or Hamby (1991). Assuming the yield of grain is the same as produce, the yield, Y_v, is given as 0.7 (wet) kg m^{-2} in Hamby (1991), Table 2, page 13. The interception fraction, r, is 0.2 for particulates (RG 1.109, page 1.109-68).

The relationship between the concentration in food and deposition for direct deposition on grain is

$$C_{\text{grain, direct}} = (r / Y_v) \times {}_iD \tag{9}$$

$$= 2.9 \times 10^{-1} \text{ m}^2 \text{ kg}^{-1} \times {}_iD \tag{10}$$

$$_iT_{\text{grain, direct}} = {}_iC_{\text{grain, direct}} / {}_iD = 2.9 \times 10^{-1} \text{ m}^2 \text{ kg}^{-1} \tag{11}$$

This value of the aggregated transfer factor is applicable to any particulate, since it is independent of radionuclide species. This value is the same as for leafy vegetables since interception fractions and yields are the same. The value for the aggregated transfer factor ($T_{\text{grain, direct}}$) is probably very conservative (high) since the edible parts of cereals are often less exposed than the edible parts of leafy vegetables.

Coefficients and aggregated transfer factors are presented in Appendix D for many particulate radionuclides potentially found in postulated source terms from SRS facilities.

Internal contamination of grain by root uptake

This pathway models the root uptake of radionuclides by grain grown in contaminated soil. Radionuclides are drawn out of the soil and incorporated into the edible portions of the plant as it grows.

The soil-to-plant transfer factors $_iCR_{soil\ to\ plant,\ dry}$ (Bq per dry weight crop / Bq per dry weight soil) are presented in Table VI of IAEA (1994), pages 17 to 25. The category "cereals" is chosen for grain. Dry weight contents of cereals are presented in Table V, page 15, of IAEA (1994). The average dry weight content of cereals is about 86%. This value is consistent with the grains class average in Table 5.16, page 5-48, of Till and Meyer (1983). Each dry weight-based transfer factor must be multiplied by the dry weight content, since concentrations in food calculated here are based on wet food weight.

An areal concentration value of 280 kg m^{-2} is assumed.

The relationship between deposition and the concentration in grain due to root uptake of the ith radionuclide from the soil is

$$_iC_{soil\ uptake,\ grain} = (_iCR_{soil\ to\ plant,\ dry} \times 0.86) \times (_iD\ /\ 280) \qquad (12)$$
$$= (_iCR_{soil\ to\ plant,\ dry} \times _iD)\ /\ 326) \qquad (13)$$

The overall transfer factor, for the ith radionuclide, for this pathway is given by

$$_iT_{soil\ uptake,\ grain} = _iCR_{soil\ to\ plant,\ dry}\ /\ 326\ m^2\ kg^{-1} \qquad (14)$$

Coefficients and aggregated transfer factors are presented in Appendix E for many particulate radionuclides potentially found in postulated source terms from SRS facilities.

External contamination of grain during harvest

Resuspension and soil adhesion are processes that result in external contamination of the food product during harvest. It may be significant after weathering has reduced the amount of material deposited initially on the plant to negligible levels. An estimate of external contamination of grain is 4 grams of soil per kilogram (dry weight) harvested (IAEA (1994) Table VII, page 27). Washing or other processing may reduce this amount. It is necessary to express the soil adhesion fraction in terms of wet weight harvested. This adjustment may be made using the dry weight content of 0.86 dry weight/wet weight. The relationship between the concentration in food and deposition for this pathway, assuming a soil areal density of 280 kg m^{-2}, is

$$_iC_{adhesion,\ grain} = [(0.86\ dry/wet)(4\ g\ soil\ /\ 1000\ g\ dry\ grain)] \times _iD\ /\ 280\ kg\ m^{-2} \qquad (15)$$

$$= 1.2 \times 10^{-5}\ m^2\ kg^{-1} \times _iD \qquad (16)$$

$$_iT_{adhesion,\ grain} = _iC_{adhesion,\ grain}\ /\ _iD = 1.2 \times 10^{-5}\ m^2\ kg^{-1} \qquad (17)$$

This value of the aggregated transfer factor is applicable to any particulate, since it is independent of radionuclide species.

Coefficients and aggregated transfer factors are presented in Appendix F for many particulate radionuclides potentially found in postulated source terms from SRS facilities.

Contamination of dairy products

The milk pathway is assumed to characterize pathways for all dairy products. This pathway describes the concentration in milk resulting from fresh deposition. Different calculations are necessary to describe long-term effects, since the concentrations of radionuclides associated with forage are expected to decrease as time after deposition increases.

The milk pathway is described by a two-step process. Deposition contaminates forage, then the forage is consumed by cows and contaminated milk is produced. The amount of external contamination on forage due to direct deposition of radionuclide i is

$$_iC_{\text{forage, direct}} = (r/Y_v) \times {_iD} \tag{18}$$

The fraction of deposition initially retained on pasture grass, r, is 0.2 for chronic releases (RG 1.109, page 1.109-68). A deposition fraction of 0.5 is given on page 13 of Shleien and Chiacchierini (1982), and is adopted as the value for pasture following an acute release of particulates in the following calculation. The SRS-specific agricultural productivity per unit area (measured in wet weight) (Y_v) for the grass-cow-milk pathway is 1.8 kg m^{-2} (Hamby 1991). This is somewhat greater than the generic value for agricultural productivity for this pathway of 0.7 kg m^{-2} (RG 1.109, page 1.109-69). The SRS-specific value is used in the following calculations.

Equation C-10 of RG 1.109, page 1.109-27, provides a means to estimate the radionuclide concentration in milk ($_iC^m$) if the contamination level of feed is known:

$$_iC^m = {_iF^m} \times {_iC^v} \times Q_F \times \exp(-\lambda_i \times t_f) \tag{19}$$

where,

> $_iF^m$ is the average fraction of a cow's daily intake of radionuclide i that appears in each liter of milk. $_iF^m$ has units of Bq L^{-1} of milk per Bq day^{-1} consumed by the cow, or d L^{-1}.

> $_iC^v$ is the concentration of radionuclide i in the cow's feed, with units of Bq kg^{-1} (wet weight). Feed may be either pasture grass (contaminated forage) or stored feed (assumed uncontaminated). $_iC^v$ is set equal to $_iC_{\text{forage, direct}}$ for contaminated forage.

> Q_F is the amount of contaminated feed consumed by the cow per day. It should be expressed in terms of wet weight, since the contamination level of forage is also in wet weight. The total consumption rate (wet weight per day) of forage consumed by a dairy

cow is 52 kg d^{-1} (Hamby 1991). The SRS-specific fraction of intake from pasture is 0.56 (Hamby 1991). The product of these factors results in a daily consumption rate of contaminated forage (Q_F) of 29.12 kg d^{-1}.

λ_i is the radiological decay constant for the ith radionuclide in units of days^{-1}.

t_f, the time to market, is a time factor that combines the time required to get activity from the feed into the milk and the milk to the receptor.

Equation 19 is for chronic intake by the cow and represents an upper bound to the acute case if deposition levels immediately after the accident are used to calculate contamination on forage. Contamination levels would be expected to decrease over time due to weathering, resulting in lower concentrations of radionuclides in milk following the initial peak.

The argument of the exponential factor is the product of the decay constant for radionuclide i and the time to market (t_f). The decay constants for radionuclides of concern are very small. Time to market is usually taken as 2 days (RG 1.109, page 1.109-27). The product of the decay constant and time to market is about 0, resulting in the exponential term having a value of about one. For long-lived radionuclides, the exponential term can be set equal to unity.

The simplified equation is now

$$_iC^m = \,_iF^m \times \,_iC_{forage,\ direct} \times Q_F \tag{20}$$

Substituting in the expression for $_iC_{forage,\ direct}$ from Equation 18 into Equation 20 gives

$$_iC^m = \,_iF^m \times (r\,/Y_v) \times \,_iD \times Q_F \tag{21}$$

The aggregated transfer factor $_iT^m$ for the milk pathway from direct deposition of the ith radionuclide is therefore

$$_iT^m = \,_iC^m\,/\,_iD = \,_iF^m \times (r\,/Y_v) \times Q_F \tag{22}$$

Since milk has a density of 1 kg L^{-1}, the aggregated transfer factor is numerically equivalent whether expressed in units of m^2 L^{-1} or m^2 kg^{-1}.

Coefficients and aggregated transfer factors are presented in Appendix G for many particulate radionuclides potentially found in postulated source terms from SRS facilities.

Contamination of egg contents

Chicken eggs may become contaminated due to hens consuming radionuclides in feed. Since only the egg contents are consumed, radionuclides in the shell are not included.

The relationship between the concentration of long-lived radionuclide i in egg contents in Bq kg^{-1} ($_iC^e$), and the amount of contaminated feed consumed per day is similar to the relationship for contaminated forage and level of radionuclides in milk:

$$_iC^e = {_iF^e} \times {_iC^v} \times Q_F \qquad\qquad (23)$$

$_iF^e$ is the average fraction of a laying hen's daily intake of radionuclide i that appears in each kilogram of egg contents. $_iF^e$ has units of Bq kg^{-1} of egg contents per Bq day^{-1} consumed by the laying hen, or d kg^{-1}.

$_iC^v$ is the concentration of radionuclide i in the laying hen's feed, with units of Bq kg^{-1} (wet weight). The typical feedstuffs are cereals and protein feed (IAEA (1994), Table X, page 32). If the entire diet is assumed to consist of grain contaminated by fresh deposition, the parameters from the section on externally contaminated grain may be used. The conservative assumption is made that all of the laying hens' feed is from contaminated grain. $_iC^v$ is set equal to $_iC_{grain, direct}$.

The concentration of radionuclide i resulting from direct deposition onto grain is

$$_iC_{grain, direct} = (r / Y_v) \times {_iD} \qquad\qquad (24)$$

Q_F is the amount of feed consumed by the hen per day. It should be expressed in terms of wet weight, since the contamination level of grain is also in wet weight. Laying hens have a consumption rate of dry matter of 0.1 kg d^{-1} (IAEA (1994) Table XI, page 33). Dry weight contents of cereals (assumed to be representative of grain) are presented in IAEA (1994), Table V, page 15. The average dry weight content of cereals is about 86%, so the wet consumption rate is (0.1 kg d^{-1} / 0.86) = 0.116 kg d^{-1}.

The relationship between the concentration in eggs and deposition may be estimated by combining Equation 23 and Equation 24.

$$_iC^e = {_iF^e} \times {_iC_{grain, direct}} \times Q_F \qquad\qquad (25)$$

$$= {_iF^e} \times r / Y_v \times {_iD} \times Q_F \qquad\qquad (26)$$

The aggregated transfer factor for nuclide i is

$$_iT^e = {_iC^e} / D_i = {_iF^e} \times (r / Y_v) \times Q_F \qquad\qquad (27)$$

A yield (wet) of 0.7 kg m^{-2} and an interception fraction r of 0.2 are assumed.

Coefficients and aggregated transfer factors are presented in Appendix H for many particulate radionuclides potentially found in postulated source terms from SRS facilities.

Contamination of meat

This pathway describes the level of contamination in meat due to consumption of forage contaminated by fresh deposition. Contamination levels in meat should decrease over time as the contamination level in forage decreases. Meats considered are beef, veal, sheep, lamb, pork, and poultry.

The concentration of radionuclides in meat ($_iC^F$) is dependent on the consumption rate of forage by the animal and the contamination level of the forage. Equation C-12 of RG 1.109, page 1.109-28, is

$$_iC^F = {}_iF^f \times {}_iC^v \times Q_F \times \exp(-\lambda_i \times t_s) \tag{28}$$

As in the analysis for the milk pathway, the exponential term may be set equal to unity for long-lived radionuclides (t_s, the time to slaughter, is 20 days; λ_i is very close to zero for long-lived radionuclides; the product of the two terms is essentially zero). The simplified equation is

$$_iC^F = {}_iF^f \times {}_iC^v \times Q_F \tag{29}$$

where,

> $_iF^f$ is the fraction of daily intake by the animal of radionuclide i that appears in the edible flesh. It has units of Bq kg^{-1} of meat per Bq d^{-1} consumed by the animal, or d kg^{-1}. It varies by radionuclide and animal. Expected values may be found in IAEA (1994), Tables XV to XVIII, pages 37-39.

> Q_F is the amount of contaminated forage consumed by the animal per day. It should be expressed in terms of wet weight, since the contamination level of forage is also in wet weight. The site-specific total wet forage consumption rate for beef is 36 kg d^{-1} (Hamby 1991). As with the milk pathway, the total forage consumption rate is assumed to consist of contaminated pasture grass and uncontaminated other feed. The SRS-specific value for the fraction of intake from pasture for beef is 0.75 (Hamby 1991). The product of the total consumption rate and the fraction of intake from pasture gives a contaminated forage consumption rate of 27 kg d^{-1}, and is presented in Table 3. The quantities (dry weight) of forage consumed by other animals are also presented in Table 3, and are values from IAEA (1994), Table XI, page 33. Wet forage consumption rates are 4.5 times the dry consumption rates per Table 5.16, page 5-48 of Till and Meyer (1983). For meat pathways other than beef, all forage consumed by the animal is assumed to be contaminated.

> $_iC^v$ is the concentration of radionuclide i in the animal's feed, with units of Bq kg^{-1} (wet weight). Feed is assumed to be forage contaminated by direct deposition.

Table 3: Forage consumption rates

Meat	Contaminated forage consumption rate, dry kg d^{-1}	Contaminated forage consumption rate, wet kg d^{-1}
Beef	-	27
Veal	1.9	8.6
Sheep	1.3	5.9
Lamb	1.1	5.0
Pork	2.4	11
Poultry	0.07	0.32

The equation relating concentration of radionuclide i in forage ($_iC_{\text{forage, direct}}$) to the amount of radionuclide i deposited on the ground ($_iD$) is

$$_iC^v = {}_iC_{\text{forage, direct}} = (r/Y_v) \times {}_iD \tag{30}$$

Substituting the expression for $_iC_{\text{forage, direct}}$ in Equation 30 for $_iC^v$ in Equation 29 gives

$$_iC^F = {}_iF^f \times (r/Y_v) \times {}_iD \times Q_F \tag{31}$$

The aggregated transfer factors for the meat pathways are

$$_iT^F = {}_iC^F / {}_iD = {}_iF^f \times (r/Y_v) \times Q_F \tag{32}$$

The agricultural production rate Y_v is measured in wet weight. An SRS-specific value of 1.8 kg m^{-2} (wet weight of pasture grass per unit area) is chosen for meat calculations (Hamby 1991). An interception fraction r for pasture of 0.5 is assumed as in the dairy pathway calculation.

Coefficients and aggregated transfer factors are presented in Appendices I to N for many particulate radionuclides potentially found in postulated source terms from SRS facilities. The transfer factors consider only the intake from direct deposition, and do not account for added intake from soil adhesion. Additional discussion can be found on page 33 of IAEA (1994).

Contamination of beverages

Drinking water is assumed to be representative of the beverage pathway.

The concentration in water is conservatively calculated by diluting instantaneously deposited activity throughout the depth of water. For insoluble contaminants, this will usually be a very conservative assumption, since particulates are expected to settle into the sediments. For a water depth (d) of 1.0 meter and density ρ_w of 1.0×10^3 kg m^{-3}, the activity of radionuclide i per unit mass of water ($_iC_w$) from a deposition ($_iD$) is

$$_iC_w = {_iD} / (\rho_w \times d) \tag{33}$$

$$_iC_w = {_iD} / (1.0 \times 10^3 \text{ kg m}^{-3} \times 1.0 \text{ m}) \tag{34}$$

Where $_iC_w$ is in Bq kg^{-1} and $_iD$ is in Bq m^{-2}. The transfer factor relating concentration in water ($_iC_w$) to deposition ($_iD$) is

$$_iT_{water} = {_iC_w} / {_iD} = \rho_w \times d \tag{35}$$

$$= 1.0 \times 10^{-3} \text{ m}^2 \text{ kg}^{-1}. \tag{36}$$

The value 1.0×10^{-3} m^2 kg^{-1} should be considered a conservative upper bound on the aggregated transfer factor for drinking water. Sedimentation and other processes will reduce the activity in water. If deposition occurs on flowing bodies of water, the period of exposure will be small.

The value of this aggregated transfer factor is applicable to any particulate, since it is independent of radionuclide species. Additional modifications may be made if the solubility of the particulate is known.

Coefficients and aggregated transfer factors are presented in Appendix O for many particulate radionuclides potentially found in postulated source terms from SRS facilities.

Contamination of fish

Acute uptake in fish will be bounded by the chronic uptake. This calculation assumes fish are continuously exposed to the initial level of deposited radionuclides in water. This would occur only in stagnant bodies of water, with no settling of radionuclides into sediment. In flowing bodies of water (such as the Savannah River), waterborne concentration at a particular location would decrease rapidly over time after the initial deposition, and concentrations of radionuclides in fish would be expected to be much lower than for fish chronically exposed in stagnant bodies of water.

Given $_iC_w$ from the calculation for drinking water, the concentration in fish is

$$_iC_{fish} = B_p \times {_iC_w} , \tag{37}$$

Where B_p is a concentration factor for edible portions of fish with an expectation value (Bq kg^{-1} wet weight per Bq L^{-1} of water) given in IAEA (1994), Table XXII, page 45). The relationship between deposition and water concentration is given in Equation 34. Combining Equation 34 and Equation 37 gives

$$_iC_{fish} = B_p \times {_iC_w} = B_p \times {_iD} / (1.0 \times 10^3 \text{ kg m}^{-3} \times 1.0 \text{ m}) \tag{38}$$

The aggregated transfer factor is

$$_iT_{fish} = {}_iC_{fish} / {}_iD = B_p / (1.0 \times 10^3 \text{ kg m}^{-3} \times 1.0 \text{ m}) \tag{39}$$

This value is probably too high by a factor of at least ten for many insoluble transuranic compounds that are encountered at SRS. A typical rule of thumb is that only a few percent of the deposited plutonium is available in the water; the rest is bound in the sediments. Additionally, it takes time for concentrations of radionuclides in fish to come to equilibrium.

Coefficients and aggregated transfer factors are presented in Appendix P for many particulate radionuclides potentially found in postulated source terms from SRS facilities.

Derived Response Levels

Derived response levels may be calculated once the mix of the total deposition (as opposed to just the deposition associated with the respirable fraction), transfer factors, and DILs are known. A unit deposition of the mix is assumed, and the resulting concentrations of radionuclides determined in foodstuffs. Division of the DILs by foodstuff concentrations that correspond to the unit deposition gives the DRLs in terms of the activity of the mix deposited per unit area. Once the DRLs are known, a suitable dispersion model is run with the DRLs set as deposition values of interest.

Particulate Dispersion and Deposition Model Description

For particulate releases, a Gaussian-based dispersion model, capable of calculating deposition from an acute release, should be adequate. Since minimizing code complexity should maximize clarity and economy, the HOTSPOT computer program (Homann 1994) is used to perform dispersion and deposition calculations for non-tritium releases. HOTSPOT incorporates a straight-line Gaussian plume model. Deposition values (DRLs) resulting in concentrations in food equal to FDA DILs may be calculated in a spreadsheet format. Deposition isopleths at which FDA DILs are exceeded may then be determined using HOTSPOT.

The meteorology parameters are chosen so that they are consistent with the Emergency Preparedness Hazards Assessment (EPHA) guidance (WSRC 1999). Adverse (95th percentile) and average meteorology cases should be run. Adverse meteorology provides an indication of maximum impacts, while average meteorology provides a more typical perspective.

Meteorological parameters are presented in Table 4.

Table 4. Meteorological Input Parameters for Particulates for Average and Adverse Conditions

Parameter	Average Met.	Adverse Met.
Wind Speed Height	10 m	10 m
Stability Class	C	E
Wind Speed	2.5 m/s	1.7 m/s
Inversion Layer	500 m	300 m

The 300-meter inversion layer height for adverse meteorological conditions is derived from Holzworth (1972). An inversion layer height of 200 meters has been used until recently and is in the current EPHA guidance (WSRC 1999); however, this guidance is under revision.

A surface roughness of 100 cm is used to model the forested terrain surrounding SRS. Deposition values of 0.1 cm/s, 1 cm/s, and 10 cm/s are typically used.

The source geometry should be selected as appropriate for the scenario. A 3 meter by 3 meter cross-sectional area is the standard source geometry used in EPHAs (WSRC 1999).

Contour levels corresponding to DRLs are entered in the general plume routine of HOTSPOT and deposition plots produced.

An example calculation is included in Appendix Q.

Summary for Particulates

The process used to evaluate accidental releases on the ingestion pathway is outlined below.

1. Determine the source terms (radionuclide-specific and total airborne releases).

2. Calculate the concentrations of each radionuclide in foodstuffs for a unit deposition of the total (as opposed to respirable) particulate mix.

3. For radionuclides with FDA (1998) Derived Intervention Levels (DILs), divide the DIL by the foodstuff concentration from a unit deposition. The Derived Response Level, or DRL, is the deposition that gives a DIL for a specific nuclide (group) and pathway.

4. Once DRLs are determined, ranges and areas affected are predicted with the dispersion/deposition model HOTSPOT.

Procedure for Other Radionuclides

If a source term is encountered includes significant amounts of non-tritium[1] radionuclides not specifically discussed or included in the Appendices A through P, the process to handle them is similar to that outlined above. First, determine whether an FDA DIL exists for the radionuclide by reviewing the radionuclides included in Tables 2 and E-6 of the FDA guidance document (1998). If the radionuclide is included there, use the given DIL. If a DIL for the radionuclide being considered is not included in FDA (1998), it can be developed using the method outlined in Appendix D of that document. From that point, the evaluation should follow the procedure as outlined herein.

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[1] The special case of tritium is addressed in the next section.

IMPACT ANALYSIS FOR TRITIUM

For tritium releases, a dispersion and environmental transfer code that can model the incorporation of tritium into the food chain from an acute release is desirable. Tritiated water has a much greater mobility in the environment than most radionuclides. Due to this mobility, assessment of tritium releases is best done with a tritium-specific model.

Source Term

In this following discussion, tritium in its oxide form (HTO, DTO, and T_2O), unless otherwise specified, is HTO. Likewise, tritium in its elemental form (HT, DT, and T_2) is HT. The chemical and physical behaviors of these isotopic species are similar, so differences in movement through the environment are not appreciable.

Tritium releases will usually be in gaseous (HT) or tritiated water vapor (HTO) form. The organically bound form of tritium is not present in any significant quantity in a source term, but may chemically transition to that form within vegetation following a release as tritium is incorporated into the food chain.

Environmental Modeling of Tritium Releases

Because of the large amounts of tritium at SRS and the mobility of tritium through the food chain, a tritium-specific model is used. The computer model UFOTRI is used for assessment of tritium releases [Raskob 1990, 1993]. UFOTRI was developed at the German Karlsruhe Laboratory to assess the radiological consequences of accidental atmospheric tritium releases. UFOTRI examines tritium specific processes such as the conversion of tritium gas (HT) into tritiated water (HTO), re-emission after deposition, and conversion of HTO into organically bound tritium (OBT) [O'Kula et al. 1998]. UFOTRI calculates inhalation/skin absorption doses from plume passage and couples the short-term atmospheric dispersion model with a first order compartment module that dynamically describes the long-term behavior of tritium in the food chains. Concentrations of tritium in foodstuffs after plume passage can be compared to FDA DILs. The higher degree of pathway model complexity available in computer models such as UFOTRI is needed to assess the effects of an acute release of tritium to the environment. The underlying dispersion model is Gaussian, consistent with regulatory recommendations.

Four food groups modeled in UFOTRI are of interest for ingestion dose assessment. These are vegetables, wheat grain, meat, and milk. Tritium concentrations in these food groups are calculated as a function of time. The concentration in a foodstuff may be the result of uptake from multiple pathways. For example, the concentration of tritium in vegetables may be the result of absorption of tritium from the atmosphere (during plume passage) and uptake of tritium from the soil through the plant's root system. Re-emission from the plant and conversion of HTO into OBT are modeled.

Input Parameters

In the discussion which follows, a brief summary covering various input parameters is given, then more detail, along with examples, is presented.

As with particulates, adverse (95th percentile) and average meteorology should be run. Adverse meteorology provides an indication of maximum impacts, while average meteorology provides a more typical perspective.

The basic meteorological parameters are summarized in Table 5.

**Table 5. Meteorological Input Parameters for Tritium Facilities
for Average and Adverse Conditions**

Parameter	Average Met.	Adverse Met.
Wind Speed Height	10 m	10 m
Stability Class	C	E
Wind Speed	2.5 m/s	1.7 m/s
Inversion Layer	500 m	200 m
Temperature	25°C	29°C

From WSRC-TR-99-00118 (Marx 1999b)

The release height is scenario dependent.

The chemical form of tritium when released can be HT, HTO, or a mixture of the two, depending on the particular accident scenario. As noted earlier, OBT may be present after tritium is absorbed and incorporated into organic matter.

Additional input parameters are summarized in Table 6.

Table 6. Additional Input Parameters for UFOTRI

Source Term Information		Meteorology	
Chemical Forms*		No Rainfall	0 mm/h
(0-100)% HT / (0-100) 100% HTO		Wind direction (in degrees)	Arbitrary
No building wake effect model assumed for IPZ modeling		Dispersion parameters	Briggs
Thermal energy of release 0 cal/sec		Relative humidity	0.8
Soil and vegetation		**Code coefficients**	
Soil type	Sandy loam	HTO dry deposition velocity**	0.5 cm/s
Initial soil water content	35%	HT dry deposition velocity**	0.05 cm/s
Pore volume (default)	50 %		

*   Varies depending on scenario
**   Deposition is calculated in UFOTRI without user-specified constants; values are place holders.

O'Kula et al. (1998) provides a detailed explanation of the UFOTRI model along with SRS-specific parameters. Because that document is concerned with the plume exposure pathway, the ingestion pathway is not analyzed. A description of input data and assumptions for ingestion pathway analysis follows.

The UFOTRI model uses one input file for site geometry, source term, meteorological conditions, environmental characteristics, radiological parameters, and output formats. In the following, a short description of a block of input is provided, followed by example input (**boldface** and indented). Examples are taken from Marx (1999b, WSRC-TR-99-00118), with several modifications.

Site geometry and gridding

1. UFOTRI allows a maximum of 20 radial distances and 72 angular segments. For the ingestion pathway application, an appropriate number of radial bands are used with the maximum number of sectors. In the example, 13 radial rings and 72 angular segments (5° of arc each) are used. The large number of geometry elements results in each geometry element being approximately square. This is important for the area source model for reemission of tritium after plume passage. The user must specify the radial distance endpoints (RA array) and representative internal points (R array). For ingestion pathway calculations, a receptor should be located at the site boundary (11,540 meters for the H-Area example). Additional receptors should be located to help define the range and shape of the impacted area. In the example, receptors are located at 150 m, 500 m, 1,000 m, 3,500 m, 5,000 m, 7,500 m, 10,000 m, 10,800 m, 11,540 m, 30,000 m, 50,000 m, 75,000 m, and 100,000 m.

    IMAX=13,JMAX=72,
    R= 150., 500., 1000., 3500., 5000., 7500., 10000., 10800.,
    11540., 30000., 50000., 75000., 100000.
    RA= 350., 990., 1010., 4950., 5050., 9900., 10100., 11500.,
    11600., 49900., 50100., 99900., 100100.
    &END

2. The population in each geometry element must be specified although population doses are not desired in this calculation. The identification number of the site according to the population data file is "00", and is named "HOMOGEN". The population distribution is defined by distance bands out to and including band "IEIN", and uniform outside (NSTOPT=2). The probability of the HOMOGEN site is 1.0 since it is the only site. The uniform population density outside of band "IEIN" is 56.9 persons/km^2. IEIN is set equal to the 8th band. The population is input for each angular segment, one ("North") through seventy-two in clockwise iterations, providing close-in data first, followed by increasingly more distant radial distances. For foodstuff concentration applications, the population numbers are placeholder values, since the code requires this information to execute.

    00HOMOGEN   2 1.00E- 0
    5.69E+01   8
      0   0   0   0   0   0   0   0
      0   0   0   0   0   0   0   0
      0   0   0   0   0   0   0   0
      .
      .
      .
    (total of 72 angular segments)

Source term

3. Two tritium chemical species can be modeled in UFOTRI, tritium gas (HT, DT, and T$_2$) and tritiated water vapor (HTO, DTO, and T$_2$O). These are specified with default deposition velocities (VA array), whether a simple deposition or a more detailed biophysics model is invoked by the user. The more detailed biophysics model is used for ingestion pathway calculations, so the values in the VA array are placeholders. The order used in the UFOTRI code is tritium gas (1) and tritiated water vapor (2).

        ISOTOPE
        &ISOPAR
        NABL=2,
        VA=5.E-4, 0.005

4. The source term for the ingestion pathway example is "BDBAVG", there is one release phase, and a one-hour shift of the beginning of the weather sequences to the chosen start times (this has no effect with constant meteorology). The time between the end of the nuclear process and the start of each release phase is zero [IPHASE(1)=0]. The release height is from a 60 meter stack [IHO(1)=60] for this example (other scenarios may have a ground level release). There is no sensible heat in the release [QH(1)=0.0]. No building wake effects are considered in this analysis, therefore the building width and height are each set to 1 meter [(BR(1)=HOE(1)=1.000E0].

        SOURCE
        BDBAVG   1   1   0
          0   60   0.000E0   1.000E0   1.000E0

5. The source term is specified in one release phase, 100% HTO [Q(2,1)=1.0], and 0% HT [Q(1,1)=0.0]. The total activity released is 3.7×10^{15} Bq (10^5 Ci) in the example cited here.

        Q(2,1)=1.0,Q(1,1)=0.0,Q1=3.7E15

Meteorological conditions

6. Precalculated washout coefficients and precipitation rates (IWASH=0) would be used if rainfall occurs. (Precipitation is turned off by setting the rainfall rate to zero in Step 8 below).

        IWASH=0

7. The meteorological "zone" is "SRSHTOST". Since constant meteorology has been specified, there is only one sequence sampled (LMAX=1). There is only one meteorological site considered (NSTMAX=1). A uniform probability distribution (LPOPT=0) is specified since meteorology is constant. A file is used to specify the start time of each sequence (LWOPT=1), although in this example with constant meteorology the start time of 4332 hours is a placeholder. The index of surface roughness for the choice of dispersion parameters is for "mean roughness length", $10 \text{ cm} < z \leq 1\text{m}$, applicable to rural areas with low plants (IRAU=2). IPZ sensitivity studies may also run cases with IRAU=3, corresponding to the "great roughness length", $z > 1\text{m}$. For SRS, this selection would be useful to characterize forested areas. The windspeed height for the input data is 10 m (IHOM=10). The time between sequences (IBEWE=0) is irrelevant here since there is only one sequence.

        METEOZON
        SRSHTOST   1   1   0   1   2   10   0
          4332

8. Constant meteorology is used (METIN=1). Parameters are generally consistent with guidance for performing Emergency Preparedness Hazards Assessments (TP-95-002 rev. 3) for the plume exposure pathway. In the example, a wind direction from the northwest (IWNDR=315), a windspeed of 2.5 m/s (IWNDG=250), and no rainfall (IREGN=0) are specified. The variable IDIKAT sets the stability class (A=1, B=2, C=3, D=4, E=5, F=6), which is "C" for average meteorological conditions at SRS.

        METEOROL
        &METPAR
         METIN=1,IWNDR=315,IWNDG=250,IREGN=0,IDIKAT=3

9. The parameter KLUGSI=2 specifies that the Briggs dispersion parameterization will be used, Associated parameters scale the Briggs duration time and surface roughness assumptions. A 10-

minute sampling time (RELTA=10.) and 10-cm surface roughness (RELRA=10) are the bases for the Briggs data. Corresponding values for the scenario used for the example are a 60-minute release duration (RELTN=60.) and 100-cm surface roughness (RELRN=100.).
Other parameter sets are available.

> **KLUGSI=2, IRELTS=1 RELTA=10., RELTN=60., RELTP=0.20,**
> **IRELRS=1, RELRA=10., RELRN=100.**

10. In the example, the default value of the windshift option is used (NOSHFT=2) indicating that for each release phase hourly changes in the wind direction may be considered. For the example, the value is irrelevant since meteorology is constant. The mixing layer height is input as a function of stability class, and is in order of A through F (1600 m, 1200 m, 500m, 400 m, 300 m, and 150 m). The wind profile exponents are SRS-specific (WPE=0.08,0.10,0.11,0.18,0.31,0.42).

> **NOSHFT=2,MIXLH=1600,1200,500,400,300,150,**
> **WPE=0.08, 0.10, 0.11, 0.18, 0.31, 0.42**
> **&END**

As indicated in the discussion on particulate dispersion, a mixing layer height of 300 meters is appropriate to use for SRS (Holzworth 1972) and should be used for future adverse meteorology (E stability) consequence calculations.

Environmental characteristics

11. The environmental model is based on the one-year meteorological dataset available (NJAHRE=1). The growing season is essentially the full year (day one=1 to day end=365). A second year under the same assumption is required input, although the code recognizes that the available basis file is one year in length.

> **&TRIDAT**
> **NJAHRE=1,**
> **LT1=1,LT2=365,LT3=366,LT4=730**

12. The minimum duration of the re-emission process is set at the default of 70 hours (NSTOP=70.). The reemission algorithm stops after two requirements have been met: re-emission has been occurring for at least NSTOP hours, and the amount of activity in the soil has been reduced to at least one-third of the tritium content after the tritium routine had started. The UFOTRI recommended value is used for BODFAK (=100.). This parameter determines the minimum source strength of a secondary area source of HTO from the soil and the vegetation, which will be considered in the reemission dispersion part of the analysis. The minimal source strength is calculated as equal to [maximal soil concentration] × BODFAK.

> **NSTOP=70,BODFAK=1.E+2**

13. The reemission rate during rain events is set at the default value of 0.3 (% per hour). The IZFREI parameter is the duration of the primary plume in seconds (IZFREI=1800 in this example). Next, IFLENG specifies the area source geometry for the reemission algorithm; the normal area source with fourteen points is specified (IFLENG=0). The IRFIX parameter indicates that UFOTRI will specify the reemission rate as the default recommendation (IRFIX=0). REFEST is the accompanying fixed reemission rate (=5.0), but this is not used if IRFIX=0. ITEMPE (in units of 0.01° C) is the environmental temperature (30° C) if a persistent meteorological condition is specified. Similarly, ISTRBE is the fixed value for the radiation balance if a persistent meteorological condition is requested (METIN=1), and is set to the default value of 100 Watts. Water stress will occur in vegetation if the solar radiation has a value greater than ISTGR (dimension is Watts/m^2 x 0.357 x 0.8). The default value of 200 joules/cm^2 corresponds to water stress at 700 Watts/m^2.

    REMRE=0.3,IZFREI=1800,IFLENG=0,
    IRFIX=0,REFEST=5.0,ITEMPE=3000,ISTRBE=100,ISTRGR=200

14. The roughness length is set at 10 cm (ARAU=0.1), and the assumed water fraction in the soil is 35% (based on SRS conditions). A roughness length of 10 cm corresponds to open country with few trees or bushes; a roughness length of 100 cm corresponds to dense forests and small towns. In contrast to plume exposure calculations that use a roughness length of 100 cm, ingestion pathway calculations use a roughness length of 10 cm, since 10 cm more closely matches areas where food and feed are grown.

    ARAU=0.1,BODEIN=0.35

15. Hard-wired models for food ingestion are present in UFOTRI. For example, NCOW, WWCOW, and WOCOW are the number of cows grazing per square kilometer, the mass content of the inorganic part (kg per cow) and mass content of the organic fraction of a cow (kg per cow). The default values are used in the example. The time checkpoints (in days) for removing food restrictions are the TIMEDO values. They are not used for calculation of radionuclide concentrations in food.

    NCOW=250,
    WWCOW=350.,WOCOW=150.
    TIMEDO=0.,3.,7.,14.,21.,30.,90.,180.,200.,365., 370., 3650.

16. UFOTRI employs an areal density for soil type and vegetation coverage. Thus, the SRS Site application must identify estimates that account for characteristics of the site on a regional basis, while minimizing unneeded UFOTRI models and food ingestion assumptions. Observing these limitations, the fraction of area assigned to various crops or vegetation must be specified. The sum of the fractions must equal one. The fraction of the area reserved for agricultural production and vegetation is assumed to be 0.5 (FAKC1=0.5). In the example, fractional areas for grazing animals (FAKC2), potatoes (FAKCP), and wheat (FAKCW) are set at 0.35, 0.05, and 0.1, respectively.

    FAKC1=0.5,FAKC2=0.35,FAKCP=0.05,FAKCW=0.1

17. The vegetation characteristics for vegetables in terms of input to UFOTRI must be estimated. The **minimum stomata diffusion resistance** (RCMIN=2.) of the canopy for the type 1 vegetation (taken as vegetables in this example) is based on the UFOTRI User's Manual.

18. A second quantity needed is the **leaf area index**. This parameter provides the vegetation coverage area (m^2) per unit area of land. The value LEAF=3.0 is based on the UFOTRI User's Manual.

19. The final two inputs are the **mass of vegetation water in vegetation type 1** and the **mass content of the organic parts of the plant**. Both parameters are in units of g/m^2. The values BEWG=1440. and BEWGZ=160 are default values from UFOTRI.

The sets of input for the other three vegetation types are default values from UFOTRI. Site-specific values should be used if available.

Table 7. Key Input Values for Four Vegetation Types in UFOTRI

Vegetation Type	RCMIN (s/cm)	Leaf area index, L_A (m^2/m^2)	Vegetation Mass in Water per unit ground area (g/m^2)	Organic Vegetation Mass per unit ground area (g/m^2)
1. Vegetables	2.	3.	1440.	160.
2. Grass	2.	3.	680.	170.
3. Potatoes	2.	4.7	2700	300.
4. Wheat	2.	7.	2000	500.

> **RCMIN=2.,LEAF=3.,BEWG=1440.,BEWGZ=160,**
> **RCMIN2=2.,LEAF2=3.,BEWG2=680.,BEWGZ2=170.,**
> **RCMINP=2.,LEAFP=4.7,BEWGP=2700.,BEWGZP=300.,**
> **RCMINW=2.,LEAFW=7.,BEWGW=2000.,BEWGZW=500.**

20. A list of consumption rates for various foodstuffs is next in the environmental input. These are potato, wheat, milk, vegetables, and meat consumption rates in grams per day.

> **IPOT=233,IWHEAT=261,IMILK=315,IVEGE=124,IMEAT=206**

21. A final set of information must be specified to control the biophysics models used in the calculation. The plant resistance model is the extended model that considers radiation balance, air temperature, air humidity water content of soil, water stress from high solar radiation (IMODEL=1). The soil option used that best characterizes the area around SRS is loamy sand (IARTBO=2) (O'Kula 1998 and WSRC 1993). The default wilting point value is used, at which stomata closure occurs (WILTP=0.1). The default value for fraction of the maximum free pore volume of soil is used (SOILMX=0.5). Next, the extended model (IBODEX=1) is used for the transport of water in soil. The extended model accounts for suction tension and soil conductivity.

> **IMODEL=1,IARTBO=2,WILTP=0.1,SOILMX=0.5,IBODEX=1**

22. The Monteith resistance approach is applied (IMONT=1) for calculating the evaporation-transpiration. It is assumed that irrigation of agricultural and grassy areas is not performed (IRRIGA=IRRIGG=0). The full resistance model for HTO deposition to soil is invoked (IFLAGS=1) in conjunction with the soil resistance model (IFLAGR=1). Similarly, the resistance model is used for HT deposition to soil (IDEPHT=1) rather than the predefined deposition velocity.

> **IMONT=1,IRRIGA=0,IRRIGG=0,IFLAGS=1,IFLAGR=1,IDEPHT=1**

23. The initial water content is assumed to be the BODEIN value (35%), equal in all three layers (IBODFX=0). The ICOVER parameter indicates the choice of model for calculating the actual plant stage, and setting ICOVER equal to 1 specifies replacing the initial values by the calculated ones. The day of release is set to the default of Day 181 (IRELIN=181). IPHOTO=1 calculates the photosynthesis rate which is associated with the hourly HTO transfer rates into OBT. Finally, IARIV = 0 indicates that the plume arrival and footprint as a function of travel time is not requested.

> **IBODFX=0,ICOVER=1,IRELIN=181,IPHOTO=1,IARIV=0**
> **&END**

Radiological specifications

24. As recommended by the International Commission on Radiological Protection (ICRP) in Publication 30, the fifty-year committed effective dose equivalent conversion factor for tritium oxide is used [ICRP, 1978]. Others shown are 1.7E-15 Sv/Bq for HT and 4.0E-11 Sv/Bq for OBT [Raskob, 1990]. The assumed breathing rate is 3.33×10^{-4} cubic meters per second which is the DOE occupational breathing rate [DOE, 1989]; the skin absorption rate is one-half that through breathing (1.665E-04). These dose-related factors are not used when comparing concentrations in foods to FDA DILs.

> **DOSF=1.7E-11,**
> **DOSHT=1.7E-15,DOSFOB=4.0E-11,BRRATE=3.33E-4,SKRATE=1.665E-04**

Output specification

25. A detailed printout of the concentration for each tritium species at the various grid radii is requested (NOOTKZ=1). No detailed printout is requested for meteorological and trajectory data

(NOOTMT=0). A printout for all thirteen distance bands is specified (IACT=13*1). Most options for detailed concentration printout by region are turned off (IZUSD, IZUAUS, and KAUSDR). KAUSDR(2)=1 provides a printout of concentrations in foodstuffs. Output listings for concentrations in foodstuffs are limited to one location. The location is specified by sector (IFACHS) and radius (IEINR2). In the example, concentrations in Sector 28 (IFACHS=28) at a distance of the first radius (IEINR2=1) are requested (directly downwind for the specified wind direction of 315°. Concentrations as a function of time are obtained.

```
        PRINTOUT
         &OUTPAR
        NOOTKZ=1,NOOTMT=0,
        IACT=13*1
                &END

        IZUSD=0,IZUAUS=0,KAUSDR=0,1,0,0,0,0,0,0,0,0,0,0
        IFACHS=28
        IEINR2=1
```

A sample input file is provided in Appendix R.

Several full input files are included in Marx (1999a and 1999b). While research into SRS-specific parameters for use in tritium dispersion models has been performed, UFOTRI code-specific parameters may still need to be refined depending on the nature of the IPZ calculation.

Comparison with FDA DILs

To evaluate the release, calculated concentrations in vegetables, wheat grain, meat, and milk for multiple distances and times following the release are compared with the HTO and OBT DILs. DILs for HTO and OBT were presented in Table 2. Tritium concentrations in grass, although calculated in UFOTRI, are not examined since grass is not directly consumed by humans. However, tritium concentrations in grass are indirectly incorporated via the meat and milk pathways. In all instances, the HTO and OBT concentrations are summed prior to comparison with the appropriate DIL.

For short-term concentrations, the time at which the peak HTO concentration occurs in each food type should be found. The summed HTO and OBT concentrations are compared with the HTO DIL. In the time immediately following the release, the HTO concentration quickly reaches its peak and is the dominant form of tritium present in foodstuffs.

For long-term concentrations, two evaluation times, one week (168 hours) and one year (8760 hours), are used. The OBT DIL is used for these comparisons because the tritium will be incorporated into organic compounds that have a greater biological half-life than HTO. For plants, the HTO half-life is approximately one hour while the OBT half-life ranges from 8 hours to over 10 days. Examinations of long-term concentrations are useful to determine if interdiction is still required.

Concentrations for both the short and long-term should be examined at the facility boundary, 1 km, 10 km, site boundary, 50 km, and 100 km from the release. The facility and site boundary concentrations may be used to determine if any intervention will be necessary. The concentration at 100 km is used for comparison with the particulate concentrations. (The code

used to calculate concentrations for particulates, HOTSPOT, calculates up to a maximum distance of 100 km.) The remaining distances are chosen to examine intermediate distances.

CONCLUSION

A recommended methodology has been described to evaluate the ingestion pathway consequences of accidental airborne radiological releases from facilities at the Savannah River Site. Due to the variation in behavior of particulate and tritium species in the environment, the approaches differ. Specific values of coefficients and transfer factors for many radionuclides potentially released as part of SRS source terms are presented in appendices. For radionuclides not explicitly addressed here, a recommended default procedure is outlined.

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APPENDIX A. PRODUCE TRANSFER FACTORS (DIRECT DEPOSITION)

Table A-1 lists the transfer coefficients for external contamination of produce from direct deposition.

Table A-1. External Contamination of Produce from Direct Deposition

Nuclide	r	Y_v	T (m^2/kg)
Am-241	0.2	0.7	0.29
Am-243	0.2	0.7	0.29
Ba-133	0.2	0.7	0.29
Ce-144	0.2	0.7	0.29
Cf-249	0.2	0.7	0.29
Cf-252	0.2	0.7	0.29
Cm-244	0.2	0.7	0.29
Cm-246	0.2	0.7	0.29
Co-60	0.2	0.7	0.29
Cs-137	0.2	0.7	0.29
Np-237	0.2	0.7	0.29
Pm-147	0.2	0.7	0.29
Pu-238	0.2	0.7	0.29
Pu-239	0.2	0.7	0.29
Pu-240	0.2	0.7	0.29
Pu-241	0.2	0.7	0.29
Pu-242	0.2	0.7	0.29
Sr-90	0.2	0.7	0.29
Tc-99	0.2	0.7	0.29
Th-232	0.2	0.7	0.29
Tl-204	0.2	0.7	0.29
U-235	0.2	0.7	0.29
U-238	0.2	0.7	0.29

Reference: Thompson 1999c: Ingestion Pathway Transfer Factors for Particulates.

"r" values are from RG 1.109, page 68.
"Y_v" values are from Hamby 1991.

APPENDIX B. PRODUCE TRANSFER FACTORS (ROOT UPTAKE)

Table B-1 lists the transfer factors for internal contamination of produce from root uptake.

Table B-1. Internal Contamination of Produce from Root Uptake

Nuclide	$_iCR_{soil\ to\ produce,\ dry}$	$_iCR_{soil\ to\ produce,\ dry}/7=B_{wet}$	$T=B_{wet}/280\ m^2/kg$
Am-241	6.60E-04	9.43E-05	3.37E-07
Am-243	6.60E-04	9.43E-05	3.37E-07
Ba-133	3.00E-02	4.29E-03	1.53E-05
Ce-144	3.00E-02	4.29E-03	1.53E-05
Cf-249	∗	∗	∗
Cf-252	∗	∗	∗
Cm-244	7.70E-04	1.10E-04	3.93E-07
Cm-246	7.70E-04	1.10E-04	3.93E-07
Co-60	2.00E-01	2.86E-02	1.02E-04
Cs-137	4.60E-01	6.57E-02	2.35E-04
Np-237	3.70E-02	5.29E-03	1.89E-05
Pm-147	∗	∗	∗
Pu-238	7.30E-05	1.04E-05	3.72E-08
Pu-239	7.30E-05	1.04E-05	3.72E-08
Pu-240	7.30E-05	1.04E-05	3.72E-08
Pu-241	7.30E-05	1.04E-05	3.72E-08
Pu-242	7.30E-05	1.04E-05	3.72E-08
Sr-90	3.00E+00	4.29E-01	1.53E-03
Tc-99	2.00E+02	2.86E+01	1.02E-01
Th-232	1.80E-03	2.57E-04	9.18E-07
Tl-204	∗	∗	∗
U-235	8.30E-03	1.19E-03	4.23E-06
U-238	8.30E-03	1.19E-03	4.23E-06

∗ factors not available
Reference: Thompson 1999c: Ingestion Pathway Transfer Factors for Particulates.

Dry concentration ratios are from IAEA 364, Table VI. Conversion to wet weight (factor of 7) per IAEA 364, section 2.4, page 26. When concentration ratios for different soil types were listed, the most limiting concentration ratio was selected. The soil depth (20 cm) and density (1.4 g cm^{-3}) are combined to give an areal density of 280 kg m^{-2}, consistent with IAEA 364.

APPENDIX C. LEAFY VEGETABLE TRANSFER FACTORS (EXTERNAL CONTAMINATION DURING HARVEST)

Table C-1 lists the transfer factors for external contamination of leafy vegetables during harvest.

Table C-1. External Contamination of Leafy Vegetables During Harvest

Nuclide	dry kg/wet kg	soil/dry produce	T (m^2/kg)
Am-241	0.14	0.01	5.10E-06
Am-243	0.14	0.01	5.10E-06
Ba-133	0.14	0.01	5.10E-06
Ce-144	0.14	0.01	5.10E-06
Cf-249	0.14	0.01	5.10E-06
Cf-252	0.14	0.01	5.10E-06
Cm-244	0.14	0.01	5.10E-06
Cm-246	0.14	0.01	5.10E-06
Co-60	0.14	0.01	5.10E-06
Cs-137	0.14	0.01	5.10E-06
Np-237	0.14	0.01	5.10E-06
Pm-147	0.14	0.01	5.10E-06
Pu-238	0.14	0.01	5.10E-06
Pu-239	0.14	0.01	5.10E-06
Pu-240	0.14	0.01	5.10E-06
Pu-241	0.14	0.01	5.10E-06
Pu-242	0.14	0.01	5.10E-06
Sr-90	0.14	0.01	5.10E-06
Tc-99	0.14	0.01	5.10E-06
Th-232	0.14	0.01	5.10E-06
Tl-204	0.14	0.01	5.10E-06
U-235	0.14	0.01	5.10E-06
U-238	0.14	0.01	5.10E-06

Reference: Thompson 1999c: Ingestion Pathway Transfer Factors for Particulates.

The ratio dry kg/wet kg is assumed equal to 1/7, per IAEA 364, section 2.4, page 26. The soil weight per kg dry weight of the plant is 10 g per kilogram, or 0.01 per Table VII of IAEA 364. The soil depth (20 cm) and density (1.4 g cm^{-3}) are combined to give an areal density of 280 kg m^{-2}, consistent with IAEA 364.

APPENDIX D. GRAIN TRANSFER FACTORS (DIRECT DEPOSITION)

Table D-1 lists the transfer factors for external contamination of grain from direct deposition.

Table D-1. External Contamination of Grain

Nuclide	r	Y_v	T (m^2/kg)
Am-241	0.2	0.7	0.29
Am-243	0.2	0.7	0.29
Ba-133	0.2	0.7	0.29
Ce-144	0.2	0.7	0.29
Cf-249	0.2	0.7	0.29
Cf-252	0.2	0.7	0.29
Cm-244	0.2	0.7	0.29
Cm-246	0.2	0.7	0.29
Co-60	0.2	0.7	0.29
Cs-137	0.2	0.7	0.29
Np-237	0.2	0.7	0.29
Pm-147	0.2	0.7	0.29
Pu-238	0.2	0.7	0.29
Pu-239	0.2	0.7	0.29
Pu-240	0.2	0.7	0.29
Pu-241	0.2	0.7	0.29
Pu-242	0.2	0.7	0.29
Sr-90	0.2	0.7	0.29
Tc-99	0.2	0.7	0.29
Th-232	0.2	0.7	0.29
Tl-204	0.2	0.7	0.29
U-235	0.2	0.7	0.29
U-238	0.2	0.7	0.29

Reference: Thompson 1999c: Ingestion Pathway Transfer Factors for Particulates.

"r" values are from RG 1.109, page 68.
"Y_v" values are from Hamby 1991.

APPENDIX E. GRAIN TRANSFER FACTORS (ROOT UPTAKE)

Table E-1 lists the transfer factors for internal contamination of grain by root uptake.

Table E-1. Internal Contamination of Grain by Root Uptake

Nuclide	$_iCR_{soil\ to\ grain,\ dry}$	$B_{wet} = {}_iCR_{soil\ to\ grain,\ dry} \times 0.86$	$T = B_{wet}/280\ m^2/kg$
Am-241	2.20E-05	1.89E-05	6.76E-08
Am-243	2.20E-05	1.89E-05	6.76E-08
Ba-133	3.00E-02	2.58E-02	9.21E-05
Ce-144	3.00E-02	2.58E-02	9.21E-05
Cf-249	*	*	*
Cf-252	*	*	*
Cm-244	2.10E-05	1.81E-05	6.45E-08
Cm-246	2.10E-05	1.81E-05	6.45E-08
Co-60	3.70E-03	3.18E-03	1.14E-05
Cs-137	8.30E-02	7.14E-02	2.55E-04
Np-237	2.70E-03	2.32E-03	8.29E-06
Pm-147	*	*	*
Pu-238	8.60E-06	7.40E-06	2.64E-08
Pu-239	8.60E-06	7.40E-06	2.64E-08
Pu-240	8.60E-06	7.40E-06	2.64E-08
Pu-241	8.60E-06	7.40E-06	2.64E-08
Pu-242	8.60E-06	7.40E-06	2.64E-08
Sr-90	2.10E-01	1.81E-01	6.45E-04
Tc-99	7.30E-01	6.28E-01	2.24E-03
Th-232	3.40E-05	2.92E-05	1.04E-07
Tl-204	*	*	*
U-235	1.30E-03	1.12E-03	3.99E-06
U-238	1.30E-03	1.12E-03	3.99E-06

* factors not available
Reference: Thompson 1999c: Ingestion Pathway Transfer Factors for Particulates.

Dry concentration ratios are from IAEA 364, Table VI. Conversion to wet weight (factor of 0.86) per IAEA 364, Table V, page 15. When concentration ratios for different soil types were listed, the most limiting concentration ratio was selected. The soil depth (20 cm) and density (1.4 g cm^{-3}) are combined to give an areal density of 280 kg m^{-2}, consistent with IAEA 364.

APPENDIX F. GRAIN TRANSFER FACTORS (EXTERNAL CONTAMINATION DURING HARVEST)

Table F-1 lists the transfer factors for external contamination of grain during harvest.

Table F-1. External Contamination of Grain During Harvest

Nuclide	dry kg/wet kg	soil/dry grain	T (m^2/kg)
Am-241	0.86	0.004	1.23E-05
Am-243	0.86	0.004	1.23E-05
Ba-133	0.86	0.004	1.23E-05
Ce-144	0.86	0.004	1.23E-05
Cf-249	0.86	0.004	1.23E-05
Cf-252	0.86	0.004	1.23E-05
Cm-244	0.86	0.004	1.23E-05
Cm-246	0.86	0.004	1.23E-05
Co-60	0.86	0.004	1.23E-05
Cs-137	0.86	0.004	1.23E-05
Np-237	0.86	0.004	1.23E-05
Pm-147	0.86	0.004	1.23E-05
Pu-238	0.86	0.004	1.23E-05
Pu-239	0.86	0.004	1.23E-05
Pu-240	0.86	0.004	1.23E-05
Pu-241	0.86	0.004	1.23E-05
Pu-242	0.86	0.004	1.23E-05
Sr-90	0.86	0.004	1.23E-05
Tc-99	0.86	0.004	1.23E-05
Th-232	0.86	0.004	1.23E-05
Tl-204	0.86	0.004	1.23E-05
U-235	0.86	0.004	1.23E-05
U-238	0.86	0.004	1.23E-05

Reference: Thompson 1999c: Ingestion Pathway Transfer Factors for Particulates.

The estimate of external contamination of grain is from IAEA 364, Table VII, page 27. The soil depth (20 cm) and density (1.4 g cm^{-3}) are combined to give an areal density of 280 kg m^{-2}, consistent with IAEA 364.

APPENDIX G. DAIRY PRODUCT TRANSFER FACTORS

Table G-1 lists the transfer factors for contamination of dairy products.

Table G-1. Contamination of Dairy Products

Nuclide	$_iF^m$ (milk) d/L	r	Y_v kg/m^{2}wet	Q_F kg/d (wet)	T_{milk} m^2/L
Am-241	1.50E-06	0.5	1.8	29.12	1.21E-05
Am-243	1.50E-06	0.5	1.8	29.12	1.21E-05
Ba-133	4.80E-04	0.5	1.8	29.12	3.88E-03
Ce-144	3.00E-05	0.5	1.8	29.12	2.43E-04
Cf-249	**2.00E-06**	0.5	1.8	29.12	1.62E-05
Cf-252	**2.00E-06**	0.5	1.8	29.12	1.62E-05
Cm-244	**2.00E-06**	0.5	1.8	29.12	1.62E-05
Cm-246	**2.00E-06**	0.5	1.8	29.12	1.62E-05
Co-60	3.00E-04	0.5	1.8	29.12	2.43E-03
Cs-137	7.90E-03	0.5	1.8	29.12	6.39E-02
Np-237	5.00E-06	0.5	1.8	29.12	4.04E-05
Pm-147	**6.00E-05**	0.5	1.8	29.12	4.85E-04
Pu-238	1.10E-06	0.5	1.8	29.12	8.90E-06
Pu-239	1.10E-06	0.5	1.8	29.12	8.90E-06
Pu-240	1.10E-06	0.5	1.8	29.12	8.90E-06
Pu-241	1.10E-06	0.5	1.8	29.12	8.90E-06
Pu-242	1.10E-06	0.5	1.8	29.12	8.90E-06
Sr-90	2.80E-03	0.5	1.8	29.12	2.26E-02
Tc-99	2.30E-05	0.5	1.8	29.12	1.86E-04
Th-232	**5.00E-06**	0.5	1.8	29.12	4.04E-05
Tl-204	**3.00E-03**	0.5	1.8	29.12	2.43E-02
U-235	4.00E-04	0.5	1.8	29.12	3.24E-03
U-238	4.00E-04	0.5	1.8	29.12	3.24E-03

Reference: Thompson 1999c: Ingestion Pathway Transfer Factors for Particulates.

$_iF^m$ is the average fraction of a cow's daily intake of radionuclide i that appears in each liter of milk. $_iF^m$ has units of Bq L^{-1} of milk per Bq day^{-1} consumed by the cow, or d L^{-1}. Most coefficients are from Table XII of IAEA 364. Coefficients for nuclides not listed in IAEA 364 are from NCRP 123. **Shaded bold** values indicate values from NCRP 123, Table 5.2. The value for cobalt corresponds to that for the organic form, which is the most limiting.

A deposition fraction "r" of 0.5 is given on page 13 of Shleien and Chiacchierini (1982), and is adopted as the value for pasture following an acute release of particulates in the following calculation. The SRS-specific agricultural productivity per unit area (measured in wet weight) (Y_v)for the grass-cow-milk pathway is 1.8 kg m^{-2} (Hamby 1991).

The total consumption rate (wet weight per day) of forage consumed by a dairy cow is 52 kg d^{-1} (Hamby 1991). The SRS-specific fraction of intake from pasture is 0.56 (Hamby 1991). The product of these factors results in a daily consumption rate of contaminated forage (Q_F) of 29.12 kg d^{-1}.

APPENDIX H. EGG CONTENTS TRANSFER FACTORS

Table H-1 lists the transfer factors for contamination of egg contents.

Table H-1. Contamination of Egg Contents

Nuclide	$_iF^e$ (eggs) d/kg	r	Y_v kg/m^{2}wet	Q_F kg/d (wet)	T_{eggs} m^2/kg
Am-241	4.00E-03	0.2	0.7	0.116	1.33E-04
Am-243	4.00E-03	0.2	0.7	0.116	1.33E-04
Ba-133	9.00E-01	0.2	0.7	0.116	2.98E-02
Ce-144	9.00E-05	0.2	0.7	0.116	2.98E-06
Cf-249		0.2	0.7	0.116	
Cf-252		0.2	0.7	0.116	
Cm-244		0.2	0.7	0.116	
Cm-246		0.2	0.7	0.116	
Co-60	1.00E-01	0.2	0.7	0.116	3.31E-03
Cs-137	4.00E-01	0.2	0.7	0.116	1.33E-02
Np-237		0.2	0.7	0.116	
Pm-147	2.00E-02	0.2	0.7	0.116	6.63E-04
Pu-238	5.00E-04	0.2	0.7	0.116	1.66E-05
Pu-239	5.00E-04	0.2	0.7	0.116	1.66E-05
Pu-240	5.00E-04	0.2	0.7	0.116	1.66E-05
Pu-241	5.00E-04	0.2	0.7	0.116	1.66E-05
Pu-242	5.00E-04	0.2	0.7	0.116	1.66E-05
Sr-90	2.00E-01	0.2	0.7	0.116	6.63E-03
Tc-99	3	0.2	0.7	0.116	9.94E-02
Th-232		0.2	0.7	0.116	
Tl-204		0.2	0.7	0.116	
U-235	1	0.2	0.7	0.116	3.31E-02
U-238	1	0.2	0.7	0.116	3.31E-02

Reference: Thompson 1999c: Ingestion Pathway Transfer Factors for Particulates.

$_iF_e$ values are from IAEA 364, Table XX, page 41.
"r" values are from RG 1.109, page 68.
"Y_v" values are from Hamby 1991.

Laying hens have a consumption rate of dry matter of 0.1 kg d^{-1} (IAEA (1994) Table XI, page 33). Dry weight contents of cereals (assumed to be representative of grain) are presented in IAEA (1994), Table V, page 15. The average dry weight content of cereals is about 86%, so the wet consumption rate is $(0.1$ kg d^{-1} / 0.86$) = 0.116$ kg d^{-1}.

APPENDIX I. BEEF TRANSFER FACTORS

Table I-1 lists the transfer factors for contamination of beef.

Table I-1. Contamination of Beef

Nuclide	$_iF^f$ d/kg	r	Y_v kg/m^{2}wet	Q_F kg/d	T m^2/kg
Am-241	4.00E-05	0.5	1.8	27	3.00E-04
Am-243	4.00E-05	0.5	1.8	27	3.00E-04
Ba-133	2.00E-04	0.5	1.8	27	1.50E-03
Ce-144	2.00E-05	0.5	1.8	27	1.50E-04
Cf-249	**6.00E-05**	0.5	1.8	27	4.50E-04
Cf-252	**6.00E-05**	0.5	1.8	27	4.50E-04
Cm-244	**2.00E-05**	0.5	1.8	27	1.50E-04
Cm-246	**2.00E-05**	0.5	1.8	27	1.50E-04
Co-60	1.00E-02	0.5	1.8	27	7.50E-02
Cs-137	5.00E-02	0.5	1.8	27	3.75E-01
Np-237	1.00E-03	0.5	1.8	27	7.50E-03
Pm-147	**2.00E-03**	0.5	1.8	27	1.50E-02
Pu-238	1.00E-05	0.5	1.8	27	7.50E-05
Pu-239	1.00E-05	0.5	1.8	27	7.50E-05
Pu-240	1.00E-05	0.5	1.8	27	7.50E-05
Pu-241	1.00E-05	0.5	1.8	27	7.50E-05
Pu-242	1.00E-05	0.5	1.8	27	7.50E-05
Sr-90	8.00E-03	0.5	1.8	27	6.00E-02
Tc-99	1.00E-06	0.5	1.8	27	7.50E-06
Th-232	**1.00E-04**	0.5	1.8	27	7.50E-04
Tl-204	**2.00E-02**	0.5	1.8	27	1.50E-01
U-235	3.00E-04	0.5	1.8	27	2.25E-03
U-238	3.00E-04	0.5	1.8	27	2.25E-03

Reference: Thompson 1999c: Ingestion Pathway Transfer Factors for Particulates.

$_iF^f$ values are from IAEA (1994), Table XV (preferred) and NCRP 123, Table 5.2 (**shaded bold**).

The agricultural production rate Y_v is measured in wet weight. An SRS-specific value of 1.8 kg m^{-2} (wet weight of pasture grass per unit area) is chosen for meat calculations (Hamby 1991). An interception fraction r for pasture of 0.5 is assumed.

The site-specific total wet forage consumption rate for beef is 36 kg d^{-1} (Hamby 1991). The SRS-specific value for the fraction of intake from pasture for beef is 0.75 (Hamby 1991). The product of the total consumption rate and the fraction of intake from pasture gives a contaminated forage consumption rate (Q_F) of 27 kg d^{-1}.

APPENDIX J. VEAL TRANSFER FACTORS

Table J-1 lists the transfer factors for contamination of veal.

Nuclide	$_iF^f$ Veal	r	Y_v kg/m^{2}wet	Q_F kg/d	T_{veal} m^2/kg
Am-241	1.00E-03	0.5	1.8	8.6	2.39E-03
Am-243	1.00E-03	0.5	1.8	8.6	2.39E-03
Ba-133	∗	0.5	1.8	8.6	∗
Ce-144	∗	0.5	1.8	8.6	∗
vCf-249	∗	0.5	1.8	8.6	∗
Cf-252	∗	0.5	1.8	8.6	∗
Cm-244	∗	0.5	1.8	8.6	∗
Cm-246	∗	0.5	1.8	8.6	∗
Co-60	∗	0.5	1.8	8.6	∗
Cs-137	2.00E-01	0.5	1.8	8.6	4.78E-01
Np-237	∗	0.5	1.8	8.6	∗
Pm-147	∗	0.5	1.8	8.6	∗
Pu-238	1.00E-03	0.5	1.8	8.6	2.39E-03
Pu-239	1.00E-03	0.5	1.8	8.6	2.39E-03
Pu-240	1.00E-03	0.5	1.8	8.6	2.39E-03
Pu-241	1.00E-03	0.5	1.8	8.6	2.39E-03
Pu-242	1.00E-03	0.5	1.8	8.6	2.39E-03
Sr-90	1.00E-01	0.5	1.8	8.6	2.39E-01
Tc-99	∗	0.5	1.8	8.6	∗
Th-232	∗	0.5	1.8	8.6	∗
Tl-204	∗	0.5	1.8	8.6	∗
U-235	∗	0.5	1.8	8.6	∗
U-238	∗	0.5	1.8	8.6	∗

Table J-1. Contamination of Veal

∗ factors not available
Reference: Thompson 1999c: Ingestion Pathway Transfer Factors for Particulates.

$_iF^f$ values are from IAEA (1994), Table XV.

The agricultural production rate Y_v is measured in wet weight. An SRS-specific value of 1.8 kg m^{-2} (wet weight of pasture grass per unit area) is chosen for meat calculations (Hamby 1991). An interception fraction r for pasture of 0.5 is assumed.

The quantities (dry weight) of forage consumed are values from IAEA (1994), Table XI, page 33. Wet forage consumption rates (Q_F) are 4.5 times the dry consumption rates per Table 5.16, page 5-48 of Till and Meyer (1983). All forage consumed by the animal is assumed to be contaminated.

APPENDIX K. SHEEP TRANSFER FACTORS

Table K-1 lists the transfer factors for contamination of sheep.

Table K-1. Contamination of Sheep

Nuclide	$_iF^f$ Sheep	r	Y_v kg/m^{2}wet	Q_F kg/d	T_{sheep} m^2/kg
Am-241	2.00E-04	0.5	1.8	5.9	3.28E-04
Am-243	2.00E-04	0.5	1.8	5.9	3.28E-04
Ba-133	*	0.5	1.8	5.9	*
Ce-144	2.00E-04	0.5	1.8	5.9	3.28E-04
Cf-249	*	0.5	1.8	5.9	*
Cf-252	*	0.5	1.8	5.9	*
Cm-244	*	0.5	1.8	5.9	*
Cm-246	*	0.5	1.8	5.9	*
Co-60	6.20E-02	0.5	1.8	5.9	1.02E-01
Cs-137	1.70E-01	0.5	1.8	5.9	2.79E-01
Np-237	*	0.5	1.8	5.9	*
Pm-147	*	0.5	1.8	5.9	*
Pu-238	9.40E-05	0.5	1.8	5.9	1.54E-04
Pu-239	9.40E-05	0.5	1.8	5.9	1.54E-04
Pu-240	9.40E-05	0.5	1.8	5.9	1.54E-04
Pu-241	9.40E-05	0.5	1.8	5.9	1.54E-04
Pu-242	9.40E-05	0.5	1.8	5.9	1.54E-04
Sr-90	4.00E-02	0.5	1.8	5.9	6.56E-02
Tc-99	*	0.5	1.8	5.9	*
Th-232	*	0.5	1.8	5.9	*
Tl-204	*	0.5	1.8	5.9	*
U-235	*	0.5	1.8	5.9	*
U-238	*	0.5	1.8	5.9	*

∗ factors not available
Reference: Thompson 1999c: Ingestion Pathway Transfer Factors for Particulates.

$_iF^f$ values are from IAEA (1994), Table XVI.

The agricultural production rate Y_v is measured in wet weight. An SRS-specific value of 1.8 kg m^{-2} (wet weight of pasture grass per unit area) is chosen for meat calculations (Hamby 1991). An interception fraction r for pasture of 0.5 is assumed.

The quantities (dry weight) of forage consumed are values from IAEA (1994), Table XI, page 33. Wet forage consumption rates (Q_F) are 4.5 times the dry consumption rates per Table 5.16, page 5-48 of Till and Meyer (1983). All forage consumed by the animal is assumed to be contaminated.

APPENDIX L. LAMB TRANSFER FACTORS

Table L-1 lists the transfer factors for contamination of lamb.

Table L-1. Contamination of Lamb

Nuclide	$_iF^f$ Lamb d/kg	r	Y_v kg/m^{2}wet	Q_F kg/d	T_{lamb} m^2/kg
Am-241	4.10E-03	0.5	1.8	5	5.69E-03
Am-243	4.10E-03	0.5	1.8	5	5.69E-03
Ba-133	∗	0.5	1.8	5	∗
Ce-144	∗	0.5	1.8	5	∗
Cf-249	∗	0.5	1.8	5	∗
Cf-252	∗	0.5	1.8	5	∗
Cm-244	∗	0.5	1.8	5	∗
Cm-246	∗	0.5	1.8	5	∗
Co-60	∗	0.5	1.8	5	∗
Cs-137	4.90E-01	0.5	1.8	5	6.81E-01
Np-237	∗	0.5	1.8	5	∗
Pm-147	∗	0.5	1.8	5	∗
Pu-238	3.10E-03	0.5	1.8	5	4.31E-03
Pu-239	3.10E-03	0.5	1.8	5	4.31E-03
Pu-240	3.10E-03	0.5	1.8	5	4.31E-03
Pu-241	3.10E-03	0.5	1.8	5	4.31E-03
Pu-242	3.10E-03	0.5	1.8	5	4.31E-03
Sr-90	3.30E-01	0.5	1.8	5	4.58E-01
Tc-99	∗	0.5	1.8	5	∗
Th-232	∗	0.5	1.8	5	∗
Tl-204	∗	0.5	1.8	5	∗
U-235	∗	0.5	1.8	5	∗
U-238	∗	0.5	1.8	5	∗

∗ factors not available
Reference: Thompson 1999c: Ingestion Pathway Transfer Factors for Particulates.

$_iF^f$ values are from IAEA (1994), Table XVI.

The agricultural production rate Y_v is measured in wet weight. An SRS-specific value of
1.8 kg m^{-2} (wet weight of pasture grass per unit area) is chosen for meat calculations (Hamby
1991). An interception fraction r for pasture of 0.5 is assumed.

The quantities (dry weight) of forage consumed are values from IAEA (1994), Table XI, page
33. Wet forage consumption rates (Q_F) are 4.5 times the dry consumption rates per Table 5.16,
page 5-48 of Till and Meyer (1983). All forage consumed by the animal is assumed to be
contaminated.

APPENDIX M. PORK TRANSFER FACTORS

Table M-1 lists the transfer factors for contamination of pork.

Table M-1. Contamination of Pork

Nuclide	$_iF^f$ Pork d/kg	r	Y_v kg/m²wet	Q_F kg/d	T_{pork} m²/kg
Am-241	1.70E-04	0.5	1.8	11	5.19E-04
Am-243	1.70E-04	0.5	1.8	11	5.19E-04
Ba-133	*	0.5	1.8	11	*
Ce-144	1.00E-04	0.5	1.8	11	3.06E-04
Cf-249	*	0.5	1.8	11	*
Cf-252	*	0.5	1.8	11	*
Cm-244	*	0.5	1.8	11	*
Cm-246	*	0.5	1.8	11	*
Co-60	2.00E-03	0.5	1.8	11	6.11E-03
Cs-137	2.40E-01	0.5	1.8	11	7.33E-01
Np-237	*	0.5	1.8	11	*
Pm-147	*	0.5	1.8	11	*
Pu-238	8.00E-05	0.5	1.8	11	2.44E-04
Pu-239	8.00E-05	0.5	1.8	11	2.44E-04
Pu-240	8.00E-05	0.5	1.8	11	2.44E-04
Pu-241	8.00E-05	0.5	1.8	11	2.44E-04
Pu-242	8.00E-05	0.5	1.8	11	2.44E-04
Sr-90	4.00E-02	0.5	1.8	11	1.22E-01
Tc-99	1.50E-04	0.5	1.8	11	4.58E-04
Th-232	*	0.5	1.8	11	*
Tl-204	*	0.5	1.8	11	*
U-235	6.20E-02	0.5	1.8	11	1.89E-01
U-238	6.20E-02	0.5	1.8	11	1.89E-01

* factors not available
Reference: Thompson 1999c: Ingestion Pathway Transfer Factors for Particulates.

$_iF^f$ values are from IAEA (1994), Table XVIII.

The agricultural production rate Y_v is measured in wet weight. An SRS-specific value of
1.8 kg m⁻² (wet weight of pasture grass per unit area) is chosen for meat calculations (Hamby
1991). An interception fraction r for pasture of 0.5 is assumed.

The quantities (dry weight) of forage consumed are values from IAEA (1994), Table XI, page
33. Wet forage consumption rates (Q_F) are 4.5 times the dry consumption rates per Table 5.16,
page 5-48 of Till and Meyer (1983). All forage consumed is assumed to be contaminated.

APPENDIX N. POULTRY TRANSFER FACTORS

Table N-1 lists the transfer factors for contamination of poultry.

Table N-1. Contamination of Poultry

Nuclide	iF^f Poultry d/kg	r	Y_v kg/m^{2}wet	Q_F kg/d	$T_{poultry}$ m^2/kg
Am-241	6.00E-03	0.5	1.8	0.315	5.25E-04
Am-243	6.00E-03	0.5	1.8	0.315	5.25E-04
Ba-133	9.00E-03	0.5	1.8	0.315	7.88E-04
Ce-144	4.00E-03	0.5	1.8	0.315	3.50E-04
Cf-249	*	0.5	1.8	0.315	*
Cf-252	*	0.5	1.8	0.315	*
Cm-244	*	0.5	1.8	0.315	*
Cm-246	*	0.5	1.8	0.315	*
Co-60	2	0.5	1.8	0.315	1.75E-01
Cs-137	10	0.5	1.8	0.315	8.75E-01
Np-237	*	0.5	1.8	0.315	*
Pm-147	2.00E-03	0.5	1.8	0.315	1.75E-04
Pu-238	3.00E-03	0.5	1.8	0.315	2.63E-04
Pu-239	3.00E-03	0.5	1.8	0.315	2.63E-04
Pu-240	3.00E-03	0.5	1.8	0.315	2.63E-04
Pu-241	3.00E-03	0.5	1.8	0.315	2.63E-04
Pu-242	3.00E-03	0.5	1.8	0.315	2.63E-04
Sr-90	8.00E-02	0.5	1.8	0.315	7.00E-03
Tc-99	3.00E-02	0.5	1.8	0.315	2.63E-03
Th-232	*	0.5	1.8	0.315	*
Tl-204	*	0.5	1.8	0.315	*
U-235	1	0.5	1.8	0.315	8.75E-02
U-238	1	0.5	1.8	0.315	8.75E-02

∗ factors not available
Reference: Thompson 1999c: Ingestion Pathway Transfer Factors for Particulates.

$_iF^f$ values are from IAEA (1994), Table XIX.

The agricultural production rate Y_v is measured in wet weight. An SRS-specific value of
1.8 kg m^{-2} (wet weight of pasture grass per unit area) is chosen for meat calculations (Hamby
1991). An interception fraction r for pasture of 0.5 is assumed.

The quantities (dry weight) of forage consumed are values from IAEA (1994), Table XI, page
33. Wet forage consumption rates (Q_F) are 4.5 times the dry consumption rates per Table 5.16,
page 5-48 of Till and Meyer (1983). All forage consumed by the animal is assumed to be
contaminated.

APPENDIX O. BEVERAGE TRANSFER FACTORS

Table O-1 lists the transfer factors for contamination of beverages.

Table O-1. Contamination of Beverages

Nuclide	T_{water} (m^2/L)
Am-241	0.001
Am-243	0.001
Ba-133	0.001
Ce-144	0.001
Cf-249	0.001
Cf-252	0.001
Cm-244	0.001
Cm-246	0.001
Co-60	0.001
Cs-137	0.001
Np-237	0.001
Pm-147	0.001
Pu-238	0.001
Pu-239	0.001
Pu-240	0.001
Pu-241	0.001
Pu-242	0.001
Sr-90	0.001
Tc-99	0.001
Th-232	0.001
Tl-204	0.001
U-235	0.001
U-238	0.001

Reference: Thompson 1999c: Ingestion Pathway Transfer Factors for Particulates.

A depth of water (d) of 1 meter is assumed. The density of water is 10^3 kg m^{-3}.

APPENDIX P. FISH TRANSFER FACTORS

Table P-1 lists the transfer factors for contamination of fish.

Table P-1. Contamination of Fish

Nuclide	B_p L/kg	factor T_{water} (m²/L)	T_{fish} m²/kg
Am-241	30	0.001	0.03
Am-243	30	0.001	0.03
Ba-133	4	0.001	0.004
Ce-144	30	0.001	0.03
Cf-249	**25**	0.001	0.025
Cf-252	**25**	0.001	0.025
Cm-244	30	0.001	0.03
Cm-246	30	0.001	0.03
Co-60	300	0.001	0.3
Cs-137	2000	0.001	2
Np-237	30	0.001	0.03
Pm-147	30	0.001	0.03
Pu-238	30	0.001	0.03
Pu-239	30	0.001	0.03
Pu-240	30	0.001	0.03
Pu-241	30	0.001	0.03
Pu-242	30	0.001	0.03
Sr-90	60	0.001	0.06
Tc-99	20	0.001	0.02
Th-232	100	0.001	0.1
Tl-204	**1.00E+04**	0.001	10
U-235	10	0.001	0.01
U-238	10	0.001	0.01

Reference: Thompson 1999c: Ingestion Pathway Transfer Factors for Particulates.

Concentration factors (B_p) values are from IAEA (1994), Table XXII (preferred) and NCRP 123, Table 6.1 (**shaded bold**). Fish are assumed to live in stagnant water one meter deep. No sedimentation/precipitation of the contaminant is assumed.

APPENDIX Q. EXAMPLE PARTICULATE CALCULATION

This appendix presents the steps in an example calculation for particulates. It follows the process outlined in the body of this report. The overall approach used to evaluate the impact of an atmospheric release of radionuclides on the food chain has been divided into several steps that follow radioactive material through the environment and food chain to man and are described in the body of this report. These steps follow the basic outline of Table 1 in the body of the report.

The analysis presented in this appendix is fully documented in Thompson (1999b) *Ingestion Pathway Consequences of an H-Separations Coil and Tube Failure*.

METHOD

The method used to determine Derived Response Levels (DRLs) is outlined below.

1. Determine the source terms (radionuclide-specific and total airborne releases).

2. Calculate the concentrations of each radionuclide in foodstuffs for a unit deposition of the total (as opposed to respirable) particulate mix.

3. For radionuclides with FDA (1998) Derived Intervention Levels (DILs), divide the DIL by the foodstuff concentration from a unit deposition. The DRL is the deposition that gives a DIL for a specific nuclide (group) and pathway.

4. Once a DRL is determined, ranges and areas affected may be predicted with a dispersion/deposition model such as HOTSPOT.

The first pathway step described in Table 1 of the main body of this report, involves quantifying the radioactive material released (i.e., the source term). Nuclide-specific source terms for this accident scenario were taken from a previous emergency preparedness hazards assessment (EPHA) evaluating the inhalation dose from plume passage. For consequence analyses when inhalation pathways are the primary concern, the respirable (aerodynamic diameters less than 10 microns) airborne release is used. For consequences involving the ingestion pathways, it is more appropriate to use the total (the sum of the respirable and nonrespirable) airborne release. In the specific case of this accident scenario, the respirable fraction (the respirable activity divided by the total airborne activity) is unity, so the respirable and total airborne activities are the same. The total source term is listed in Table Q-1.

Table Q-1. H-Separations total airborne source term

Nuclide	Airborne Release (Ci)
Am-241	6.57E-01
Pu-238	1.62E+00
Pu-239	4.23E-03
Pu-240	2.43E-01
Pu-241	3.26E+01
Pu-242	1.54E-02
Total	3.51E+01

Classification of release into FDA radionuclide groups

The Pu-238 + Pu-239 + Am-241 group is the only one of the five radionuclide groups that is represented. This group has a DIL of 2 Bq kg^{-1} (or 2 Bq L^{-1} for milk or water) The only one of the fifteen additional radionuclides evaluated in FDA (1998) that is in this source term is Pu-241. Pu-241 has a DIL of 120 Bq kg^{-1}. DILs for Pu-240 and Pu-242 are not given in FDA (1998).

Evaluation of the deposition needed to exceed a DIL

Assume a unit deposition of 1 Bq m^{-2} (2.70×10^{-11} Ci m^{-2}) of the nuclide mix, and that all radionuclides deposit similarly. In this case, the relative concentrations of the deposited material will be the same as that released. The quantities of the individual radionuclides present for this unit deposition are given in Table Q-2.

Table Q-2. Areal concentrations for a unit deposition

Nuclide	Areal concentration per unit deposition (Bq m^{-2})
Am-241	1.87E-02
Pu-238	4.61E-02
Pu-239	1.20E-04
Pu-240	6.92E-03
Pu-241	9.28E-01
Pu-242	4.38E-04

The concentrations in various foodstuffs due to this unit deposition may now be evaluated. The concentration of a particular radionuclide in a foodstuff is equal to the deposition times the (radionuclide-specific) overall transfer factor. Division of the DIL by the concentration in the foodstuff resulting from a unit deposition gives the deposition needed for a DIL. This process is presented in Tables Q-3 and Q-4 for the dairy pathway.

Aggregated transfer factors for plutonium and americium are taken from Appendix G. Plutonium and americium encompass all elements released in scenario 1-RD-2.35.

Table Q-3. Radionuclide concentration in milk per unit deposition of particulate mix

Nuclide	Areal concentration per unit deposition (Bq m^{-2}) of mix	Aggregated transfer factor T_{milk} (m^2 L^{-1})	Concentration in milk (Bq L^{-1}) per unit deposition	Radionuclide Group concentration (Bq L^{-1})	Radionuclide Group
Am-241	1.87E-02	1.21E-05	2.27E-07		
Pu-238	4.61E-02	8.90E-06	4.10E-07	6.38E-07	Pu-238 + Pu-239 + Am-241
Pu-239	1.20E-04	8.90E-06	1.07E-09		
Pu-240	6.92E-03	8.90E-06	6.15E-08	NA	NA
Pu-241	9.28E-01	8.90E-06	8.25E-06	8.25E-06	Pu-241
Pu-242	4.38E-04	8.90E-06	3.90E-09	NA	NA

Table Q-4. Derived response levels for the milk pathway

Radionuclide Group	Radionuclide Group concentration (Bq L^{-1}) per unit deposition	DIL (Bq L^{-1})	Deposition of mix corresponding to 1 DIL (Ci m^{-2})
Pu-238 + Pu-239 + Am-241	6.38E-07	2	8.47E-05
Pu-241	8.25E-06	120	3.93E-04

Table Q-4 presents depositions necessary to equal a DIL for the Pu-238 + Pu-239 + Am-241 group and the individual radionuclide Pu-241. The activity of the depositions includes that from all radionuclides in the mix, even though the radionuclide(s) in a limiting group may only be a small fraction of the total activity released. The most limiting radionuclide group for the milk pathway is the Pu-238 + Pu-239 + Am-241 group.

The processes outlined above may be repeated for other pathways. Table Q-5 lists total depositions of the radionuclide mix (in Ci m^{-2}) corresponding to 1 DIL of the Pu-238 + Pu-239 + Am-241 group and the individual radionuclide Pu-241 for all pathways.

Table Q-5. Derived response levels for all pathways

Pathway	Deposition of mix (Ci m^{-2})corresponding to 1 DIL of nuclide group	
	Pu-238 + Pu-239 + Am-241	Pu-241
Milk	8.47E-05	3.93E-04
Egg contents	1.67E-05	2.11E-04
Beef	5.96E-06	4.66E-05
Veal	3.49E-07	1.46E-06
Sheep	4.08E-06	2.27E-05
Lamb	1.77E-07	8.12E-07
Pork	2.57E-06	1.43E-05
Poultry	2.46E-06	1.33E-05
Fish	2.78E-08	1.17E-07
Produce-direct deposition	2.91E-09	1.22E-08
Produce - root uptake	6.74E-03	9.39E-02
Produce-soil adhesion	1.63E-04	6.85E-04
Grain-direct deposition	2.91E-09	1.22E-08
Grain-root uptake	2.18E-02	1.32E-01
Grain-soil adhesion	6.78E-05	2.85E-04
Beverage	8.33E-07	3.50E-06

In all cases, the Pu-238 + Pu-239 + Am-241 group is more limiting than Pu-241, reaching a DIL of the Pu-238 + Pu-239 + Am-241 group at a lower areal deposition than Pu-241. Since DILs are not additive between groups, the following discussion focuses on the Pu-238 + Pu-239 + Am-241 group only.

Table Q-6 ranks the pathways by the deposition needed to reach a DIL of the Pu-238 + Pu-239 + Am-241 group.

Table Q-6. Food pathways ranked by DRL

Pathway	Deposition of mix (Ci m^{-2}) corresponding to 1 DIL of Pu-238 + Pu-239 + Am-241 group
Produce-direct deposition	2.91E-09
Grain-direct deposition	2.91E-09
Fish	2.78E-08
Lamb	1.77E-07
Veal	3.49E-07
Beverage	8.33E-07
Poultry	2.46E-06
Pork	2.57E-06
Sheep	4.08E-06
Beef	5.96E-06
Egg contents	1.67E-05
Grain-soil adhesion	6.78E-05
Milk	8.47E-05
Produce-soil adhesion	1.63E-04
Produce - root uptake	6.74E-03
Grain-root uptake	2.18E-02

The direct deposition pathways reach the DIL first (i.e., they have the lowest DRLs). These pathways are important only for crops in the field at the time of airborne plume passage. The fish pathway is modeled for fish in stagnant ponds with no absorption of the radionuclides into the sediment. The ranking reflects the bioaccumulation factors for fish that are greater than unity. The meat pathways postulate ingestion of fodder contaminated by directly deposited radionuclides; fodder grown after the deposition and subsequently fed to animals would result in much lower concentrations in animal products.

Determination of range and area of consequences

The HOTSPOT computer code (Homann 1994) was selected to evaluate the consequences of particulate releases. In the following calculations, a source term equal to the total activity of 35.1 Ci is used, and the range and area affected for different meteorological parameters and DRLs found. The specific HOTSPOT Parameters used for the H-Area Coil & Tube release are listed in Table Q-7.

Table Q-7. HOTSPOT Parameters used for the H-Separations Coil & Tube release

Parameter	Average Meteorology	95% Adverse Meteorology
Release height	Ground	Ground
Wind speed	2.5 m/s	1.7 m/s
Surface roughness	100 cm	100 cm
Stability class	C	E
Deposition velocity	0.1/1/10 cm/sec	0.1/1/10 cm/sec
Release duration	120 min	120 min
Inversion layer	500 m	200 m

Meteorological data is consistent with TP-95-002, Revision 3, Consequence Assessment for
Emergency Preparedness Hazards Assessments (Hadlock 1997).

RESULTS

Tables Q-8 and Q-9 summarize ingestion pathway consequences for adverse meteorology. If a
contour (DRL) is not exceeded and/or the area affected is insignificant, "N/E" is entered for the
value. Figure Q-1 is typical of a plot produced by the HOTSPOT runs for adverse meteorology
and a deposition velocity of 1 cm s^{-1}. The contours of 5.96, 4.08, and 2.57 μCi m^{-2} correspond to
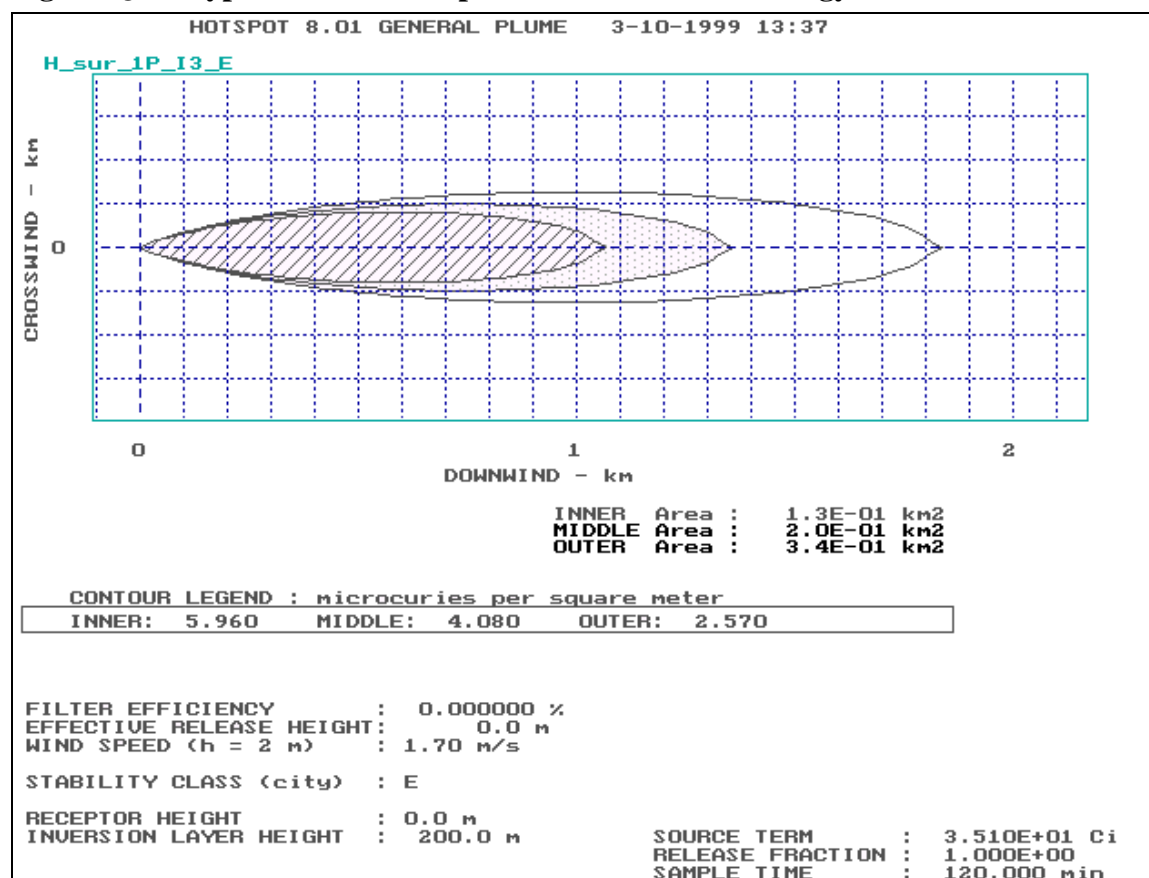the DRLs for beef, sheep, and pork pathways, respectively.

**Table Q-8. Ranges until deposition less than DRL, 95% adverse meteorology,
for three deposition velocities**

Pathway	DRL (Ci m^{-2})	0.1 cm s^{-1} (km)	1 cm s^{-1} (km)	10 cm s^{-1} (km)
Produce-direct deposition	2.91E-09	>100	>100	>100
Grain-direct deposition	2.91E-09	>100	>100	>100
Fish	2.78E-08	25	>100	32
Lamb	1.77E-07	3	30	7
Veal	3.49E-07	1.8	11	4
Beverage	8.33E-07	1.0	4	2.5
Poultry	2.46E-06	0.5	2	1.5
Pork	2.57E-06	0.5	2	1.5
Sheep	4.08E-06	0.4	1.4	1.1
Beef	5.96E-06	0.3	1.0	0.9
Egg contents	1.67E-05	0.2	0.6	0.6
Grain-soil adhesion	6.78E-05	0.09	0.3	0.3
Milk	8.47E-05	0.08	0.2	0.28
Produce-soil adhesion	1.63E-04	0.06	0.16	0.25
Produce - root uptake	6.74E-03	N/E	0.025	0.05
Grain-root uptake	2.18E-02	N/E	0.015	0.035

Table Q-9. Areas above DRL, 95% adverse meteorology, for three deposition velocities

Pathway	DRL (Ci m^{-2})	0.1 cm s^{-1} (km^2)	1 cm s^{-1} (km^2)	10 cm s^{-1} (km^2)
Produce-direct deposition	2.91E-09	>6.0E+02	>8.6E+02	>5.7E+02
Grain-direct deposition	2.91E-09	>6.0E+02	>8.6E+02	>5.7E+02
Fish	2.78E-08	2.2E+01	>5.3E+02	3.9E+01
Lamb	1.77E-07	7.3E-01	2.6E+01	3.3E+00
Veal	3.49E-07	3.2E-01	5.1E+00	1.8E+00
Beverage	8.33E-07	1.1E-01	1.4E+00	7.5E-01
Poultry	2.46E-06	3.2E-02	3.5E-01	2.7E-01
Pork	2.57E-06	3.1E-02	3.4E-01	2.6E-01
Sheep	4.08E-06	1.9E-02	2.0E-01	1.7E-01
Beef	5.96E-06	1.2E-02	1.3E-01	1.3E-01
Egg contents	1.67E-05	4.1E-03	4.0E-02	5.2E-02
Grain-soil adhesion	6.78E-05	N/E	8.9E-03	1.6E-02
Milk	8.47E-05	N/E	7.1E-03	1.4E-02
Produce-soil adhesion	1.63E-04	N/E	3.7E-03	8.0E-03
Produce - root uptake	6.74E-03	N/E	N/E	N/E
Grain-root uptake	2.18E-02	N/E	N/E	N/E

Figure Q-1. Typical HOTSPOT plot for adverse meteorology run

Tables Q-10 and Q-11 summarize ingestion pathway consequences for average meteorology. If a contour (DRL) is not exceeded and/or the area affected is insignificant, "N/E" is entered for the value. Figure Q-2 is typical of a plot produced by the HOTSPOT runs for average meteorology and a deposition velocity of 1 cm s^{-1}. Contours correspond to the beef (inner), sheep (middle), and pork (outer) DRLs.
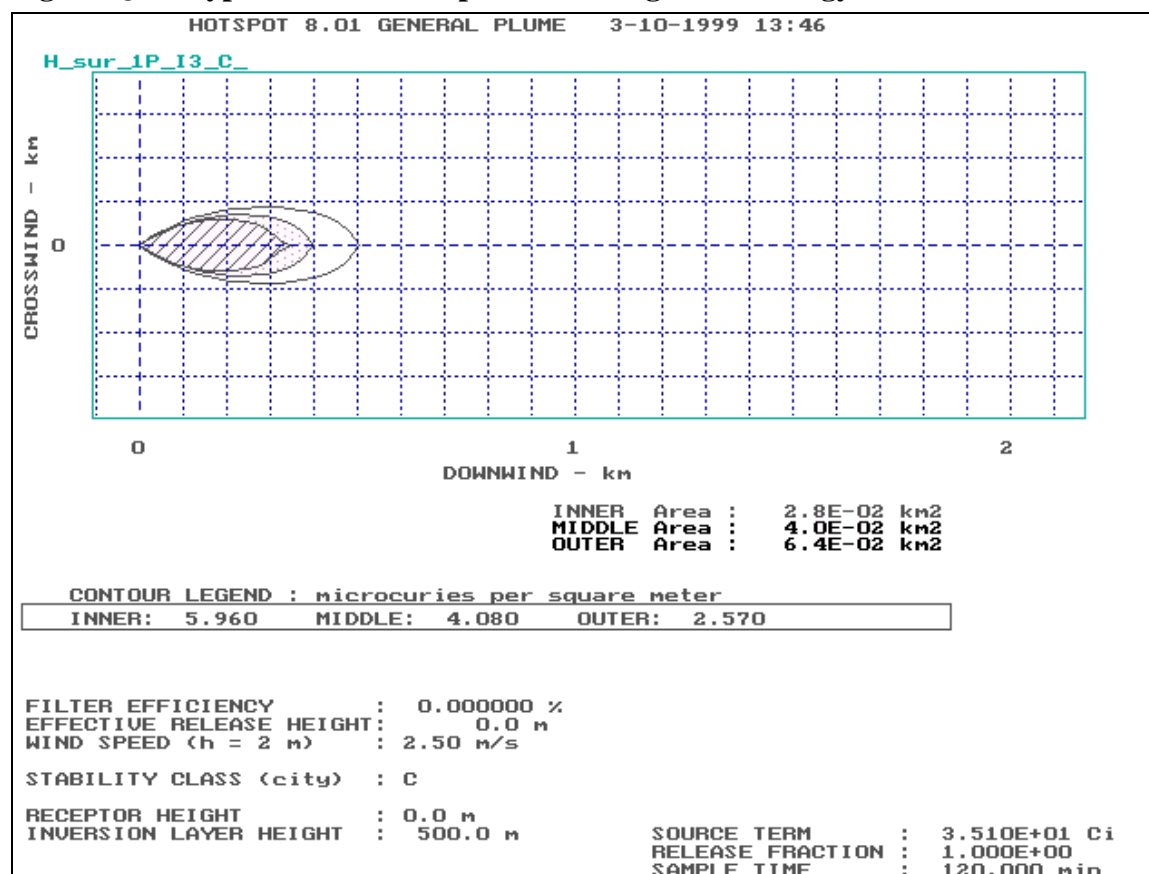
Table Q-10. Ranges until deposition less than DRL, average meteorology, for three deposition velocities

Pathway	DRL (Ci m^{-2})	0.1 cm s^{-1} (km)	1 cm s^{-1} (km)	10 cm s^{-1} (km)
Produce-direct deposition	2.91E-09	40	>100	>100
Grain-direct deposition	2.91E-09	40	>100	>100
Fish	2.78E-08	1.5	40	>100
Lamb	1.77E-07	0.6	2.0	15
Veal	3.49E-07	0.45	1.5	6.0
Beverage	8.33E-07	0.3	0.9	2.0
Poultry	2.46E-06	0.15	0.5	1.2
Pork	2.57E-06	0.15	0.5	1.2
Sheep	4.08E-06	0.10	0.4	0.9
Beef	5.96E-06	0.10	0.3	0.75
Egg contents	1.67E-05	0.06	0.2	0.5
Grain-soil adhesion	6.78E-05	0.03	0.1	0.25
Milk	8.47E-05	0.03	0.08	0.2
Produce-soil adhesion	1.63E-04	0.02	0.06	0.15
Produce - root uptake	6.74E-03	N/E	0.01	0.03
Grain-root uptake	2.18E-02	N/E	N/E	0.015

Table Q-11. Areas above DRL, average meteorology, for three deposition velocities

Pathway	DRL (Ci m^{-2})	0.1 cm s^{-1} (km^2)	1 cm s^{-1} (km^2)	10 cm s^{-1} (km^2)
Produce-direct deposition	2.91E-09	1.0E+02	>1.3E+03	>1.6E+03
Grain-direct deposition	2.91E-09	1.0E+02	>1.3E+03	>1.6E+03
Fish	2.78E-08	5.8E-01	8.6E+01	>8.7E+02
Lamb	1.77E-07	9.9E-02	8.0E-01	2.0E+01
Veal	3.49E-07	5.0E-02	4.8E-01	4.7E+00
Beverage	8.33E-07	2.1E-02	2.0E-01	9.8E-01
Poultry	2.46E-06	6.7E-03	6.7E-02	3.5E-01
Pork	2.57E-06	6.4E-03	6.4E-02	3.4E-01
Sheep	4.08E-06	4.1E-03	4.0E-02	2.2E-01
Beef	5.96E-06	2.6E-03	2.8E-02	1.5E-01
Egg contents	1.67E-05	N/E	9.9E-03	5.8E-02
Grain-soil adhesion	6.78E-05	N/E	N/E	1.5E-02
Milk	8.47E-05	N/E	N/E	1.3E-02
Produce-soil adhesion	1.63E-04	N/E	N/E	6.7E-03
Produce - root uptake	6.74E-03	N/E	N/E	N/E
Grain-root uptake	2.18E-02	N/E	N/E	N/E

Figure Q-2. Typical HOTSPOT plot for average meteorology run

The results presented in Thompson (1999b) demonstrate that higher deposition rates may not always result in consequences being manifest at greater ranges or larger areas. This is due to the plume being depleted close to the source at high deposition rates, thereby leaving less material to deposit far from the source.

CONCLUSION

Tables Q-8 to Q-11 present ingestion pathway consequences from H-Separations accident scenario 1-RD-2.35, Coil and Tube Failure. The Pu-238 + Pu-239 + Am-241 group is the most limiting for all pathways. The most significant pathways are those involving ingestion of freshly deposited radionuclides on produce and grain. Contamination of produce and grain exceeds FDA guidelines out to at least 40 km in all cases, and out to greater than 100 km in most cases. Additionally, under some conditions, it may be possible for fish and lamb foodstuffs to exceed FDA guidelines offsite. Sampling and analysis of these pathways would be recommended. Ranges for all other pathways are less than the distance to the site boundary (approximately 11 km), so protective actions for these other pathways would not be recommended for offsite locations.

APPENDIX R. SAMPLE UFOTRI INPUT FILE

```
&    SIGMA PARAMETER: BRIGGS PARAM. DATA SET: SAMPLE IPZ CALC.*
&    RELEASE HEIGHT:  60M 3.7E15 Bq         BDBAVG            *
&    2045 POP. OUT TO 100. KM    NSHFT=2  09/00 NSTOP=168     *
&    ADVERSE MET.  E/1.7NO BUILDING WAKE EFFECTS    1 M X 1M  *
POLGRID
 &GRDPAR
 IMAX=13,JMAX=72,
 R= 150.,   500., 1000., 3500., 5000., 7500., 10000., 10800.,
 11540., 30000., 50000., 75000., 100000.
 RA= 350., 990., 1010., 4950., 5050., 9900., 10100., 11500.,
 11600., 49900., 50100., 99900., 100100.
 &END
ISOTOPE
 &ISOPAR
 NABL=2,
 VA=5.E-4,0.005,
 IWASH=0
 &END
SOURCE
BDBAVG              1          1         0
        0         60    0.000E0   1.000E0    1.000E0
METEOZON
 SRSHTOST          1          1    0    1    2   10    0
      4332
00HOMOGEN          2  1.00E- 0
  5.69E+01          8
          0         0         0         0         0         0         0         0
          0         0         0         0         0         0         0         0
.
. (total of 72)
.
          0         0         0         0         0         0         0         0
PRINTOUT
 &OUTPAR
 NOOTKZ=1,NOOTMT=0,
 IACT=13*1
 &END
METEOROL
 &METPAR
 METIN=1,IWNDR=315,IWNDG=170,IREGN=0,IDIKAT=5,
 KLUGSI=2, IRELTS=1 RELTA=10., RELTN=60., RELTP=0.20,
 IRELRS=1, RELRA=10., RELRN=100.,
 NOSHFT=2,MIXLH=1600,1200,500,400,300,150,
 WPE=0.08, 0.10, 0.11, 0.18, 0.31, 0.42
 &END
END
 &TRIDAT
 NJAHRE=1,LWETE=3000,INUKL=2,IPRPLT=1,IWRITE=0,
 IDMP=1,IDMPMX=13,JDMP=1,JDMPMX=72,IFACHS=28,
 IEINR1=1,IEINR2=1,IEINR3=12,IEINR4=13,
 LT1=1,LT2=365,LT3=366,LT4=730,
 NSTOP=70,BODFAK=1.E+2,REMRE=0.3,IZFREI=1800,IFLENG=0,BODEIN=0.35,
 IRFIX=0,REFEST=5.0,ITEMPE=2500,ISTRBE=200,ISTRGR=200,
 RELFA=0.8,ARAU=0.1,
 IZUSD=0,IZUAUS=0,KAUSDR=0,1,0,0,0,0,0,0,0,0,0,0,
 Q(2,1)=1.0,Q(1,1)=0.0,Q1=3.7E15,
 NBOX=10,NINI=10,NINT=10,NOUT=10,NTIM=3,ITIMD=9,NCOW=250,
```

```
WWCOW=350.,WOCOW=150.
TIMEDO=0.,3.,7.,14.,21.,30.,90.,180.,200.,365., 370., 3650.,
FAKC1=0.5,FAKC2=0.35,FAKCP=0.05,FAKCW=0.1,
RCMIN=2.,LEAF=3.,BEWG=1440.,BEWGZ=160.,
RCMIN2=2.,LEAF2=3.,BEWG2=680.,BEWGZ2=170.,
RCMINP=2.,LEAFP=4.7,BEWGP=2700.,BEWGZP=300.,
RCMINW=2.,LEAFW=7.,BEWGW=2000.,BEWGZW=500.,
IPOT=233,IWHEAT=261,IMILK=315,IVEGE=124,IMEAT=206,DOSF=1.7E-11,
DOSHT=1.7E-15,DOSFOB=4.0E-11,BRRATE=3.33E-4,SKRATE=1.665E-04,
IMODEL=1,IARTBO=2,WILTP=0.1,SOILMX=0.5,IBODEX=1,
IMONT=1,IRRIGA=0,IRRIGG=0,IFLAGS=1,IFLAGR=1,IDEPHT=1,
IBODFX=0,ICOVER=1,IRELIN=181,IPHOTO=1,IARIV=0
&END
```